Determining the Optimal Nuclear Safety Regulatory Approach for South Africa's Expanding Nuclear Power Industry

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Abstract

South Africa is poised to expand significantly its nuclear power generation industry. Considering that the current South African nuclear safety regulatory approach is applied to regulate the operation and maintenance of one mature nuclear power plant, it is expected that significant adaptation of this approach will occur for the regulatory system to accommodate the planned industry expansion. This dissertation tests the hypothesis that the optimal nuclear safety regulatory approach for South Africa's planned nuclear industry can already be determined by systematically comparing the suitability of various alternatives in use in the international nuclear industry. Investigating the validity of this hypothesis improves the understanding of the possibilities available for future nuclear safety regulation in South Africa and aids preparations and decision-making in this regard.

Research was conducted on the various nuclear safety regulatory approaches applied internationally and on what determines the suitability of each approach in different circumstances. The characteristics of South Africa's current and planned nuclear power generation industry were investigated. Applying multi-criteria decision making analysis methodology, a test was developed and used to systematically assess the relative suitability of the various regulatory approaches to the South African context. The three primary approaches to nuclear safety regulation considered were the prescriptive approach, the performance based approach and the goal-setting approach. Based on currently available information, the test results show that the goal-setting regulatory approach is the optimal approach for South Africa's planned nuclear power industry.

However research findings also show that the state level bilateral cooperation the South African government would pursue to develop South Africa's fleet approach to the 9,6 gigawatt nuclear new build programme may have sufficient influence on South Africa's nuclear industry to change South Africa's optimal nuclear safety regulatory approach or make this plant specific. The benefits of aligning South Africa's nuclear safety regulatory approach with the approach applied in the fleet vendor company's country of origin may outweigh other considerations. The vendor company for South Africa's nuclear new build programme is not yet known.

Even though systematic comparison of the suitability of various regulatory approaches shows that the goal-setting nuclear safety regulatory approach is the optimal approach for South Africa, the hypothesis is shown to be false. The optimal nuclear safety regulatory approach for South Africa's planned nuclear industry cannot already be determined, since bilateral cooperation with the nuclear new build fleet vendor company's country of origin may be the dominant factor in shaping South Africa's nuclear safety regulatory approach.

In the interim and in the event that strategic regulatory alignment for the new build fleet is not embarked upon, the research findings and test results have an important implication: Applying the goal-setting approach as the dominant nuclear safety regulatory approach can optimize nuclear safety regulation of South Africa's nuclear industry.

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Abbreviations

AHTR	Advanced High Temperature Reactor
ALARP	As Low As Reasonably Practicable
ALARA	As Low As Reasonably Achievable
ASME	American Society of Mechanical Engineers
CNSC	Canadian Nuclear Safety Commission
DBA	Design Basis Accident
DOE	Department of Energy
DME	Department of Minerals and Energy
ECCS	Emergency Core Cooling System
EPR	European Pressurized-water Reactor
GW	Gigawatt
IAEA	International Atomic Energy Agency
NAIIC	Nuclear Accident Independent Investigation Commission (Japan)
NECSA	South African Nuclear Energy Corporation
NNR	National Nuclear Regulator (South Africa)
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (Unites States of America)
OECD	Organisation for Economic Co-Operation and Development
OLCs	Operational Limits and Conditions
ONR	Office for Nuclear Regulation (United Kingdom)
PBMR	Pebble Bed Modular Reactor
PRA	Probabilistic Risk Assessment
PWR	Pressurised Water Reactor
SAPs	Safety Assessment Principles
SAR	Safety Analysis Report
SCSSINP	State Committee for the Supervision of Safety in Industry and Nuclear Power (USSR)
SSCs	Structures, Systems and Components
STUK	Radiation and Nuclear Safety Authority (Finland)
TVO	Teollisuuden Voima (Finnish nuclear power company)
UCT	University of Cape Town
UK	United Kingdom
UNENE	The University Network of Excellence in Nuclear Engineering (Canada)
US	Unites States (of America)
USA	Unites States of America
USSR	Ukrainian Soviet Socialist Republic of the Soviet Union

VTT	Technical Research Centre of Finland
WANO	World Association of Nuclear Operators
WNA	World Nuclear Association
YVL	STUK documentation naming convention for ‘Regulatory Guides on Nuclear Safety and Security’ (Finnish)

1 Introduction

1.1 Background: South Africa's Nuclear Power Generation Industry

Eskom, the South African power utility, is the owner, operator and maintainer of the only commercial nuclear power plant (NPP) on the African continent. Koeberg NPP is a two unit, pressurized water reactor (PWR) with each unit having a rated capacity of 0,9 GW electrical. The reactor units were designed and built by the French company, Framatome and commissioned in 1984 and 1985. The units have a nominal 40 year design life. With ample design margins in hand, Eskom is aiming to extend the lifespan to at least 60 years.

South Africa is poised to expand significantly its nuclear power industry. In 2008 the Department of Minerals and Energy (DME) outlined the government's vision for the development of an extensive nuclear energy programme, stating that the long term goal for South Africa is to be self-sufficient in all aspects of the nuclear fuel cycle as well as the performance of research and development in the field of nuclear energy. The DME further states that South Africa intends on implementing a PWR programme applying a fleet approach and on developing an advanced high temperature reactor (AHTR) programme. [DME, 2008, pp. 4, 17, 28] In 2011 the Department of Energy (DOE) concluded that by 2030 South Africa will require "a nuclear fleet of 9,6 GW" [DOE, 2011, p.6].

South Africa's National Nuclear Regulator (NNR) is mandated by the National Nuclear Regulator Act to "exercise regulatory control related to safety over the siting, design, construction, operation, manufacture of component parts, and decontamination, decommissioning and closure of nuclear installations" [NNR Act, 1999, s.5(b)]. The objectives of the NNR include providing "for the protection of persons, property and the environment against nuclear damage through the establishment of safety standards and regulatory practices" [NNR Act, 1999, s.5(a)].

Within the international nuclear power industry various nuclear safety regulatory approaches are utilized, adapted to the need in different countries. In the United States of America (USA) for example, nuclear safety regulation follows a prescriptive approach and in the United Kingdom (UK) a goal-setting approach is applied.

In South Africa the NNR currently applies a partially performance based and partially prescriptive regulatory approach incorporating process based elements to regulate the safe operation of Koeberg NPP [NNR, 2016, p.4].

1.2 South Africa's Nuclear Safety Regulatory Approach in the Light of a Growing Nuclear Power Generation Industry

The International Atomic Energy Agency (IAEA) states that the choice of regulatory approach depends on what activities and facilities are to be regulated, the number of different facilities and activities requiring regulation and on whether the nuclear technology employed is tried and tested or cutting edge. The IAEA further states that the legal framework in which the regulator must operate affects the choice in regulatory approach as do the experience, capabilities and resources of the regulatory body and the operating organisation. The country's industrial practices must be taken into account, and the regulatory approach selected must promote nuclear safety culture. [IAEA, 2011, pp.28-32] [IAEA, 2013]

South Africa's planned industry expansion includes implementing a fleet approach to PWRs of newer technology than that of Koeberg NPP and developing first-of-a-kind nuclear technology. Considering the current South African nuclear safety regulatory approach applied to regulate the operation and maintenance of one mature NPP, it is expected that significant adaptation of this approach will occur for the regulatory system to accommodate the planned expansion. Potential also exists to optimize the regulatory approach to maximise efficiency and to review the safety of South Africa's nuclear industry. The future regulatory approach that will be selected by the NNR is not known at this point.

The IAEA states that a regulator should decide on its regulatory approach after a policy decision on whether to launch the nuclear power programme has been taken and when safety infrastructure preparatory work for construction of an NPP begins. The decision on approach should be taken and its implementation commenced before implementation of the first NPP begins. [IAEA, 2011, pp.2, 29] For the nuclear new build programme, South Africa currently falls in this phase.

However Eskom must ensure that it is prepared to participate in and operate under a changing nuclear safety regulatory system. It is in Eskom's interest to develop a robust approach to functioning optimally under a potentially different regulatory system and to inform and support the NNR in the choice of its future regulatory approach. Improving the understanding of the possibilities available and potentially identifying the optimal nuclear safety regulatory approach for South Africa will support Eskom's preparations and its capacity to make relevant decisions in respect of operations, skills development and strategic planning.

1.3 Hypothesis

This dissertation explores the validity of the hypothesis that the optimal nuclear safety regulatory approach for South Africa's planned nuclear industry can already be determined by systematically comparing the suitability of various alternatives in use in the international nuclear industry.

1.4 Research Questions

Several questions must be considered to facilitate testing of this hypothesis:

- What are the characteristics of the nuclear power generation industry that South Africa is planning for the future?
- What are the alternative nuclear safety regulatory approaches applied internationally in the nuclear power generation industry?
- What determines the suitability of each approach to different contexts?
- How does the NNR currently regulate the safe operation of Koeberg NPP and is the current approach the most effective approach for Koeberg NPP as it enters long term operation?
- Should two or more nuclear safety regulatory approaches operate in parallel and why might this be beneficial?
- Can South Africa simply copy a nuclear safety regulation system from a different country with an advanced nuclear industry?
- Considering the South African context, what constraints or limitations exist that would exclude certain regulatory approaches from possibly being implemented?
- How should South Africa adapt its nuclear safety regulatory approach for the planned industry expansion if adaptation is required at all?
- How can South Africa benefit from optimizing its nuclear safety regulatory approach?

These questions help to define the problem facing the South African Government, the NNR, Eskom, and in fact all of the South African nuclear industry’s stakeholders as each organisation determines or influences the choice of how best to regulate and manage the safety of South Africa’s changing and expanding nuclear power generation industry.

1.5 Scope

This dissertation concerns nuclear safety regulation of the nuclear power generation industry. The conclusions drawn specifically concern the nuclear safety regulation of South Africa’s current and planned nuclear power generation industry.

1.6 Methodology and Structure

In order to explore the validity of the hypothesis, a test is developed and implemented to systematically compare regulatory approaches and to identify the most suitable approach (or mix of approaches) for the South African context. The test applies multi-criteria decision making analysis methodology. The following methodology description provides the outline and structure of this dissertation.

Literature Review

In Chapter 2 the literature review is presented. The literature review aims to determine the extent to which the research questions have been answered in existing literature. In order to facilitate testing of the hypothesis, the literature review also aims to gather the input information necessary to define the characteristics of South Africa's current and planned nuclear power industry as well as the various nuclear safety regulatory approaches applied internationally. The literature review aims to identify factors that shape the suitability of the regulatory approaches to differing contexts and to identify any constraints that limit the options available for regulatory approaches in South Africa.

Theory Development

Based on the input information obtained in the literature review, the options that are available for nuclear safety regulatory approaches in South Africa are established in Chapter 3.

Test parameters are developed in Chapter 3 to represent the South African context and to reflect the legal requirements, recommendations and contextual and physical elements that have an influence on the optimal regulatory approach for South Africa.

Test Design

Following a multi-criteria decision making analysis methodology, a test matrix is developed in Chapter 4 which sets the test parameters against the options of regulatory approaches. A scoring system is developed to reflect the suitability of each regulatory approach to each test parameter.

Test Implementation

In Chapter 5 each test parameter is considered individually. The relative suitability of each regulatory approach to the test parameter for the South African context is discussed considering the strengths, weaknesses, pros and cons of each regulation system. A basis is developed and used to allocate scores indicating relative suitability of each approach to each parameter.

The scores are transcribed into the test matrix and the populated matrix is presented in Chapter 5.

Test Results, Interpretation and Discussion

In Chapter 6 the test results are determined and presented. Following multi-criteria decision making analysis methodology, for each regulatory approach the summation of the scores allocated for each test parameter reveals their relative suitability for the overall South African context. Important factors in the interpretation and analysis of the results are discussed.

Conclusion

Taking into account South Africa's nuclear power generation industry context including legal requirements, governance and organisational frameworks, culture and the different role players, conclusions are drawn in Chapter 7 on the most suitable, sustainable and efficient nuclear safety regulatory approach for South Africa. Conclusions are drawn on the validity of the hypothesis of this dissertation.

Implications of the Research Findings

Implications of the research findings are presented in Chapter 8.

2 Literature Review

In order to compare the suitability of various regulatory approaches, the South African context must be understood since the optimal approach is the one that best suits the characteristics of South Africa's planned nuclear power generation industry. A literature review is conducted on the current and planned nuclear power generation industry of South Africa. This includes the relevant role players, the characteristics of South African nuclear safety culture and the organisational framework within which the regulatory body operates, aiming to determine whether any of these may influence the optimal regulatory approach.

Literature review is conducted on the legal requirements applicable to the regulator and the nuclear power generation industry as well as on the broader governance frameworks in which the regulator must operate in order to identify whether any governance constraints exist that limit the options available for regulatory approaches in South Africa.

Literature review is further conducted to determine what options exist for nuclear safety regulation systems by reviewing information on theoretical regulatory approaches and on the regulatory approaches implemented in some example countries. Research is conducted into the suitability of the regulatory approaches to differing contexts.

Regulatory lessons learned from major nuclear accidents and from new nuclear build programmes are investigated to determine whether these may influence the optimal regulatory approach.

Testing the hypothesis requires a large amount of input information which is summarized in this chapter.

2.1 Role Players in South Africa's Nuclear Power Generation Industry

To determine whether any of the national and international role players or the organisational framework within which the NNR operates could influence the optimal regulatory approach, research was conducted on the role players involved in

- decision and law making relating to South Africa's nuclear power industry undertakings;
- design and manufacturing of NPP structures, systems and components (SSCs);
- nuclear power generation; and
- regulation of electricity and nuclear power.

The role players identified as having an influence on South Africa's optimal nuclear safety regulatory approach are described following together with a summary of the key findings illustrating the way in which they influence the regulatory approach.

2.1.1 The Government

In terms of its IAEA commitments, the South African government needs to fulfil its international obligations and promote international cooperation to enhance the global nuclear safety regime [IAEA, 2016, p.16]. The features of this regime were reviewed including international conventions, codes of conduct and internationally agreed IAEA safety standards.

The government is to establish the national policy, strategy and laws for nuclear safety to achieve this fundamental safety objective: Protect people and the environment from harmful effects of ionizing radiation. The government should apply the fundamental safety principles established in the IAEA Safety Standard: Safety Fundamentals (SF-1). [IAEA, 2006, p.4]

As described in IAEA documentation, the government's role includes legally establishing and maintaining a regulatory body and providing it with the resources necessary. The government is responsible for ensuring that the regulatory body is effectively independent in its safety related decision making. The IAEA further states that the government is to assign the prime responsibility for safety to the organization responsible for a nuclear facility or activity and must confer on the regulatory body the authority to require these organizations to comply with regulatory requirements and to demonstrate their compliance. The government's IAEA commitments include promoting nuclear safety culture. [IAEA, 2016, p.8]

The 2008 Nuclear Energy Policy states that the South African government pursues bilateral cooperation with other states that have nuclear programmes from/with which South Africa can learn, benefit, transfer technology or export South African nuclear services and manufactured goods [DME, 2008, p.20].

2.1.2 The Regulator

Researchers from the University Network of Excellence in Nuclear Engineering (UNENE) define a good regulatory approach as one that has a climate of openness, fairness and high expectations of safe performance that operators will internalize. International regulatory trends and approaches should be constantly reviewed and considered for adoption and implementation by a national regulator. UNENE further emphasizes that the responsibility for safe plant design remains with the designer and the responsibility for safe plant operation remains with the operator – these responsibilities are not held by the regulator. [UNENE, 2014, p.6]

The regulatory body, as designated and authorized by government, implements the government's national policy and laws for nuclear safety through establishing a regulatory programme and strategy and through establishing or adopting regulations or standards [IAEA, 2016, p.3].

The regulations should specify the requirements for all stages of the authorization process for nuclear facilities and for ensuring adequate protection, providing advance information to the operator on the requirements for each major stage of authorization [IAEA, 2002a, p.4].

In developing regulations and guides, account should be taken of international standards and recommendations, obligations imposed by conventions, industrial standards, advances in technology and regulations and guides from other countries [IAEA, 2002, p.9]. The regulatory process must provide a high degree of confidence that nuclear safety is optimized [IAEA, 2016, p.17].

The IAEA requires that regulatory bodies foster mutual understanding and respectful, open and formal relationships with licensees/applicants to achieve the common objective of ensuring nuclear safety. Although continuous improvement must be emphasized, the IAEA states that the regulator must also recognize the risks associated with modifying well established practices. [IAEA, 2016, pp.23, 24]

In South Africa, the NNR was established in terms of the National Nuclear Regulator Act (Act No. 47 of 1999) in order to regulate nuclear activities in South Africa. The NNR Act empowers the regulator to grant, amend or revoke nuclear authorisations and installation licences. Key objectives of the NNR from the act include providing safety standards and regulatory practices for the protection of persons, property and the environment from nuclear damage. [NNR Act, 1999, ss.5(a), 7(1)(a), 27(1)]

The Nuclear Energy Policy for the Republic of South Africa states that the NNR is responsible for ensuring efficient and cost-effective enforcement of compliance with legal requirements and internationally benchmarked regulatory requirements. It also states that the NNR will remain the responsible regulatory authority for the implementation of South Africa's planned nuclear industry expansion. [DME, 2008, pp.19, 23]

2.1.3 Nuclear Facility Operator

The IAEA emphasizes that the organization responsible for a nuclear facility or activity bares the prime responsibility for safety; this responsibility cannot be delegated. Mere compliance with regulations is not sufficient to demonstrate responsibility for safety. [IAEA, 2016, p.8]

2.1.4 Eskom

Eskom Holdings Limited ("Eskom") is a state owned enterprise, where the government of South Africa is the sole shareholder [Eskom, 2017a]. Eskom is the key player in the electricity supply industry in South Africa, operating 23 power stations with a total nominal capacity of 42 090MW and currently building new power stations, high voltage power lines and distribution networks [Eskom, 2017b]. Eskom is the owner, operator and maintainer of Koeberg NPP [Eskom, 2017b]. Eskom or its subsidiaries has been designated as the procurer for the 9,6 GW nuclear new build programme [DOE, 2016, ss.1, 4].

2.1.5 The Vendor

The vendor will enter into a contract to supply NPP(s) to South Africa. All of the world's leading NPP vendors have developed and voluntarily adopted 'The Nuclear Power Plant Exporters' Principles of Conduct'. The Principles of Conduct outline the role that the vendor will play and are briefly summarized following.

The vendor will verify that South Africa, as the customer state, is party to the necessary IAEA and United Nations Conventions including the IAEA's Convention on Nuclear Safety and the IAEA's Convention on the Physical Protection of Nuclear Materials. The vendor will verify that the customer state has the legislative, regulatory, and organizational infrastructure needed for implementing a safe nuclear power programme as advised in the IAEA Safety Standards. [NPP Exporters, 2014]

The vendor will export NPPs that apply high safety standards and are based on proven, reliable technology. The NPPs exported will apply the IAEA suite of Fundamental Safety Principles, Safety Requirements and Safety Guides, and will meet the regulatory requirements of the customer state. The vendor will ensure adequate information exchange with experts of the customer state to adapt the NPP design to the local, site-specific conditions and will include design provisions for emergency response and security requirements. The vendor will ensure that SSCs are constructed or manufactured and installed in accordance with appropriate nuclear standards, and the vendor will provide assurance of competent construction management. If the vendor makes use of subcontracts, the vendor will only subcontract to companies that have proven their qualifications and competence and have been evaluated by the vendor and found to meet the necessary requirements. The vendor will ensure that the customer state's human resources are adequately developed for safe, long-term operation, and that all necessary procedures and guidance are developed. The vendor will ensure adequate provision of safety documentation and safety analysis reports. [NPP Exporters, 2014]

The vendor will verify that the customer state has enacted national nuclear laws or developed a regulatory framework to ensure the management of spent fuel and radioactive waste and the decommissioning of closed-down nuclear facilities. The vendor will also ensure that the customer state has a legal regime in place able to provide prompt compensation to the public with adequate liability limits in response to the unlikely event of an accident. [NPP Exporters, 2014]

2.2 Nuclear Safety Culture in South Africa

Fundamental information about nuclear safety culture was reviewed primarily from US NRC documentation where nuclear safety culture is defined as “the core values and behaviours resulting from a collective commitment by leaders and individuals to emphasize safety over competing goals to ensure protection of people and the environment” [US NRC, 2016].

The best information available on South African nuclear safety culture is from the annual ‘Nuclear Safety Culture Report for Koeberg Operating Unit’. This report assesses the nuclear safety culture of all individuals associated with Koeberg NPP throughout South Africa. “Continuous Learning” and “Personal Accountability” are the two strongest South African nuclear safety culture traits. The weakest trait is “Respectful Work Environment”. [Eskom, 2017d]

Continuous Learning Trait:
The World Association of Nuclear Operators (WANO) defines important elements of this trait as “opportunities to continuously learn are valued, sought out and implemented” and “nuclear safety is kept under constant scrutiny through a variety of monitoring techniques” [WANO, 2013, p.8].

Personal Accountability Trait:
“All individuals take personal responsibility for safety” [WANO, 2013, p.5].

These two traits have been getting stronger consistently over time [Eskom, 2017d].

Respectful Work Environment Trait:
Anecdotal evidence from observations and discussions identifies that certain factors are evident and could contribute to a poor respectful work environment, such as improper implementation of the Employment Equity Act, low staff morale, and an unstable organisational structure characterised by

- leaders performing their tasks in “acting” positions without being formally appointed;
- suspensions of leaders;
- frequent leadership changes;
- skilled staff leaving in large numbers for overseas opportunities;
- unclear roles and responsibilities;
- lack of accountability;
- frequent decision changes, often from outside the Koeberg unit;
- frequent organisational restructuring; and
- poor communication.

Notably, South Africans generally have poor levels of rule compliance. This can be illustrated by, for example, Transparency International who ranks 180 countries and territories by their perceived levels of public sector corruption using a scale of 0 to 100, where 0 is highly corrupt and 100 is very clean. South Africa’s Corruption Perceptions Index score is 43 and South Africa is ranked 71st in the rankings from least to most corrupt. [Transparency International, 2017]

An additional example of South Africa’s poor rule compliance in a regulated environment is illustrated by the report of the Auditor-General of South Africa for the 2016/2017 financial year. In South Africa’s Auditor-General briefing dated 17 October 2017, one of the concerns raised related to the challenges faced by the Auditor-General of South Africa. These included threats of litigation by entities contesting audit findings, attempts to interfere in audits, personal threats, intimidation and delays in providing documentary evidence. Nineteen state-owned enterprises had been audited and only five obtained clean audits. Irregular expenditure at state-owned enterprises amounted to R2.884 billion. Some state-owned enterprises had outstanding audits due to failure to submit their financial statements. Unauthorised expenditure totalling R1.467 billion had been identified in the nineteen government departments audited. It was also suggested that language such as “irregular expenditure” was being used to cover up theft and fraud. These are just some examples illustrating South Africa’s poor rule compliance in a regulated environment from the 2016/2017 financial year report of the Auditor-General of South Africa and the associated briefing. [PMG, 2017]

2.3 South Africa's Current Nuclear Power Industry

Eskom is the owner, operator and maintainer of Koeberg NPP, a two unit, three loop PWR. Each unit has a rated capacity of 0,9 GW electrical energy. The reactor units were designed and built under a turnkey contract primarily by the French company, Framatome under licence from Westinghouse. Koeberg unit 1 was commissioned in 1984 and unit 2 in 1985. [SAR, 2017, p.3] Koeberg is designed for a nominal 40 year service life. With adequate design margins, Eskom aims to enter into Koeberg's life extension operational phase in 2025. After at least 20 years in the life extension operational phase i.e. in or after 2045, Eskom plans for Koeberg to enter the decommissioning phase. Koeberg NPP is a standard, commercial, generation II PWR.

The Pebble Bed Modular Reactor (PBMR), an AHTR, was previously being developed as a project by the PBMR (Pty) Ltd. Company in South Africa and Eskom had the role of customer and future operator of the demonstration NPP [Eskom, 2009]. In 2010 the South African government cancelled further investment in the project. In 2016 it was announced internally to Eskom that work has recommenced on an AHTR project with the aim of building and operating the AHTR as a proof-of-concept reactor [Reported speech from the Chief Executive Officer of Eskom, personal communication, 2016-03-18]. South Africa has a declared intention to pursue a nationally developed PBMR Programme subject to success of the first demonstration unit [DME, 2008, p.28].

NECSA, holding ASME III N Stamp (Nuclear Design) certification, designs and manufactures ASME III nuclear grade components for the world market [NECSA, 2017].

The NNR's Strategic Plan 2017-2021 states that NNR funding is a source of concern and it raises the risks of an insufficient number of staff and insufficient skills capacity [NNR, 2017a, pp.17, 21].

2.4 South Africa's Nuclear Power Industry Plans for the Future

In June 2008 South Africa's DME published the 'Nuclear Energy Policy for the Republic of South Africa'. Its objectives include promotion of nuclear energy as an important electricity supply option and attainment of global leadership and self-sufficiency in the nuclear energy sector [DME, 2008, pp.9-10].

The policy states that all nuclear energy sector activities will take place within a legal regulatory framework consistent with international best practice. The policy supports research, development and innovation in the use of nuclear technology, including participation in global nuclear energy technology innovation programmes. The policy promotes implementation of a fleet approach to reactor procurement to optimise the industrialization process and ensure economy of scale. [DME, 2008, pp.15-17]

The policy states that nuclear architectural engineering, component manufacturing and construction capability will be established to design, manufacture, market, commercialise, sell and export nuclear energy SSCs and services [DME, 2008, p.24].

In South Africa's 'Policy-Adjusted Integrated Resource Plan for Electricity from 2010 to 2030' South Africa's DOE concluded that by 2030 South Africa will require a nuclear fleet of 9,6 GW. The plan takes into account the costs associated with Generation III NPPs. [DOE, 2011, p.6]

South African Government Gazette Notice dated 14 December 2016 states that Eskom Holdings (SOC) Limited or its subsidiaries shall be the procurer for the 9,6 GW nuclear new build programme [DOE, 2016, ss.1, 4].

In an interview published on 18 January 2017, Eskom's chief nuclear officer Dave Nicholls stated that Eskom, or an Eskom subsidiary, has been designated as the owner-operator of the new NPPs. Mr. Nicholls explained that Eskom intends on buying a generic NPP that the vendor is already building in another country. Eskom aims to secure the rights to build the NPPs itself and to export locally manufactured nuclear components and entire NPPs in the future. [Eskom, 2017]

Eskom released a media statement on 1 February 2017 stating that 27 companies have stated that they intend to respond to the Request for Information relating to the proposed nuclear new build programme including major nuclear vendors from China, France, Russia and South Korea [Eskom, 2017c].

2.5 Legal Framework for the South African Regulatory Body

2.5.1 International Legal Framework

The IAEA, established by the United Nations in 1956, comprises 167 member states and is an intergovernmental forum for co-operation in the nuclear field. South Africa became a member in 1957. [IAEA, 2016a]

The IAEA states that its member states, under international law, must fulfil their national and international undertakings and obligations. Specific legally binding obligations on member states are set out in international safety related conventions. To support state implementation of these undertakings and obligations, the IAEA states that it publishes internationally agreed nuclear safety standards. Although not legally binding, these standards provide a basis for states to demonstrate their performance. The IAEA safety standards represent established international consensus requirements for the nuclear power industry. [IAEA, 2016, pp.xi, xii]

The Convention on Nuclear Safety is important in describing the international legal framework in which the South African nuclear industry operates. It legally commits member states to maintain a high level of safety by setting international benchmarks. The obligations set by the Convention are based on the principles contained in the IAEA's top tier Safety Standard "Fundamental Safety Principles (SF-1)". [IAEA, 2017] SF-1 was reviewed and two of the ten safety principles were found to be particularly relevant:

Principle 1: 'Responsibility for Safety' specifies that the prime responsibility for safety must rest with the organization responsible for facilities and activities that give rise to radiation risks; this responsibility cannot be delegated [IAEA, 2006, p.6].

Principle 2: 'Role of Government' states that the government is responsible for the establishment of an independent regulatory body which must have adequate legal authority, competence and human and financial resources to fulfil its responsibilities [IAEA, 2006, p.7].

2.5.2 South African Regulatory Body Legal Framework

The IAEA states that the regulator must prepare its regulations and guides in order to implement the laws and policies established by the government [IAEA, 2016, p.3]. For this reason the South African government's nuclear related regulations, notices and policies were reviewed since these, together with the NNR Act (Act No. 47 of 1999), form the basis and the minimum scope of the regulations that must be developed by the NNR.

Government regulation R388: "Safety Standards and Regulatory Practices" was found to have an influence on the NNR's approach to regulation. It specifies principal radiation protection and nuclear safety requirements including

- radiation dose limits,
- risk of fatality limits,
- optimization of radiation protection and nuclear safety through the application of the as low as reasonably achievable (ALARA) principle,
- prior safety assessment to identify all significant radiation hazards and risks,
- application of good engineering practice,
- fostering and maintaining a nuclear safety culture,
- regulatory approval of radiation protection and nuclear safety measures,
- application of defence-in-depth, and
- application of a graded approach [DME, 2006].

2.6 Theoretical Nuclear Safety Regulation Systems

The aim of this portion of the literature review is to determine what options exist for nuclear safety regulatory approaches and to identify factors that influence the suitability of the approaches to differing contexts.

2.6.1 Introduction to Nuclear Safety Regulation Systems

The regulatory approaches currently in use vary significantly from one country to another, depending on the size and maturity of the nuclear power programme in the country and on whether the country has an NPP vendor or imports NPPs. The choice of approach should suit the country's political, legal and industrial practices. The approach chosen has a major influence on the required number and qualifications of the regulatory staff and on the need for external support for the regulator. [IAEA, 2011, pp.30-32]

The approach chosen should be informed by the regulatory approach implemented in the country from where the nuclear technology is being adopted [IAEA, 2013, p.6]. After selection of the NPP vendor through the bid evaluation process, the IAEA recommends that the regulatory body implement a cooperation programme with the regulatory body of the vendor state and with other regulatory bodies that have experience regulating NPPs of the same type and from the same vendor as that selected. The IAEA states that there are clear benefits to be gained from this cooperation. For example, the technical standards of the vendor state or of a state having experience in regulating the type of NPP selected could be accepted for use by the regulator. The regulator can learn and benefit from the previously conducted independent analyses and safety assessments performed by the other regulators for the type of NPP selected. The other regulatory bodies can provide key insights into the quality levels achieved by the manufacturers and suppliers; this information can be used by the regulator to optimize its focus on the auditing and evaluating of these organisations. To take advantage of these benefits and potentially many more, the IAEA states that the regulator should implement a cooperation programme most importantly with the regulator of the vendor state and preferably also with the regulators of other states experienced in regulating the same type of NPP from the same vendor. The IAEA cautions that this could influence the intended regulatory approach tentatively planned before the vendor was chosen. [IAEA, 2011, pp.21, 35]

A regulatory system may include prescriptive and non-prescriptive regulations, striking an appropriate balance to match the workload that can be accommodated by and the skills of the regulator's staff [IAEA, 2002a, p.12].

Regardless of which regulatory approach is applied, the role of the vendor will remain the same: to export reliable, proven technology, high safety standard NPPs that apply the IAEA Fundamental Safety Principles; are designed in accordance with the IAEA Safety Requirements, with due consideration to the relevant IAEA Safety Guides; and that meet the regulatory requirements of the customer state [NPP Exporters, 2014]. How the vendor demonstrates that the regulatory requirements of the customer state are met and the amount of work that this will involve will depend on numerous factors including the regulatory approach applied in the customer state and on the regulatory approach applied in the vendor state.

2.6.2 Prescriptive Regulatory Approach

Prescriptive regulations clearly set out the regulatory requirements with the entire set of acceptance criteria, providing a clear roadmap for compliance to the licensee who must demonstrate that the regulatory requirements are met [IAEA, 2013, pp.13, 26]. This approach stresses the importance of regulations for safety requiring detailed development and establishing clear, comprehensive requirements and expectations which promote systematic interaction between the regulator and other parties [IAEA, 2011, p.32].

Both the IAEA and the Technical Research Centre of Finland (VTT) provide similar descriptions of prescriptive regulations, summarized as follows: The regulations specify the means and method to be used to comply with requirements. This results in well-defined licensing rules and a high level of regulatory certainty and predictability. Prescriptive regulations are more resource intensive and difficult to develop and update; the regulator requires more in depth and specific expert resources. Prescriptive regulations are narrowly applicable and require regular updates to remain current with technology and situational changes. Prescriptive regulations not kept up to date can end up promoting old technology having a negative effect on safety and economics. Prescriptive regulations reduce the time and skills necessary to perform a licensing review, to grant an authorization or to conduct an inspection since verification of compliance is comparatively easy. The prescriptive approach limits the flexibility of the operating organisation in achieving safety. Excessively detailed, prescriptive regulatory requirements can inhibit engineering innovation and good management initiatives, limiting the licensee's ability to strive for better performance. Safer means and methodologies than those prescribed are discouraged. The prescriptive approach can hinder the development of a strong safety culture in the operating organisation. [IAEA, 2002a, p.12] [VTT, 2001, s.1.1]

A highly prescriptive regulatory approach can shift the burden of proof of safety from the designer or operator to the regulator. UNENE states that if the designer or operator is required primarily to follow detailed rules set by the regulator and if the regulator misses something, part of the responsibility for safety has shifted from the designer or operator to the regulator. UNENE further states that a prescriptive approach without an integrated risk informed methodology can lead to misallocation of resources and regulatory focus towards severe but rare events, as opposed to more frequent ones with apparently milder consequences. An integrated risk informed prescriptive approach allows for prioritisation of risks, resources and focus. [UNENE, 2014, p.13]

A prescriptive approach can lead to a minimum compliance attitude and a culture of focussing only on rule compliance rather than considering safety. It can lead to an "us and them" relationship where the utility is seen to focus on production and the regulator on constraints to this.

2.6.3 Performance Based Regulatory Approach

The IAEA states that in this approach, the regulator prescribes only the basic, high level acceptance criteria. It is up to the licensee to set its own specific acceptance criteria and methodologies in order to meet the high level acceptance criteria. The regulator requires the licensee to demonstrate that criteria are satisfactorily met. This approach allows for fewer and less detailed regulations. [IAEA, 2013, pp.14, 30]

The US NRC states that performance based regulations have the following attributes:

- Measurable, calculable or objectively observable parameters exist to assess or monitor performance.
- Objective criteria to assess performance are established based on risk insights, deterministic analyses or performance history.
- Licensees have flexibility to determine how to meet the established performance criteria in ways that encourage and reward improvements.
- A framework is developed in which failure to meet a performance criterion, while undesirable, will not in itself result in an immediate safety concern. [US NRC, 2015]

The IAEA states that a high level of involvement is required from the operating organisation in determining how the regulations will be met. This encourages the operating organisation to own its overall responsibility for safety since the operating organisation is clearly responsible for producing the detailed level of requirements and the safety demonstrations. [IAEA, 2011, p.32]

Determining whether measures put in place by the operating organisation are adequate to meet the established safety criteria can be challenging and requires effective inter-organisational interaction and high level professional competence [IAEA, 2011, p.32]. The regulator must consider how the operating organisation interpreted the performance based regulation and judge whether it has been fulfilled in a case-specific manner [IAEA, 2002a, p.11]. Performance based regulations are comparatively easy to develop, low in administrative burden and have the advantage of not needing frequent updates to accommodate new information or technology [IAEA, 2002a, p.11].

This approach can sometimes lead to wasted efforts if the operating organisation cannot convince the regulator that what has been done is adequate to meet the safety criteria [IAEA, 2013, p.32].

The flexibility associated with performance based regulations tends to promote continual improvement on the part of the operating organisation, as better approaches are constantly sought [IAEA, 2002a, p.11]. Performance based regulations can improve the objectivity and transparency of regulatory decision making [US NRC, 2002, p.iii].

2.6.4 Goal-Setting Regulatory Approach

The regulatory authority or the law sets safety goals and the licensee must demonstrate adequate safety in relation to the safety goal [IAEA, 2013, p.15].

Examples of high-level numerical safety goals may include goals that are set so that the predicted health effects of normal operation and accidents in NPPs are small compared to other social risks [UNENE, 2014, p.20]. Examples of safety goals for existing NPPs from the IAEA include targeting a frequency of occurrence of severe core damage that is below about 10^{-4} events per plant operating year, and a probability of large off-site releases requiring short term off-site response that is below about 10^{-5} events per plant operating year [IAEA, 1999, p.11].

2.6.5 Risk Based Regulatory Approach

UNENE states that Probabilistic Risk Assessment (PRA) is performed to estimate the risk (the likelihood and the consequences) of a large number of failure event sequences on an NPP. In this way the different risks posed are numerically quantified and can be ranked in importance. In a largely risk based regulatory approach, numerical risk results from PRAs are utilized to focus regulatory attention on prioritised risks that present the greatest risk of harm. Risk based goals or requirements are set by the regulator and the licensee must demonstrate that the NPP design and operating conditions do not exceed the allowable levels of risk. UNENE finds that a risk based approach is logical; it quantifies and prioritises risk leaving major design and operating decisions up to the licensee, who decides how to meet the risk goals/requirements. This allows a great deal of flexibility to the licensee, promoting innovation and evolution. However a risk based approach can lead to uncertainty in licensing since the calculation and demonstration of numerical risk can be subjective or limited by a lack of knowledge. Some types of failure events and sequences are difficult to identify in PRAs resulting in some risk contributors being underestimated. [UNENE, 2014, p.13]

Wallis explains that, in modern nuclear safety regulation, risk based approaches are being incorporated into the traditional deterministic approaches. In traditional, deterministic safety regulations, the requirements for design basis accident analysis are specified to include the deterministic acceptance criteria and the conservative calculation methods to be applied. One run of the analysis code is performed and it is determined whether the acceptance criteria are met. In modern nuclear safety regulation, it is becoming increasingly common for analyses to no longer focus on the single most penalizing scenario, but instead to include consideration of a wide range of scenarios and input assumptions that are varied probabilistically as the analysis code is run a large number of times. A range of results is generated with associated probabilities. The results are analysed statistically to obtain the required level of confidence that the acceptance criteria would not be exceeded. Wallis states that reactor licensees no longer have to show that they meet the acceptance criteria based on the results from a calculation of the single most penalizing scenario where all uncertainties are combined in the most conservative manner, instead they have to show that there is a high level of probability that the acceptance criteria would not be exceeded. [Wallis , 2006, pp.1586, 1587]

2.6.6 Process Based Regulatory Approach

The literature review on theoretical nuclear safety regulatory approaches did not identify any information on a process based regulatory approach. Looking outside of nuclear industry related sources, some general information defining the process based regulatory approach was found.

The Organisation for Economic Co-Operation and Development (OECD) states that process based regulations are regulations requiring organisations to develop processes that ensure a systematic approach to controlling and minimising risks. OECD explains that process based regulation is based on the principle that the organisation will be more effective in identifying hazards and developing lowest cost solutions than the regulatory authority. Process based regulation is well suited to organisations having multiple and complex sources of risk. In the example discussed by the OECD of process based regulation of seafood safety in the USA, the regulated process requires producers to analyse the stages of the production process, identify key points at which hazards arise and put in place site-specific strategies to manage the hazards. [OECD, 2002, p.136]

May states that a regulatory approach mandating a process that can be either highly prescriptive or defined in terms of the desired outcomes of that process is called a management based regulatory approach. May explains that, under the management based regulatory approach, regulated organisations establish regulator approved management processes for identifying and correcting deficiencies. In this approach, responsibility is placed in the hands of the industry. [May, 2004, pp.2, 8, 12]

Coglianese and Lazer state that there exists comparatively little analysis of management based regulation as a general regulatory approach. Although little literature exists on the management based regulatory approach, it has been implemented in a variety of regulatory contexts around the world. This approach compels regulated organisations to improve their internal management. Coglianese and Lazer state that typically, under the management based regulatory approach, regulatory criteria specify that organisations must develop processes for hazard identification, implementing risk mitigation actions, and procedures for monitoring and correcting problems. In addition, a process must be established for evaluating and refining the organisation’s management with respect to its objective. Management based regulation requires organisations to develop processes based on the information they gather and on analysis that they perform. Coglianese and Lazer report that this regulatory approach places the responsibility for decision-making with those most knowledgeable about the risks and potential control methods. The actions that the organisation takes under a management-based approach may therefore be more cost effective and successful than under government-imposed regulatory standards. Coglianese and Lazer find that the management-based regulatory approach allows the organisation flexibility to experiment and find better, more innovative solutions. [Coglianese and Lazer, 2003]

2.7 Country Specific Examples of Nuclear Safety Regulation Systems

The aim of this portion of the literature review is to further explore the options existing for nuclear safety regulatory approaches, how they are implemented in practice and to identify factors influencing the suitability of the approaches to differing contexts. For each example country the overall regulatory approach was reviewed and a specific application was researched to better understand the application of the approach. The specific application considered was how the regulatory approach is applied to the case of the acceptance criteria for the design of the Emergency Core Cooling System (ECCS). This specific example facilitates a more detailed comparison of the regulatory approaches. The characteristics of the nuclear industry regulated in each country were briefly reviewed to better understand the country specific context.

2.7.1 United States of America - a Prescriptive Approach

The regulatory approach of the United States Nuclear Regulatory Commission (NRC) is classified by the IAEA as a prescriptive approach and is used by the IAEA as a reference example. The IAEA states that the NRC has developed its regulatory infrastructure in detail with nuclear safety requirements formulated in terms of required systems and plant features for NPPs. The NRC regulatory literature is large and complex, consisting effectively of a long checklist of requirements for safety-related SSCs. In the USA compliance with regulatory requirements is deemed to provide reasonable assurance of adequate protection. [IAEA, 2013, pp.18, 19]

The regulations are highly prescriptive and provide explicit acceptance criteria [UNENE, 2014, p.25].

NRC Regulations Title 10, Code of Federal Regulations section 50.46: “Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors” includes:
“(a)(1)(i) Each boiling or pressurized light-water nuclear power reactor fuelled with uranium oxide pellets within cylindrical zircaloy or ZIRLO cladding must be provided with an emergency core cooling system (ECCS) that must be designed so that its calculated cooling performance following postulated loss-of-coolant accidents conforms to the criteria set forth in paragraph (b) of this section.”
“(b)(1) *Peak cladding temperature.* The calculated maximum fuel element cladding temperature shall not exceed 2200° F.
(2) *Maximum cladding oxidation.* The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.
(3) *Maximum hydrogen generation.* The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react” [US NRC, 2007].

The NRC states that historically it relied on prescriptive regulations that specified a rigid solution to a licensee on how to achieve a safety objective. The NRC states it employed a deterministic analysis approach coupled with a defence-in-depth approach where regulators postulated what they considered to be credible sequences of failure events and deterministically analysed the consequences. The NRC created regulations enforcing requirements for redundant safety features that could prevent or mitigate the deterministically identified consequences. [US NRC, 2010, pp.70-73]

Wallis explains that the traditional safety regulations of the US NRC specify certain physical limits, such as the peak clad temperature, which shall not be exceeded in a design basis accident. These regulations describe conservative calculation methods and specify deterministic acceptance criteria to be applied in the design basis accident analysis. The analysis code produces a single set of results and one run of the code is performed. The results are then compared with the acceptance criteria. [Wallis , 2006, p.1586]

This approach did not allow for effective prioritization of accident scenarios and it did not allow for effective judgment to be made as to whether the cost of additional safety measures produced a commensurate increase in safety margins. In 1994 it was concluded that the NRC's practices threatened America's nuclear power generation industry by making its pricing non-competitive. It was recommended that the NRC place greater emphasis on performance based regulation, allowing licensees flexibility in determining how to accomplish regulatory objectives. In 1995 the NRC adopted a policy encouraging broad application of PRA to optimise decision making on safety issues and to reduce unnecessary burdens on licensees. The NRC policy still maintained the deterministic and defence-in-depth based approaches as the highest order approaches, but it specified that the insights provided by PRA should be used to identify overly conservative regulatory requirements. [US NRC, 2010, pp.70-73]

The NRC today still maintains most of its original prescriptive regulations. Risk informed performance based regulations are being developed and implemented in an incremental, phased approach. [US NRC, 2016a]

The NRC states that it uses a risk informed regulatory approach to identify additional regulatory requirements where needed and to reduce unnecessary requirements created under the traditional deterministic approach. The NRC applies performance based regulation by setting a requirement for licensees to achieve a desired outcome without direction regarding how that outcome is to be obtained. The NRC states that its performance based regulations focus on identifying performance measures that ensure adequate safety margins and offer incentives to licensees to improve safety without regulatory intervention. [US NRC, 2016b]

As an example, Dey states that in 1992, the US NRC began a major initiative to develop requirements for containment testing that are less prescriptive and more performance oriented and risk informed than current requirements. This action was a result of findings that the economic burden of certain containment testing requirements was not commensurate with their safety benefits. Probabilistic risk assessment of reactor accident risks showed that the allowed containment leak rate could be increased without significantly affecting the accident risk. This could justify relaxing the allowable containment leakage rate. Risk analysis showed that reducing the frequency of containment leak rate tests from three every 10 years to one every 10 years would to lead to an undetectable increase in risk. This could justify increasing the interval for the containment leak rate test. In addition, analyses of operational experience data showed that establishing intervals for the containment local leak rate tests on the basis of the performance of containment isolation valves and penetrations would have a marginal impact on safety. In this performance based regulatory approach, valves and penetrations that perform well would be tested less frequently. [Dey, 1996]

Dey showed that, for the example of containment testing, when the NRC finalized its performance-oriented, risk-informed revision to its containment testing requirements, a resulting cost saving of approximately 70% of the remaining costs of the new US NRC requirements was achieved [Dey, 1996, p.308].

The NRC states that it does not indorse a risk based regulatory approach where decision making is based solely on PRA numerical results due to uncertainties associated with PRA. In contrast, risk informed regulation considers risk insights together with other factors to establish regulatory requirements. This risk informed approach enhances the traditional, deterministic approach. [US NRC, 1999, p.3]

In spite of efforts to move towards risk informed performance based regulations, the current suite of the NRC's regulatory documentation is large, detailed and complex with a great number of regulatory requirements [IAEA, 2013, p.18].

The USA has 99 reactors operated by 30 power companies. There are 65 PWRs and 34 boiling water reactors. There are 4 reactors currently under construction, applying Westinghouse design technology. Additional reactors are planned for construction. Nuclear reactors are designed in the USA. The USA is an exporter of nuclear technology. [WNA, 2016a]

2.7.2 United Kingdom - a Goal-Setting Approach

The regulatory approach of the UK's Office for Nuclear Regulation (ONR) is classified by the IAEA as a goal-setting approach and is used by the IAEA as a reference example.

The UK's Health and Safety at Work etc Act of 1974 sets overall safety goals:

- Employers are to ensure the health, safety and welfare of their employees as far as is reasonably practicable.
- Risks to the health and safety of those not in their employ are to be reduced as low as reasonably practicable (ALARP).
- Designers, importers and manufacturers are to ensure as far as reasonably practicable that use of their equipment will not cause risks to the health and safety of the users.
  [UK Government, 2018, s.6(1)(a)]

The ONR states that the fundamental requirement is for risks to be reduced ALARP. This is predominantly done by applying established good practice and standards. The onus is on the licensee to implement safety measures to the point where the costs of any additional measures would be grossly disproportionate to the risk reduction that would be achieved. [ONR, 2015, p.11]

The ONR states that its risk acceptance policy is quantified through set numerical goals. These goals assist the ONR staff in judging whether radiological hazards are being adequately controlled and whether risks have been reduced ALARP. The goals assist regulatory staff in targeting resources to where the risks are greatest. In assessing safety, inspectors judge the extent to which the goals are achieved. Some goals are in the form of dose levels; others are expressed as frequencies or risks. Numerical radiological dose risk goals are set for normal operational, design basis fault and radiological accident risks to people on and off the site. These are included in the Safety Assessment Principles (SAPs) used by the ONR to judge the adequacy of safety of a licence application. [ONR, 2014, pp.150-152] Two important risk levels are defined:

Basic Safety Level:
This risk level marks the boundary between the “unacceptable risk” region and the “tolerable risk” region. Where risk exceeds the Basic Safety Level, consideration should be given to shut down the facility or prohibit the activity. [ONR, 2014, pp.150-152]

Basic Safety Objective:
This risk level marks the boundary between the “tolerable risk” region and the “broadly acceptable risk” region. The Basic Safety Objectives form benchmarks that reflect modern safety standards and expectations. The Basic Safety Objectives also indicate a level beyond which further consideration of safety would not be a reasonable use of ONR resources. ALARP considerations may be such that the applicant/licensee is justified in stopping before reaching the Basic Safety Objective, but if it is reasonably practicable to provide a higher standard of safety then the applicant/licensee must do so by law. [ONR, 2014, pp.150-152]

The ONR states that licensees must demonstrate that they have done everything reasonably practicable to reduce risks by balancing the level of risk posed by their activities against the measures required to control that risk in terms of money, time or effort. The operating organisation is afforded the flexibility required to be innovative and to adopt practices that best meet its particular circumstances, encouraging continuous improvement. [ONR, 2016, p.17]

The characteristics of this approach include ensuring that outcomes are cost effective and without unnecessary burden as well as not being unduly risk averse [ONR, 2016b, pp.8, 9].

Williams, Potter and Harbison state that in the UK’s non-prescriptive regulatory approach, the licensee is free to propose any means to achieve the required level of safety but the licensee must clearly and comprehensively demonstrate that the proposals are adequate. This is achieved through the safety case which demonstrates the safety adequacy the proposals. The safety case must describe the safety concepts, supporting research and the resulting design criteria. The safety case identifies the operational limits and constraints for safe operation. [Williams et al., 1996, p.123]

The ONR's regulatory approach is underpinned by safety case assessments with the safety cases themselves being produced by the licensees [ONR, 2016, p.18].

The ONR states that a safety case is the totality of documented information, arguments and justifications developed by the licensee that substantiates the safety of the NPP, activity, operation or modification in question. A safety case provides a written demonstration that the relevant standards have been applied and that risks have been reduced ALARP, providing a clear and comprehensive demonstration that a facility can be operated or an activity can be undertaken safely. [ONR, 2016a, pp.5, 6]

The ONR assesses each safety case independently to reach a judgement on the adequacy of the safety case based on the overriding requirement that the safety case shows that the licensee has reduced risks ALARP [ONR, 2016, p.18]. The SAPs are used to support regulatory assessment of safety cases [ONR, 2015, p.17]. SAPs are guidance for ONR inspectors to facilitate consistent regulatory judgements; they are not mandatory requirements for licensees [ONR, 2014, p.7]. Safety cases are also assessed against the numerical risk goals [ONR, 2014, p.7]. In applying the SAPs, priority is given to achieving an overall balance of safety rather than satisfying each principle or making an ALARP judgement against each principle [ONR, 2016d, p.36].

It is the responsibility of the licensee to demonstrate and deliver nuclear safety [ONR, 2016c, p.12].

Specifically concerning the ECCS design, the relevant SAPs include:

- "Structures, systems and components that are important to safety should be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected to the appropriate codes and standards" [ONR, 2014, p.42].
- "The extent of safety system provisions, their functions, levels of protection necessary to achieve defence-in-depth and reliability requirements should be specified" [ONR, 2014, p.91].
- "All Class 1 protection systems should employ diversity in their detection of and response to fault conditions, preferably by the use of different variables" [ONR, 2014, p.92].
- "The design of safety systems should avoid complexity, apply a failsafe approach and incorporate means of revealing internal faults at the time of their occurrence" [ONR, 2014, p.95].
- "In determining the safety systems to be provided, allowance should be made for the potential unavailability of equipment" [ONR, 2014, p.96].

The ONR regulates 37 nuclear sites including a PWR, advanced gas cooled reactors, a research reactor and decommissioning sites [ONR, 2017]. The ONR regulates the design and construction of new NPPs [WNA, 2017].

2.7.3 Finland - a Performance Based Approach

The regulatory approach followed by Finland's Radiation and Nuclear Safety Authority (STUK) is classified by the IAEA as a performance based approach and is used by the IAEA as a reference example. The IAEA states that STUK sets high level acceptance criteria and does not define any specific method to meet these criteria. STUK allows the licensee full flexibility in determining how specific requirements are to be met and the licensee must adequately demonstrate that the requirements have been met. [IAEA, 2013, p.22]

VTT states that Finnish legislation gives the licence holder full responsibility for safety of the NPP. STUK issues regulations, sets detailed requirements for licensed operation and monitors plant operation. STUK's regulations clearly state the safety criteria, against which alternative solutions developed by the licensee can be judged by the regulator. As far as possible, the safety criteria and requirements specified are independent of specific technical solutions. [VTT, 2001, ss.2.1, 3.1, 3.3]

STUK's regulatory documentation is divided into two sections: Regulations and Regulatory Guides. [STUK, 2017] There is only one relevant regulation: "Regulation on the Safety of a Nuclear Power Plant" (STUK Y/1/2016). This regulation was reviewed; it is brief, providing high level acceptance criteria.

STUK publishes numerous YVL Guides effectively forming the actual regulatory system. STUK describes the rules for application of the guides, stating that the safety requirements are binding on the licensee while preserving the licensee's right to propose an alternative procedure or solution to that provided for in the regulations. If the licensee can convincingly demonstrate that its proposed procedure or solution will implement the required safety level, STUK may approve this different procedure or solution. [STUK, 2017a] Although the regulatory system allows for these deviations, in practice, solutions different to those normally implemented present a regulatory approval challenge since it may be difficult for the regulator to review and approve the associated specific safety case presenting unfamiliar arguments and analyses [VTT, 2001, s.3.3].

STUK requires that applicants/licensees keep an up-to-date PRA. Risk limits are defined. STUK requires that the design, construction and operation of an NPP be managed in a risk-informed manner so that safety is always prioritised. [STUK, 2013b]

In its assessment of the YVL-guides, VTT found that there are a number of cases where the guides are more prescriptive than desired by the overall Finish regulatory approach. It was found that STUK's regulations sometimes differ from international standard practices, making compliance with these regulations challenging for international vendors and suppliers. This results in difficulty in finding vendors and suppliers willing to make the changes necessary to meet the local regulatory requirements, higher prices, re-engineering and re-documentation work and increased time durations for supply of SSCs and services. STUK has declared its intention to move its focus away from inspecting technical details and towards inspecting and reviewing the work processes of the licensees. [VTT, 2001, s.6.5]

STUK's periodic inspection programme is focused on the licensee's main working processes [STUK, 2013, p.22].

Considering the example of the acceptance criteria for the ECCS design, the following extracts from STUK Regulation Y/1/2016 illustrate STUK's approach:

"Nuclear power plant safety and the technical solutions of its safety systems shall be assessed and substantiated analytically and, if necessary, experimentally" [STUK, 2015, p.4].

"In order to prevent accidents and mitigate the consequences thereof, a nuclear power plant shall be provided with systems for shutting down the reactor and maintaining it in a sub-critical state, for removing decay heat generated in the reactor, and for retaining radioactive materials within the plant. Design of such systems shall apply redundancy, separation and diversity principles that ensure implementation of a safety function even in the event of malfunctions" [STUK, 2015, p.7].

"The most important safety functions necessary to bring the plant to a controlled state and to maintain it must be ensured even if any individual component of a system providing the safety function is inoperable and even if any other component of a system providing the same safety function or of a supporting or auxiliary system necessary for its operation is simultaneously inoperable due to the necessity for its repair or maintenance" [STUK, 2015, p.7].

"Common cause failures shall only have minor impacts on plant safety" [STUK, 2015, p.7].

STUK's Guide YVL B.1 titled "Safety Design of a Nuclear Power Plant" includes the following statements relating to ECCS acceptance criteria:

"5108. An emergency core cooling system shall be provided to cope with coolant leaks in the primary circuit and the systems directly associated with it; it shall compensate for any loss of coolant or otherwise provide efficient reactor cooling in order to ensure that the design limits for fuel are not exceeded.

5109. The capacity of the emergency core cooling system shall be adequate to compensate for leaks of various magnitudes, with the largest postulated leak equalling the complete, instantaneous break of the largest primary circuit pipe.

5110. The operability and efficiency of emergency core cooling under postulated leak conditions shall be ensured through appropriate primary circuit configuration and the positioning of the emergency core cooling connections" [STUK, 2013a, p.19].

Finland has four reactors in operation, all supplied by foreign countries. A fifth foreign supplied reactor is awaiting an operating licence, a sixth foreign supplied reactor is currently under construction and additional foreign supplied reactor units are in the planning stages. Finland does not design and build nuclear reactors. [WNA, 2016] The utilities are dependent on international vendors and suppliers.

2.7.4 Canada - A Risk Informed, Moderately Prescriptive Approach

UNENE states that Canada implements a mixed approach to nuclear safety regulation, using risk based and prescriptive approaches. The prescriptive approach offers defence against accidents not well identified through PRA. The risk based approach ensures that the regulator's attention is focused on the highest priority risks, minimising misallocation of resources to truly rare low-risk events. Canada's approach is less prescriptive than that of the USA. [UNENE, 2014, p.13]

The regulatory document 'Physical Design: Design of Reactor Facilities: Nuclear Power Plants' published by the Canadian regulatory authority, Canadian Nuclear Safety Commission (CNSC), was reviewed. It comprehensively sets out requirements and guidance for new NPP licence applications that promote defence-in-depth, are risk informed and aligned with accepted international codes and practices. To the extent practicable, the requirements and guidance are technology-neutral. This document states: "An applicant or licensee may put forward a case to demonstrate that the intent of a requirement is addressed by other means and demonstrated with supportable evidence" [CNSC, 2014, p.i]. The CNSC prescribes high level criteria for the design of reactor facilities, including acceptable core damage and release frequencies. [CNSC, 2014, pp.4-5]

Considering the example of the acceptance criteria for the ECCS design, CNSC's requirements are stated less prescriptively than in the US NRC's approach, and it is up to the designer to justify how the acceptance criteria are met [UNENE, 2014, p.25]. The following is an extract from CNSC's 'Physical Design: Design of Reactor Facilities: Nuclear Power Plants':

"The ECCS shall meet the following criteria for all DBAs [Design Basis Accidents] involving loss of coolant:

1. All fuel assemblies and components in the reactor shall be kept in a configuration such that continued removal of the residual heat produced by the fuel can be maintained.

2. A continued cooling flow (recovery flow) shall be supplied to prevent further damage to the fuel after adequate cooling of the fuel is re-established by the ECCS.

The ECCS recovery flow path shall be such that impediment to the recovery of coolant following a loss of coolant accident by debris or other material is avoided.

The design shall ensure that maintenance and reliability testing can be carried out without a reduction in the effectiveness of the system below the OLCs [operational limits and conditions], if the testing is conducted when ECCS availability is required…" [CNSC, 2014, p.108].

Canada has developed its own range of NPPs and is a long-time leader in nuclear energy research and development. There are 19 reactors in Canada. Canada is an exporter of reactor systems. [WNA, 2016b]

2.7.5 South Africa – a Mixed Regulatory Approach

The NNR states that historically, it adopted a non-prescriptive regulatory approach where it set largely risk based overall safety criteria and the applicant had to submit a safety case demonstrating safety in respect to the overall safety criteria. The conditions contained in the approved safety cases became conditions contained in the nuclear authorisations granted by the NNR i.e. licence conditions. Licensee standards, specifications and even procedures were also adopted in a similar manner, resulting in a prescriptive approach but with the detailed requirements being originally established by the licensee. In the early 2000's, the NNR moved towards process based licensing for Koeberg NPP. In this approach, in addition to its principal licensing criteria (radiological dose risk limits) and conditions of the licence, the NNR requires that the licensee complies with certain high level process requirements that have been established by the licensee and approved by the NNR. [NNR, 2016, pp.3, 4, 10] A key enabler for this approach is the safety evaluation process, used by the licensee for evaluation of any proposed safety related changes to the plant or its safety basis.

In applying process based licensing, the NNR states that it places the onus on licensees' processes, competencies and self-assessments to manage nuclear safety. These requirements include generating and updating safety cases and detailed procedures. The NNR monitors the implementation of these processes through surveillances and audits. [Personal communication, NNR, 2017]

The NNR emphasizes that the ultimate responsibility for the safety of a nuclear facility rests with the applicant or operating organization. An advantage of process based regulation is that the responsibility for technical, detailed aspects of nuclear safety is more clearly placed in the hands of the licensee. The NNR notes that the extent to which process based licensing should be implemented depends on the maturity and robustness of the licensee's processes. For certain applications a prescriptive approach might be more appropriate. [Personal communication, NNR, 2017]

The NNR, as the need arises, provides directives to the licensee or applicant on the manner in which compliance with a given requirement or authorisation condition can be satisfied. In such cases the manner of compliance prescribed by the NNR is the only way deemed adequate to ensure compliance with the requirement. [Personal communication, NNR, 2017] Prescriptive regulatory requirements are thus specified.

The NNR has published requirements on risk assessment for nuclear installations and requires that nuclear installations comply with its principal safety criteria. These refer to limits on the risk of radiological dose to members of the public and workers from normal operations and accident conditions. The NNR does not prescribe how compliance with the principal safety criteria must be achieved and maintained. [NNR, 2008]

The radiological dose and risk limits for the public and workers are considered by the NNR to be the most fundamental measures for assessing nuclear safety. Their utilization contributes towards a consistent and transparent basis for regulatory decision making. [NNR, 2017b]

The NNR's safety standards describe principal safety requirements including defence-in-depth, ALARA, good engineering practice, quality management, safety culture and the application of a graded approach. The NNR requires that protection be optimized to provide the highest level of nuclear safety that can reasonably be achieved, in accordance with the ALARA principle. All practical efforts must be made to prevent and mitigate nuclear or radiation accidents. Robust safety case development is required. [NNR, 2017b]

As part of the process for licensing a new nuclear installation, the NNR requires that the applicant produce a safety case for each licensing stage [NNR, 2002, p.3]. The safety case must demonstrate that the facility or activity is capable of meeting the NNR prescribed limits for radioactive releases and radiation doses, and that the principles of ALARA, defence-in-depth and others have been applied [Personal communication, NNR, 2017]. The NNR draws up a licence for a facility or activity that encompasses the requirements, provisions and undertakings identified within the safety case. The NNR then implements a compliance inspection and audit programme. [NNR, 2002, p.10]

The NNR therefore implements a mixed nuclear safety regulatory approach, including elements of prescriptive, process based, performance based, risk based and goal-setting regulation.

2.8 Regulatory Lessons Learned from Major Nuclear Accidents

2.8.1 Three Mile Island Nuclear Accident (1979)

UNENE reported that the accident investigation found the U.S. regulations were too voluminous and complex, requiring immense effort for compliance. The regulations equated compliance with safety. There was no requirement to look beyond the limited, single component failure events specified by the NRC to be taken into account in NPP design. Subsequent to this accident, insights from PRAs were used more widely to reveal severe accident vulnerabilities and to identify regulatory requirements that attracted disproportionately high resources compared to the risk they mitigated. [UNENE, 2014, p.14]

2.8.2 Chernobyl Nuclear Accident (1986)

Investigation revealed that the NPP design violated the existing safety regulations but was nevertheless approved by the relevant authorities. It was reported that staff lacked an adequate nuclear safety culture and regulatory authorities were found to be lax in bringing plants into line with the safety standards and regulations. [Commission to SCSSINP, 1991, pp.10, 50]

The operating organization did not have ultimate responsibility for safety [UNENE, 2014, p.15].

It was also found that the regulatory regime was ineffective in developing and enforcing requirements. It did not function as an independent organisation and it was unable to counter production pressures. [IAEA, 1992, p.21]

2.8.3 Fukushima Daiichi Nuclear Accident (2011)

UNENE states that the inadequacy of the design of the NPP was known to the utility and the regulator before the accident but was not acted on. The regulator lacked separation from the utility. [UNENE, 2014, p.14]

The regulator had a negative attitude towards the importation of new knowledge and technology from overseas. In addition the regulatory body was created as part of the Ministry of Economy, Trade and Industry, an organization that promoted nuclear power. [NAIIC, 2012, pp.16, 17]

2.9 Nuclear Regulatory Lesson Learned from New Build Experience

This literature review revealed one key finding from the cost and schedule overruns occurring at the reactor construction at Olkiluoto, Finland. The operator, TVO, and the vendor, AREVA, state that one of the root causes is the evolution of Finnish regulations during the construction process introducing additional uncertainty into the licensing process. [UNENE, 2014, p.16]

3 Theory Development

The following theory development is necessary to test the hypothesis utilizing multi-criteria decision making analysis:

- Identify the objectives of the analysis.
- Identify the available options for achieving the objectives.
- Identify the test parameters for comparison of the available options.

The information obtained from the literature review and summarized in Chapter 2 forms the basis of this theory development.

3.1 Objectives of the Analysis

The objective of the multi-criteria decision making analysis is to determine the optimal nuclear safety regulatory approach for South Africa’s envisioned nuclear power generation industry. The optimal approach for South Africa is the one that is best suited to regulating the following nuclear power generation industry as determined by the literature review

- a generation II, standard technology PWR NPP in service since 1984, entering its life extension operational phase in 2025 and owned, operated and maintained by Eskom [SAR, 2017, p.3];
- research and development of a prototype AHTR by Eskom [Reported speech from the Chief Executive Officer of Eskom, personal communication, 2016-03-18] supported by [DME, 2008, p.28];
- a nuclear new build programme to construct a fleet of generation III PWR NPPs totalling 9,6 GW with Eskom being the designated procurer working with a vendor company [DOE, 2011, p.6] [DOE, 2016, ss.1, 4]; and
- the establishment of a national capability for the design, manufacture, construction and export of nuclear energy SSCs and services [DME, 2008, p.24].

3.2 Available Options for Achieving the Objectives

The literature review on nuclear safety regulatory approaches applied in the nuclear industry internationally identified the goal-setting, performance based, prescriptive, process based and risk based approaches.

Although purely risk based regulation is sometimes considered as a regulatory approach in its own right, it is normally applied as a supporting methodology to other approaches. Similarly, process based regulation is also applied as a supporting methodology to other approaches. These two supporting methodologies are not recognized by the IAEA as regulatory approaches.

The IAEA Convention on Nuclear Safety legally commits member states to maintain a high level of safety by setting international benchmarks within the nuclear industry [IAEA, 2017]. In addition the

IAEA warns that the regulator must recognize the risks associated with modifying well established practices [IAEA, 2016, p.24]. South Africa, as an IAEA member state, is subject to legally binding obligations set out in international safety related conventions and supported by internationally agreed IAEA nuclear safety standards representing established international consensus requirements for the nuclear industry [IAEA, 2016, pp.xi, xii].

The South African government requires that international best practice be followed for the legal nuclear regulatory framework and the government emphasizes the importance of applying internationally benchmarked regulatory requirements [DME, 2008, pp.15, 19]. This shows the government's policy intent of applying internationally benchmarked, best practices which is what the IAEA standards represent.

For these reasons only established regulatory approaches applied in the international nuclear power industry and endorsed by the IAEA are considered to be options available for South Africa.

Purely risk based and purely process based regulatory approaches are therefore not considered to be options for nuclear regulatory approaches in South Africa, although these may add value when applied as supporting methodologies.

In addition since only established regulatory approaches applied in the international nuclear power industry and endorsed by the IAEA are considered to be options available for South Africa, development of a regulatory approach that is new to the nuclear industry should not be considered as an option for South Africa.

3.3 Test Parameters for Comparison of the Available Options

During the literature review, the literature was scrutinized to identify requirements, recommendations or contextual or physical elements that have an influence on the optimal regulatory approach for South Africa.

The test parameters are selected to represent the South African context. They represent the factors identified through the literature review as having an influence on South Africa's optimal regulatory approach. The parameters represent the international and national legal requirements for nuclear safety regulation that are applicable to South Africa and that have an influence on the optimal regulatory approach. The test parameters reflect the South African government's policy decisions that have an influence on the optimal regulatory approach. They reflect influential recommendations identified in the literature review concerning qualities that a good regulatory approach should promote. The test parameters represent the influential characteristics of the nuclear industry environment in South Africa. They represent the physical elements of the nuclear industry that South Africa has in place and is aspiring to develop.

As literature was reviewed a list of these requirements, recommendations and contextual and physical elements which may have an influence on South Africa's optimal regulatory approach was generated. Duplicate items were then removed. The fifteen test parameters described below represent and envelop all of the factors identified in the literature review that may have an influence on South Africa's optimal nuclear safety regulatory approach. These parameters have been selected to facilitate assessing the relative suitability of the identified regulatory approaches to the South African context. For each parameter listed below key statements from the literature review as summarized in Chapter 2 are presented, explaining the basis for the identified parameter.

Parameter 1: Alignment with Internationally Agreed IAEA Safety Standards

South Africa, as an IAEA member state, has an obligation under international law to fulfil its international undertakings and obligations. To support state implementation of these, the IAEA publishes internationally agreed but not legally binding safety standards which provide a basis for states to demonstrate their performance in fulfilling their obligations. [IAEA, 2016, p.xi]

The South African government requires that international best practice be followed for the legal nuclear regulatory framework and that regulatory requirements be internationally benchmarked [DME, 2008, pp.15, 19]. This demonstrates the government's policy intent of applying internationally benchmarked, best practices which is what the IAEA standards represent.

All of the world's leading NPP vendors have adopted 'The Nuclear Power Plant Exporters' Principles of Conduct' which apply the IAEA suite of documentation: the Conventions, the Fundamental Safety Principles, the Safety Requirements and the Safety Guides [NPP Exporters, 2014].

In addition, UNENE recommends that international regulatory trends and approaches be constantly reviewed and considered for adoption and implementation by a national regulator [UNENE, 2014, p.6].

Parameter 2: Financial and Human Resource Suitability

The regulatory approach chosen will have a major influence on the size, structure and resources needed by the regulatory body including on the number and qualifications of the regulatory staff and on the need for external support for the regulatory body [IAEA, 2011, pp.29, 31].

The IAEA states that the government provides the regulatory body with the necessary resources and competence [IAEA, 2016, p.6]. South Africa's Nuclear Energy Policy states that the government is responsible for establishing the regulatory body and that the NNR is responsible for efficient and cost-effective regulation [DME, 2008, pp.18, 19].

The NNR's funding is limited. State grants have been reduced and there are limitations on income that can be generated through fees increases on nuclear authorisations [NNR, 2017a].

Financial and human resource suitability represents a characteristic of the nuclear industry environment in South Africa having an influence on the optimal regulatory approach.

Parameter 3: Cultural Suitability

The literature review on the safety culture of Eskom and its contractors revealed that the South African nuclear safety culture is characterised by individuals taking personal responsibility for safety, continuously learning and keeping nuclear safety under constant scrutiny. Trust and respect are cultural weaknesses. [Eskom, 2017d] An additional cultural weakness is rule compliance [Transparency International, 2017] [PMG, 2017].

Cultural suitability represents a characteristic of the nuclear industry environment in South Africa having an influence on the optimal regulatory approach.

Parameter 4: Suitability for Promoting Nuclear Safety Culture

The IAEA requires that governments promote nuclear safety culture [IAEA, 2016, p.4]. Fostering and maintaining a nuclear safety culture is also a national legal requirement in South Africa [DME, 2006, s.3.5]. The literature review revealed that a lack of nuclear safety culture contributed to the Chernobyl nuclear accident [Commission to SCSSINP, 1991, p.10].

This parameter represents a legal requirement.

Parameter 5: Suitability for Ensuring Responsibility for Nuclear Safety is Held by those Responsible for the Facilities and Activities

Principle 1 of the IAEA’s top tier Safety Standard "Fundamental Safety Principles” states that the prime responsibility for safety must rest with the organization responsible for facilities and activities that give rise to radiation risks [IAEA, 2006, p.6]. The IAEA states that government must make provision for assigning this legal responsibility to those responsible for the facilities and activities [IAEA, 2016, p.5].

Parameter 6: Suitability for Promoting Optimization of Safety

Optimization of radiation protection and nuclear safety through the application of the ALARA principle is a legal requirement in South Africa as identified in the literature review [DME, 2006, s.3.2]. The South African government also states that the NNR is responsible for ensuring efficient and cost-effective enforcement of compliance with legal requirements and internationally benchmarked regulatory requirements [DME, 2008, pp.19]. The IAEA emphasizes that the regulatory process must provide a high degree of confidence that nuclear safety is optimized [IAEA, 2016, p.18].

Parameter 7: Suitability for Promoting Defence-in-Depth

Application of defence-in-depth is a legal requirement in South Africa as identified in the literature review [DME, 2006, s.3.9].

Parameter 8: Suitability for a Predictable Licensing Process

The literature review found that an uncertain and evolving regulatory licensing process contributed to cost and schedule overruns during NPP construction in Finland [UNENE, 2014, p.16].

The IAEA recommends that regulations specify the requirements for all stages of the authorization process and for ensuring adequate protection, providing advance information to the operator on the requirements for each stage of authorization [IAEA, 2002a, p.4].

Suitability for a predictable licensing process is therefore identified as a quality that a regulatory approach should promote and a quality having an influence on the optimal regulatory approach.

Parameter 9: Suitability for Good Governance

UNENE states that a good regulatory approach defines a climate of openness and fairness [UNENE, 2014, p.6]. The IAEA states that the regulatory body must foster mutual understanding and respectful, open relationships with operating organisations [IAEA, 2016, p.23]. The approach should therefore support transparent and fair regulation, resisting corruption and individual bias.

Suitability for good governance is identified as a quality that a regulatory approach should promote and a quality having an influence on the optimal regulatory approach.

Parameter 10: Suitability for Accommodating a New Build Fleet of Reactors of Standardised Technology supported by a Vendor Company

South Africa aims to implement a fleet approach to PWR procurement [DME, 2008, pp.17, 28]. By 2030 South Africa will require a nuclear fleet of 9,6 GW of Generation III technology [DOE, 2011, p.6]. Eskom will be the procurer for the new build programme [DOE, 2016, s.4]. Eskom will be the main owner and operator of the NPPs [DME, 2008, p.23].

Eskom will contract a vendor to play a major role in the construction of the new build fleet of NPPs. Eskom intends on buying a generic NPP that the vendor is already building in another country and Eskom aims to secure the rights to build the NPPs itself. [Eskom, 2017]

This parameter represents a physical element of the nuclear industry that South Africa is aspiring to develop; the regulatory approach should be suitable for a fleet of this nature.

Parameter 11: Suitability for Prototype AHTR Development

The literature review revealed that Eskom is currently developing first-of-a-kind AHTR technology [Reported speech from the Chief Executive Officer of Eskom, personal communication, 2016-03-18]. The South African government has a declared intention to pursue a Pebble Bed Modular Reactor Programme and government supports research, development and innovation in the use of nuclear technology [DME, 2008, pp.16, 28]. This parameter represents a physical element of the nuclear industry that South Africa is aspiring to develop; the regulatory approach should be suitable for AHTR development.

Parameter 12: Suitability for International Export of Nuclear SSCs and Services

The literature review showed that South Africa aims to develop the ability to "market, commercialise, sell and export nuclear energy systems and services" [DME, 2008, p.24]. Eskom stated that ultimately it aims to secure the rights to export locally manufactured nuclear components and entire NPPs in the future [Eskom, 2017].

This parameter represents a physical element of the nuclear industry that South Africa is aspiring to develop which the regulatory approach should accommodate.

Parameter 13: Suitability for an Existing, Standard Technology, Aging Reactor

Koeberg NPP, a standard, commercial, generation II PWR, is currently in its operational phase and is intending on entering its life extension operational phase in 2025 [SAR, 2017, p.3].

This parameter represents a physical element of South Africa's current nuclear industry; the regulatory approach should be suitable for this existing NPP.

Parameter 14: Suitability for Promoting International Cooperation

South Africa, as an IAEA member state, has committed to promote international cooperation to enhance the global nuclear safety regime [IAEA, 2016, p.16]. The Convention on Nuclear Safety legally commits member states to maintain a high level of safety by setting international benchmarks within the nuclear industry [IAEA, 2017]. International cooperation is emphasized in the DME's Nuclear Energy Policy principles [DME, 2008, pp.15-17].

Parameter 15: Suitability for Promoting Bilateral Cooperation with another State

The 2008 Nuclear Energy Policy for South Africa states that South Africa pursues bilateral cooperation with other states that have nuclear programmes from/with which South Africa can learn, benefit, transfer technology or export South African nuclear services and manufactured goods [DME, 2008, p.20]. For the nuclear new build fleet, Eskom intends on buying a generic NPP from a vendor company and on securing the rights to build the NPPs itself and to export locally manufactured nuclear components and entire NPPs in the future [Eskom, 2017].

The IAEA states that the regulatory approach chosen should be informed by the regulatory approach implemented in the country from where the nuclear technology is being adopted [IAEA, 2013, p.6].

This test parameter therefore represents a policy decision taken by the South African government having an influence on the optimal regulatory approach.

4 Test Design

Following multi-criteria decision making analysis methodology, the identified test parameters are set against the available regulatory approach options in a matrix format as shown in the table on the following page.

A three point scale scoring system is selected. Although lacking in discrimination, this scale provides more reliable results in terms of attributing the same score to the same stimulus on different occasions than a five point scale. [UCT, 2015] The scoring system is utilized to score the suitability of each regulatory approach to each test parameter. A zero score indicates relatively poor suitability, a one indicates a basic level of suitability and a two indicates relatively good suitability.

Table 1: Design of the Test Matrix

Test Parameter Description	**Options**		
	Goal-Setting Approach	Performance Based Approach	Prescriptive Approach
Parameter 1: Alignment with Internationally Agreed IAEA Safety Standards			
Parameter 2: Financial and Human Resource Suitability			
Parameter 3: Cultural Suitability			
Parameter 4: Suitability for Promoting Nuclear Safety Culture			
Parameter 5: Suitability for Ensuring Responsibility for Nuclear Safety is Held by those Responsible for the Facilities and Activities			
Parameter 6: Suitability for Promoting Optimization of Safety			
Parameter 7: Suitability for Promoting Defence-in-Depth			
Parameter 8: Suitability for a Predictable Licensing Process			
Parameter 9: Suitability for Good Governance			
Parameter 10: Suitability for Accommodating a New Build Fleet of Reactors of Standardised Technology supported by a Vendor Company			
Parameter 11: Suitability for Prototype AHTR Development			
Parameter 12: Suitability for International Export of Nuclear SSCs and Services			
Parameter 13: Suitability for an Existing, Standard Technology, Aging Reactor			
Parameter 14: Suitability for Promoting International Cooperation			
Parameter 15: Suitability for Promoting Bilateral Cooperation with another State			

5 Test Implementation

5.1 Scoring the Suitability of each Approach to each Test Parameter

Addressing each test parameter individually, the suitability of each regulatory approach is considered taking into account the South African context. The relative suitability of each regulatory approach to the test parameter is discussed considering the strengths, weaknesses, pros and cons of the approach and their relevance to the South African context. A basis is developed and used to determine the resulting scoring of relative suitability. This section presents the arguments forming the basis for the suitability determinations. The resulting scores are also presented.

Parameter 1: Alignment with Internationally Agreed IAEA Safety Standards

Goal-setting, performance based and prescriptive regulatory approaches are all referenced in IAEA documentation and are used as valid reference examples of regulatory approaches by the IAEA.

Goal-setting approach score: 2

Performance based approach score: 2

Prescriptive approach score: 2

Parameter 2: Financial and Human Resource Suitability

NNR funding, insufficient number of staff and insufficient skills capacity are listed as NNR sources of concern [NNR, 2017a, pp.17, 21].

Prescriptive regulations are more resource intensive and difficult to develop and update, requiring more detailed and extensive expert knowledge from the regulator [IAEA, 2002a, p.11]. Prescriptive regulatory literature is large and complex [IAEA, 2013, p.18]. This approach is poorly suited to the South African regulatory body's situation.

A performance based regulatory approach allows for fewer and less detailed regulations since the regulator prescribes only the basic, high level acceptance criteria. Performance based regulations are comparatively easy to develop, low in administrative burden, and have the advantage of not needing frequent updates to accommodate new information or technology. [IAEA, 2002a, p.11] STUK, in its performance based approach, sets high level acceptance criteria and does not define any specific method to achieve these criteria [IAEA, 2013, p.22]. Determining whether measures put in place by the operating organisation are adequate to meet the established acceptance criteria can be challenging and requires a high level of professional competence from regulator staff [IAEA, 2011, p.32].

In a goal-setting regulatory approach, the regulator sets safety goals and the licensee must demonstrate adequate safety in relation to the safety goal [IAEA, 2013, p.15]. The ONR's regulatory approach is underpinned by safety case assessments with the safety cases themselves being produced by the licensees [ONR, 2016, p.18]. Assessing the adequacy of safety cases requires a high level of professional competence from regulator staff.

The performance based and goal-setting regulatory approaches are assumed to be similar in required resource intensity, and to be less resource intensive to the regulator than a prescriptive approach.

Goal-setting approach score: 1

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 3: Cultural Suitability

South Africa's nuclear safety culture includes strengths such as individuals take personal responsibility for safety, continuously learn and keep nuclear safety under constant scrutiny, and weaknesses such as poor rule compliance, trust and respect [Eskom, 2017d] [Transparency International, 2017] [PMG, 2017]. A highly prescriptive regulatory approach effectively consisting of a long list of rules that licensee staff must follow is assumed to be a poor fit with the local culture. A goal-setting approach providing licensees flexibility in choosing the manner in which they achieve the goals with the regulator judging the extent to which the goals are achieved is presumed to be the best fit culturally since licensee staff can take full personal responsibility for safety and gain benefit from improving results over time through the application of their strength in continuously learning and keeping nuclear safety under constant scrutiny. The goal-setting approach places the responsibility for demonstrating that risks have been reduced ALARP on the licensee. This means that the licensee takes full responsibility for determining the measures implemented to ensure safety which is a good fit culturally for individuals who take full personal responsibility for safety. A performance based approach is assumed to be an adequate fit culturally on the basis that it is a more rule based and less flexible approach than the goal-setting approach, but still allows the licensee to take personal responsibility for safety and apply continuous learning through the flexibility afforded to the licensee in being allowed to set its own specific acceptance criteria and methodologies in order to meet the high level acceptance criteria set by the regulator.

Goal-setting approach score: 2

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 4: Suitability for Promoting Nuclear Safety Culture

The prescriptive regulatory approach can hinder the development of a strong safety culture in the operating organisation [IAEA, 2002a, p.12]. In a prescriptive approach compliance with regulatory requirements alone can be deemed to provide the assurance needed for adequate protection [IAEA, 2013, p.19]. These requirements may not have been optimised for the particular situation which the licensee encounters. Focussing primarily on rule compliance does not adequately promote nuclear safety culture. Prescriptive regulation is therefore poorly suited to promoting individual nuclear safety culture.

In the goal-setting approach the operating organisation is afforded the flexibility required to be innovative and to adopt practices that best meet its particular circumstances, encouraging continuous improvement [ONR, 2016, p.17]. Licensees are responsible for demonstrating that they have done everything reasonably practicable to reduce risks and must generate safety cases providing a comprehensive demonstration of safety [ONR, 2016a, pp.5, 6]. This approach is assumed to be well suited to promoting nuclear safety culture, however one contentious point stands out: The fundamental requirement is for the licensee to take all measures to reduce risk where doing so is reasonable to the point where the costs of any additional measures would be grossly disproportionate to the further risk reduction that would be achieved [ONR, 2015, p.11]. While this optimizes safety, using a cost/benefit argument to define what safety measures need to be in place may not be entirely aligned with promoting nuclear safety culture which emphasizes safety over all competing goals to ensure protection.

A performance based regulatory approach requires a high level of involvement from the operating organisation in determining how the regulations will be met encouraging the operating organisation to own its overall responsibility for safety, since it is responsible for producing the safety demonstrations [IAEA, 2002a, p.11]. Licensees have flexibility to determine how to meet the established performance criteria in ways that encourage and reward improved outcomes [US NRC, 2015]. This approach is assumed to be well suited to promoting nuclear safety culture.

Goal-setting approach score: 1

Performance based approach score: 2

Prescriptive approach score: 0

Parameter 5: Suitability for Ensuring Responsibility for Nuclear Safety is Held by those Responsible for the Facilities and Activities

A highly prescriptive regulatory approach can shift the burden of proof of safety from the designer or operator to the regulator. If the designer or operator is required primarily to follow detailed rules set by the regulator and if the regulator misses something, part of the responsibility for safety has shifted from the designer or operator to the regulator. [UNENE, 2014, p.13] In a prescriptive approach compliance with regulatory requirements in itself can be deemed to provide reasonable assurance of adequate protection [IAEA, 2013, p.19]. This approach can lead to a culture of focussing only on rule compliance rather than considering safety. A prescriptive approach is considered to be poorly suited to this parameter.

A performance based regulatory approach requires a high level of involvement from the operating organisation in determining how the regulations will be met encouraging the operating organisation to own its overall responsibility for safety since it is responsible for producing the safety demonstrations [IAEA, 2002a, p.11]. STUK sets high level acceptance criteria and the licensee must adequately demonstrate to STUK that the requirements have been met [IAEA, 2013, p.14]. While this shows good suitability, the inherent weakness is that the regulator sets the high level criteria and requirements and is therefore responsible for ensuring that the requirements are not deficient.

The ONR's goal-setting approach places the onus on the NPP designer and operator to justify why further improvements to all aspects of safety cannot be practicably achieved [UNENE, 2014, p.29]. The ONR's regulatory approach is underpinned by assessing safety cases produced by the licensees to provide a comprehensive demonstration of safety [ONR, 2016, p.18]. While this shows good suitability, the fact that it is considered acceptable to use a cost/benefit argument to define what safety measures need to be in place may remove some level of ultimate responsibility for safety from the licensee. Effectively the licensee's responsibility may be interpreted to be to optimize safety financially instead of to be ultimately responsible for safety.

Goal-setting approach score: 1

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 6: Suitability for Promoting Optimization of Safety

As found by VTT, the prescriptive regulatory approach limits the flexibility of the operating organisation in achieving safety. Excessively detailed prescriptive regulatory requirements can inhibit engineering innovation and good management initiatives, limiting the licensee's ability to strive for better performance. Safer means and methodologies than those prescribed are discouraged. Prescriptive regulations are narrowly applicable and require regular updates to remain current with technology and situational changes. Prescriptive regulations not kept up to date can promote old technology having a negative effect on safety and economics. [VTT, 2001, s.4.3] This approach is poorly suited.

The flexibility associated with performance based regulations tends to promote continual improvement on the part of the operating organisation, as better approaches are constantly sought [IAEA, 2002a, p.11]. Performance based regulations provide licensees with flexibility to determine how to meet the established performance criteria in ways that encourage and reward improved outcomes [US NRC, 2015]. STUK allows the licensee full flexibility in determining how specific requirements are to be met [IAEA, 2013, p.22]. This allows the licensee to optimize safety but only within the constraints set by the regulator's criteria that are to be achieved.

The ONR's goal-setting approach optimizes safety by requiring licensees to implement safety measures to the point where the costs of any additional measures would be grossly disproportionate to the further risk reduction that would be achieved, demonstrating that they have done everything reasonably practicable to reduce risks [ONR, 2015, p.11]. This ensures that outcomes are cost effective and without unnecessary burden [ONR, 2016b, p.8]. By allowing a cost/benefit argument to determine what safety measures are required, a graded approach to ensuring safety may be adopted which optimizes safety by focussing on those things which are more effective.

Goal-setting approach score: 2

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 7: Suitability for Promoting Defence-in-Depth

Prescriptive regulations, such as those created by the US NRC, were created using a deterministic regulatory approach coupled with a defence-in-depth approach. The NRC's prescriptive regulations apply PRA to optimise decision making but the deterministic based and defence-in-depth based approaches are maintained as the highest order approaches. [US NRC, 2010, pp.70-73] Traditional, prescriptive regulations are assumed to be highly suited to promoting defence-in-depth.

The ONR's goal-setting approach requires licensees to take all measures to reduce risk where doing so is reasonably practicable. The onus is on the licensee to implement measures to the point where the costs of any additional measures would be grossly disproportionate to the further risk reduction that would be achieved. [ONR, 2015, p.11] If it is reasonably practicable to provide a higher standard of safety, then the licensee must do so by law [ONR, 2014, p.151]. This approach supports the implementation of defence-in-depth but only as far as is reasonably practicable.

In a performance based approach the licensee sets its own specific acceptance criteria and methodologies in order to meet the high level acceptance criteria and thus demonstrate safety. The degree to which defence-in-depth is applied depends on how many layers of defence are required to achieve the high level acceptance criteria. Defence-in-depth is therefore supported by this approach but only to the degree that the high level acceptance criteria demand.

Goal-setting approach score: 1

Performance based approach score: 1

Prescriptive approach score: 2

Parameter 8: Suitability for a Predictable Licensing Process

Prescriptive regulations establish clear requirements and expectations and promote systematic interaction between the regulator and other parties [IAEA, 2011, p.32]. They provide the licensee with a clear roadmap for compliance [IAEA, 2013, p.26]. Well-defined licensing rules and a high level of regulatory certainty and predictability exist. Prescriptive regulations reduce the time and skills necessary to perform a licensing review, to grant an authorization or to conduct an inspection since verification of compliance is comparatively easy. [IAEA, 2002a, p.11] This approach is well suited.

In the performance based approach the regulator sets clear high level criteria that must be met. However this approach can sometimes lead to wasted efforts if the operating organisation cannot convince the regulator that what was done is adequate to meet the safety criteria [IAEA, 2013, p.32]. Although STUK's performance based regulations allow licensees to propose an alternative procedure or solution to that provided for in the regulations, in practice solutions different to those normally implemented present a regulatory approval challenge since it may be difficult for the regulator to review and approve the associated specific safety case presenting unfamiliar arguments and analyses [VTT, 2001 s.3.3]. This shows a basic level of suitability.

The goal-setting approach, as implemented by ONR, sets clear safety goals and utilizes SAPs providing guidance to licensees/applicants. However this approach is subject to the same licensing weakness as that of the performance based approach: Solutions different to those normally implemented present a regulatory approval challenge due to their specific safety cases presenting unfamiliar arguments and analyses. This shows a basic level of suitability.

Goal-setting approach score: 1

Performance based approach score: 1

Prescriptive approach score: 2

Parameter 9: Suitability for Good Governance

Prescriptive regulations are inherently vulnerable to having unclear and non-transparent bases. Relative to prescriptive regulation, the NRC has found that performance based regulations can improve the objectivity and transparency of regulatory decision making [US NRC, 2002, p.iii].

STUK's performance based regulations clearly state the safety limit against which alternative solutions developed by the licensee can be judged by the regulator. The regulatory documentation aims to specify a safety level to be reached but not give prescriptions for certain solutions to be selected over others. [VTT, 2001, ss.3.1, 3.3]

Similarly the goal-setting approach offers the operating organisation the flexibility required to be innovative and to adopt practices that best meet its particular circumstances [ONR, 2016, p.17].

Setting a clear objective and allowing the operating organisation flexibility in how it attains that objective improves the objectivity and transparency of regulatory decision making, supporting good governance. However both the goal-setting and the performance based approaches are subject to the same weakness in that solutions different to those normally implemented present a regulatory approval challenge due to the unfamiliar arguments and analyses presented in the safety cases. This can result in a bias towards certain solutions over others.

The prescriptive approach is less well suited than the goal-setting and performance based approaches which both show a reasonable level of suitability to this parameter.

Goal-setting approach score: 1

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 10: Suitability for Accommodating a New Build Fleet of Reactors of Standardised Technology supported by a Vendor Company

The literature review revealed that when regulations differ from international standard practices, compliance with the regulations is challenging for international vendors and suppliers. This results in difficulty in finding vendors and suppliers willing to make the changes necessary to meet the local regulatory requirements, higher prices, re-engineering and re-documentation work and increased time durations for supply of SSCs and services. [VTT, 2001, s.5.2] A prescriptive regulatory approach is therefore poorly suited to accommodating the design standards and characteristics utilized by a vendor company as is required for the nuclear new build fleet programme.

A goal-setting approach, as applied by the ONR, is focussed on managing overall risks. In applying the SAPs to assess an NPP design, priority is given to achieving an overall balance of safety rather than satisfying each principle or making an ALARP judgement against each principle. [ONR, 2016d, p.36] This approach focussed on risk management is assumed to provide the greatest flexibility in accommodating the specific aspects of the vendor company's NPP design characteristics. The performance based regulatory approach offers less flexibility in accommodating a vendor company's design characteristics since performance based regulations are inherently more specific than the goal-setting regulations which are more based on overall risk management. The goal-setting approach is therefore better suited to this parameter than the performance based approach.

Goal-setting approach score: 2

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 11: Suitability for Prototype AHTR Development

Regulating the development of a prototype reactor requires a flexible regulatory approach. Since new technology and innovative ideas are being developed, a prescriptive approach is not suitable.

In researching risk based regulation, it was found that risk based regulation is well suited to first-of-a-kind nuclear technology development. UNENE states that risk based regulation quantifies and prioritises risk leaving major design and operating decisions up to the licensee, who decides how to meet the risk goals/requirements. This allows a great deal of flexibility to the licensee, promoting innovation and evolution. [UNENE, 2014, p.13] A regulatory approach primarily focussing on risk management is assumed to be the approach best suited to affording the flexibility required to accommodate the development of innovative technology. A goal-setting approach is considered to be best suited to development of a prototype reactor, since this approach is most focussed on risk management.

Considering the attributes of performance based regulations as described in section 2.6.3 'Performance Based Regulatory Approach', it is considered that it would be more challenging to utilize a performance based approach for the regulation of the development of a prototype advanced reactor.

Goal-setting approach score: 2

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 12: Suitability for International Export of Nuclear SSCs and Services

As a long term goal, South Africa intends on exporting NPP SSCs and services [DME, 2008, p.24]. In order to export successfully, account needs to be taken of the international regulatory requirements for the technology being exported. In order to export nuclear technology, it will need to be accepted by the importing country's nuclear safety regulator. To maximise the likelihood of a country's regulator accepting South Africa's NPP SSCs and services in the future, account should be taken of international trends in regulatory approaches. In this regard the literature review revealed that regulation through risk management with numerical risk goals facilitated by the application of PRA is an increasing global trend in nuclear safety regulation. Elements of regulation through risk management, applied to differing degrees, were identified in all three regulatory approaches under consideration making PRA a regulatory common ground regardless of the chosen regulatory approach. The common element identified was the application of PRA to identify, quantify and prioritise risks. All three regulatory approaches under consideration use risk insights to influence regulatory decision making. The three approaches differ in the degree to which they apply and rely on regulation through risk management. The goal-setting approach uses risk management as the primary mode of regulation. Performance based regulation, as applied by STUK, does apply regulation through risk management using PRA to support its performance based regulatory approach. The US NRC's prescriptive approach applies risk insights provided by PRA to its primarily deterministic and defence-in-depth based approach.

The scoring for this parameter is based on the degree to which the approaches apply PRA and risk based regulation since the literature review identified this as a global common ground in regulation and since the literature review identified the global trend of the increasing level of use of PRA in regulatory approaches over time.

Goal-setting approach score: 2

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 13: Suitability for an Existing, Standard Technology, Aging Reactor

Koeberg NPP has been in operation since 1984. It is operated by a mature organisation with an established nuclear safety culture.

The design basis of Koeberg NPP is based on deterministic analysis and defence-in-depth considerations with limited application of risk insights. The design basis of an NPP must be maintained to ensure overall integrity of the NPP, though enhancements can and should be made over time. The regulatory approach applied should ensure the maintenance of the plant's deterministic analysis and defence-in-depth basis. A prescriptive approach is best suited to maintaining these elements of the NPP's design basis.

Koeberg NPP has a substantial performance history which would allow for the development of performance based regulations based on the NPP's performance history. Monitoring performance is an important part of regulating a mature NPP. Continuous improvement can be driven through performance management. Trending performance over time can be used to identify any performance degradation which would be a key indicator to flag the need for regulatory intervention. A mature NPP is thus well suited to a performance based regulatory approach.

As lessons are learned over time and as technology progresses, it is an industry wide expectation that NPPs improve their levels of safety through design modifications and various safety enhancements. PRA has improved greatly since Koeberg NPP was designed. Modern PRA is and should be applied to the existing NPP to identify areas for improvement and to ensure that the overall levels of risk posed by the NPP are acceptable according to modern standards. Risk insights gained from modern PRA methods provide important insight into safety enhancements that can and should be implemented. In addition, risk management applying the ALARP principle can enhance the overall safety of the installation in a financially optimized manner. The goal-setting regulatory approach with its application of PRA and risk management in an ALARP manner is therefore an important part of regulating a mature NPP in order to bring it into alignment with modern safety standards in a cost effective manner.

Aspects of all three regulatory approaches are applicable to a mature NPP like Koeberg and can add value when incorporated into the regulatory approach applied. A mixed approach to regulation is therefore suitable for a mature NPP.

Goal-setting approach score: 1

Performance based approach score: 1

Prescriptive approach score: 1

Parameter 14: Suitability for Promoting International Cooperation

One of the reasons why international cooperation is important is when regulations differ from international standard practices, compliance with the regulations is challenging for international vendors and suppliers. This, as previously discussed, results in difficulty in finding vendors and suppliers willing to make the changes necessary to meet the local regulatory requirements, higher prices, re-engineering and re-documentation work and increased time durations for supply of SSCs and services. [VTT, 2001, s.5.2]

As described for parameter 12, the literature review did identify a common element to all three regulatory approaches under consideration: The application of PRA to identify, quantify and prioritise risks and to use risk insights to influence regulatory decision making. The three approaches differ in the degree to which they apply and rely on regulation through risk management. The goal-setting approach uses risk management as the primary mode of regulation. Performance based regulation, as applied by STUK, utilizes regulation through risk management using PRA to support its performance based regulatory approach. The US NRC's prescriptive approach applies risk insights provided by PRA to its primarily deterministic and defence-in-depth based prescriptive approach.

The literature review identified the global trend of the increasing level of use of PRA in regulatory approaches over time. An important element of international cooperation is performing international benchmarking and comparisons. This is well facilitated through the use of PRA since PRA is a regulatory common ground irrespective of the country's regulatory approach. In addition regulation through risk management utilizing PRA to provide risk insights best accommodates differing approaches to nuclear safety by providing licensees/applicants with the most flexibility in the manner in which they can achieve regulatory objectives. The scoring for this parameter is therefore, as for parameter 12, based on the degree to which the approaches apply PRA and risk based regulation.

Goal-setting approach score: 2

Performance based approach score: 1

Prescriptive approach score: 0

Parameter 15: Suitability for Promoting Bilateral Cooperation with another State

South Africa pursues bilateral cooperation with other states to further various objectives for its domestic nuclear industry [DME, 2008, p.20].

For the required nuclear new build fleet of 9,6 GW [DOE, 2011, p.6], Eskom has declared its intention to buy a generic NPP from a vendor company and to secure the rights to build and export these NPPs or parts thereof [Eskom, 2017].

Bilateral cooperation between South Africa and the country of the vendor company providing the new build fleet is judged to be the most important and influential state level bilateral cooperation aimed to be established within the scope of South Africa's nuclear power generation industry plans. Consideration of this particular bilateral cooperation between South Africa and the fleet vendor country therefore dominates the scoring for parameter 15.

Strategic alignment of South Africa's regulatory approach with the vendor country's regulatory approach would promote this bilateral cooperation between the two states.

South Africa's regulatory approach may be chosen to align with the regulatory approach implemented in the vendor company's country of origin. This would reduce the risk of local regulatory requirements necessitating that the vendor make changes to their NPP design, resulting in a cost benefit by minimizing re-engineering and re-documentation work and resulting in reduced time durations for supply of SSCs and services from the vendor company.

In addition, aligning South Africa's nuclear safety regulatory approach with the vendor country's approach would provide the benefit of the vendor country's regulator being able to fully support the NNR in developing and implementing its regulatory system for South Africa's nuclear industry expansion. The NNR would therefore have the support of a more experienced regulatory body and have expert assistance in developing and applying its regulatory system.

This possibility is supported by the IAEA recommendation that the regulatory approach chosen be informed by the regulatory approach implemented in the country from where the nuclear technology is being adopted [IAEA, 2013, p.6]. As summarized in section 2.6.1 'Introduction to Nuclear Safety Regulation Systems', the IAEA describes many benefits that can be gained from a strong cooperation between the regulator and the regulatory body of the vendor state.

It is not yet known who the fleet vendor company will be. The required information is thus not yet available to score the relative suitability of the regulatory approaches to the South African context. All three approaches are therefore allocated the same score since there is no basis currently available for differentiating between the suitability of the three approaches.

Goal-setting approach score: 1

Performance based approach score: 1

Prescriptive approach score: 1

5.2 Test Matrix Population

The scores determined in Section 5.1 'Scoring the Suitability of each Approach to each Test Parameter' are transcribed into the test matrix developed in Chapter 4 'Test Design'. The resulting populated test matrix is presented on the following page.

Table 2: Populated Test Matrix

Test Parameter Description	Options		
	Goal-Setting Approach	Performance Based Approach	Prescriptive Approach
Parameter 1: Alignment with Internationally Agreed IAEA Safety Standards	2	2	2
Parameter 2: Financial and Human Resource Suitability	1	1	0
Parameter 3: Cultural Suitability	2	1	0
Parameter 4: Suitability for Promoting Nuclear Safety Culture	1	2	0
Parameter 5: Suitability for Ensuring Responsibility for Nuclear Safety is Held by those Responsible for the Facilities and Activities	1	1	0
Parameter 6: Suitability for Promoting Optimization of Safety	2	1	0
Parameter 7: Suitability for Promoting Defence-in-Depth	1	1	2
Parameter 8: Suitability for a Predictable Licensing Process	1	1	2
Parameter 9: Suitability for Good Governance	1	1	0
Parameter 10: Suitability for Accommodating a New Build Fleet of Reactors of Standardised Technology supported by a Vendor Company	2	1	0
Parameter 11: Suitability for Prototype AHTR Development	2	1	0
Parameter 12: Suitability for International Export of Nuclear SSCs and Services	2	1	0
Parameter 13: Suitability for an Existing, Standard Technology, Aging Reactor	1	1	1
Parameter 14: Suitability for Promoting International Cooperation	2	1	0
Parameter 15: Suitability for Promoting Bilateral Cooperation with another State	1	1	1

6 Test Results, Interpretation and Discussion

The overall test results are determined for each nuclear safety regulatory approach by summing the scores allocated to that approach for each test parameter. The results are as follows:

Goal-setting approach total score: 22

Performance based approach total score: 17

Prescriptive approach total score: 8

Based on the information currently available, the multi-criteria decision making analysis process utilized to systematically compare the alternative regulatory approaches has revealed that the goal-setting approach stands out as the nuclear safety regulatory approach best suited to the South African context. Performance based nuclear safety regulation is less well suited and a prescriptive approach to nuclear safety regulation is poorly suited to the South African context.

It is important to check whether test parameters of lower importance are disproportionally biasing the results. It is also important to check whether ranking and weighting of the test parameters may change the outcome of the analysis and suggest that a different approach to nuclear safety regulation may be optimal for South Africa.

Assessment of the individual test parameter scores shows that the performance based regulatory approach was allocated a higher score than the goal-setting regulatory approach for only one out of fifteen test parameters, namely Parameter 4: 'Suitability for Promoting Nuclear Safety Culture'. Parameter 4 is not considered to be relatively more important than most of the remaining fourteen test parameters, so it is not considered plausible that ranking and weighting of the test parameters can change the overall outcome of the analysis on the basis of the performance based approach being better suited to promoting nuclear safety culture than the goal-setting approach. Parameter 4 however represents a legal requirement in South Africa so it is important to check whether the goal-setting approach has at least a basic level of suitability to this parameter. The test result shows that a score of 1 was allocated; the goal-setting approach does have a basic level of suitability to parameter 4. By any reasonable ranking and weighting exercise, the importance of Parameter 4: 'Suitability for Promoting Nuclear Safety Culture' cannot be made large enough to make the performance based approach better suited to South Africa than the goal-setting approach.

The prescriptive regulatory approach was allocated a higher score than the goal-setting regulatory approach for two of the fifteen test parameters, namely Parameter 7: 'Suitability for Promoting Defence-in-Depth' and Parameter 8: 'Suitability for a Predictable Licensing Process'. Again, parameters 7 and 8 are not considered to be relatively more important than most of the remaining thirteen test parameters so it is not considered plausible that ranking and weighting of the test parameters can change the overall outcome of the analysis on the basis of the prescriptive approach being better suited to promoting defence-in-depth and a predictable licensing process than the goal-setting approach. Parameter 7 however also represents a legal requirement in South Africa so it is important to check whether the goal-setting approach has at least a basic level of suitability to this parameter. The test result shows that a score of 1 was allocated; the goal-setting approach does have a basic level of suitability to parameter 7. By any reasonable ranking and weighting exercise, the importance of Parameter 7: 'Suitability for Promoting Defence-in-Depth' and Parameter 8: 'Suitability for a Predictable Licensing Process' cannot be made large enough to make the prescriptive approach better suited to South Africa than the goal-setting approach.

This assessment of the test matrix results shows that test parameters of lower importance are not disproportionally biasing the overall result. The assessment of the test results has also shown that reasonable ranking and weighting of the test parameters to take into account the relative importance of the test parameters will not change the overall result: Based on the information currently available, the goal-setting approach to nuclear safety regulation has been revealed as the optimal approach for South Africa's planned nuclear industry.

The goal-setting regulatory approach is found to be well suited to the South African nuclear safety culture and to offer the most flexibility in allowing applicants or licensees to achieve high standards of safety in a manner of their own choosing. This promotes cost effective regulation, optimization of safety, innovation, transparent regulation, good governance and international cooperation and benchmarking. The goal-setting approach, providing the highest level of flexibility to the licensee or applicant on the manner in which it achieves safety goals, is found to be best suited to accommodating international vendors as is required for the nuclear new build fleet, to promoting the innovation necessary for prototype advanced reactor development and to supporting international export of nuclear SSCs and services.

However correct interpretation of the potential impact of Parameter 15: 'Suitability for Promoting Bilateral Cooperation with another State' is essential. The score of 1 has been attributed to each of the three regulatory approaches due to the fact that there is currently no basis available for differentiating between the suitability of the three approaches for this parameter. The vendor company for the 9,6 GW nuclear new build programme is not yet known. But this single parameter, representing state level bilateral cooperation between South Africa and the country of origin of the vendor company providing the nuclear fleet, may alone drive the determination of the optimal regulatory approach for South Africa. An important part of bilateral cooperation between these two states is bilateral cooperation between both states' regulatory bodies. Establishing bilateral cooperation between the NNR and the regulatory body of the vendor company's country of origin can be best facilitated by the NNR aligning its regulatory approach to that of the regulatory body of the vendor company's country. This could provide a number of benefits leading to optimization of South Africa's regulatory approach. Aligning the regulatory approaches would minimize the efforts required by the NNR to develop and implement its nuclear safety regulation system since it will have the support of the more experienced regulatory body from the vendor company's country. Aligning the regulatory approaches would minimize the changes required to be made by the vendor company to its NPP design to meet local regulations. As summarized in section 2.6.1 ‘Introduction to Nuclear Safety Regulation Systems’, the IAEA describes many benefits that can be gained from a strong cooperation between the regulator and the regulatory body of the vendor state. This cooperation can improve the effectiveness and efficiency of the regulation of South Africa’s planned nuclear industry. These factors would have cost, quality and time benefits in terms of development and implementation of the South African nuclear safety regulatory system and the nuclear new build fleet implementation.

The NNR aligning its regulatory approach with that of the regulatory body of the vendor company’s country of origin is, in principle, supported by the IAEA which recommends that the regulatory approach chosen should be informed by the approach implemented in the country from where the nuclear technology is being adopted [IAEA, 2013, p.6].

7 Conclusion

This dissertation tested the hypothesis that the optimal nuclear safety regulatory approach for South Africa's planned nuclear industry can already be determined by systematically comparing the suitability of various alternatives in use in the international nuclear industry.

The literature review identified three main nuclear safety regulatory approaches applied in the international nuclear industry and endorsed by the IAEA. These are the goal-setting, performance based and prescriptive approaches. These three approaches are considered to be the options available for the nuclear safety regulatory approaches that may be implemented in South Africa to accommodate the planned nuclear industry expansion. These approaches may be enhanced and supported by process based and risk based methodologies. A test was developed and conducted to systematically compare the relative suitability of these three approaches utilizing multi-criteria decision making analysis in order to identify the optimal approach for regulating the nuclear safety of the planned nuclear industry in South Africa. Based on the information currently available, this test reveals that the optimal nuclear safety regulatory approach for the planned South African nuclear industry is the goal-setting approach.

Systematic comparison of the three approaches reveals that the goal-setting nuclear safety regulatory approach best facilitates South Africa achieving its nuclear aspirations. This cost-effective regulatory approach is based on risk management, with regulation aimed at implementing the requirement for risks to be reduced as low as reasonably practicable through the application of set numerical risk goals. This approach is found to offer the most flexibility in allowing licensees or applicants to achieve high standards of safety in a manner of their own choosing. This promotes optimization of safety, innovation, transparent regulation, good governance and international cooperation and benchmarking. This approach is well suited to South African culture. The flexibility it affords licensees or applicants best accommodates South Africa making use of international vendors and best supports the innovation required for prototype advanced reactor development.

Regulation through risk management with numerical risk goals facilitated by the application of PRA was identified as an increasing global trend in nuclear safety regulation. Elements of regulation through risk management, applied to differing degrees, were identified in all three regulatory approaches considered, making PRA a regulatory common ground regardless of the chosen regulatory approach. The goal-setting regulatory approach which is most focussed on regulation through risk management therefore best supports international cooperation and best accommodates differing approaches to nuclear safety. Considering trends over time and the importance of international cooperation, this approach best suits South Africa's long term goal of exporting of NPP SSCs and services.

In applying its optimal nuclear safety regulatory approach, that is a goal-setting approach, South Africa would stand to benefit in numerous ways. South Africa's financial and human resources would be applied in an optimized manner, since efforts would not be spent applying a poorly suited and more resource intensive regulatory system. Human performance would be optimized since individuals would be working in a system well suited to South African culture and within a system that encourages individuals to take ownership of their personal responsibility for safety and high performance. Nuclear safety would be optimized since the regulatory system would be accommodating of alternative, innovative and modern safety related solutions and would encourage continual improvement. Governance could be improved since the regulatory system would be based on transparent, objective requirements with clear bases that do not favour certain solutions over others. South Africa would further benefit from application of its optimal regulatory approach since this flexible, non-prescriptive approach would accommodate more potential international vendors and suppliers, providing more options and more competitive pricing. Many benefits of applying an optimised regulatory approach have been identified.

While the test performed shows that the goal setting regulatory approach is the best suited to the South African context, one crucial research finding reveals the hypothesis of this dissertation to be false.

The South African government pursues state level bilateral cooperation between South Africa and the country of origin of the vendor company providing the 9,6 GW nuclear new build fleet. It is not yet known who the vendor company will be. This state level bilateral cooperation may well extend to bilateral cooperation between the NNR and the regulatory body of the vendor country which would be well facilitated by alignment of their regulatory approaches. Indeed, the IAEA recommends that the regulator implement a cooperation programme most importantly with the regulator of the vendor state. The IAEA cautions that this could influence the intended regulatory approach tentatively planned before the vendor was selected. [IAEA, 2011, pp.21, 35] Alignment of South Africa's regulatory approach with the regulatory approach implemented in the vendor's country may greatly optimize nuclear safety regulation in South Africa. The IAEA provides numerous examples of benefits that can be gained through cooperation with the vendor state's regulatory body [IAEA, 2011, p. 35], and cautions that in order to optimize regulation, the regulatory approach planned before the vendor was selected may have to be altered depending on the regulatory approach implemented in the selected vendor country [IAEA, 2013, p.6] [IAEA, 2011, p. 35].

Subsequent to the fleet vendor selection, the optimal nuclear safety regulatory approach for South Africa may therefore change to being the regulatory approach implemented in the country of origin of the fleet vendor company.

In the interim and in the event of South Africa not proceeding with strategic alignment of regulatory approaches for the planned new build fleet, the research findings and test results have an important implication: The goal-setting approach is the optimal nuclear safety regulatory approach for South Africa's nuclear industry. Applying the goal-setting approach as the dominant nuclear safety regulatory approach can optimize nuclear safety regulation in South Africa.

The hypothesis of this dissertation has been shown to be false. The optimal nuclear safety regulatory approach for South Africa's planned nuclear industry cannot already be determined by systematically comparing the suitability of various alternatives in use in the international nuclear industry.

8 Implications of the Research Findings

Selection of the vendor company for the 9,6 GW nuclear new build fleet may change the optimal nuclear safety regulatory approach for South Africa's planned nuclear industry. Conclusions on the optimal approach for South Africa cannot be drawn until after this selection is made. Reassessment of the optimal nuclear safety regulatory approach for South Africa's nuclear industry is required once the fleet vendor company is known and information is available on the nuclear safety regulatory system applied in the vendor company's country of origin.

In the interim and in the event that strategic regulatory alignment for the new build fleet is not embarked upon, the research findings and test results have important implications for South Africa's nuclear industry.

The test results show that, in the interim and in the absence of a strategic alignment of regulatory approaches for the new build fleet, the goal-setting regulatory approach is the optimal nuclear safety regulatory approach for South Africa. The test results show that applying the goal-setting approach as the dominant nuclear safety regulatory approach can optimize South Africa's nuclear safety regulation.

Concerning Koeberg NPP specifically, the research findings show that aspects of all three regulatory approaches, goal-setting, performance based and prescriptive, are applicable to a mature NPP like Koeberg and can add value when incorporated into the regulatory approach applied. The mixed regulatory approach which is currently applied at Koeberg NPP is therefore well suited to regulating its nuclear safety, though applying goal-setting regulation as the dominant approach can optimize its nuclear safety regulation by best facilitating identification of safety enhancements and alignment with modern safety standards in a cost effective manner.

In regulating the development of a prototype advanced nuclear reactor, the research findings show that a goal-setting nuclear safety regulatory approach is best suited to providing the flexibility required to promote the development of innovative technology.

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