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AN APPROACH FOR THE SITE SELECTION OF AN INTERIM STORAGE FACILITY FOR THE REACTOR COMPARTMENT OF THE DECOMMISSIONED BRAZILIAN NUCLEAR SUBMARINES

Yran Leite Maia

Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia Nuclear, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia Nuclear.

Orientador: Paulo Fernando Ferreira Frutuoso e Melo

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UMA ABORDAGEM PARA A SELEÇÃO DE SÍTIO PARA O ARMAZENAMENTO TEMPORÁRIO DAS SEÇÕES DO REATOR DOS SUBMARINOS NUCLEARES BRASILEIROS DESCOMISSIONADOS

Yran Leite Maia

Outubro de 2022

Orientador: Paulo Fernando Ferreira Frutuoso e Melo

Programa: Engenharia Nuclear

A construção do primeiro submarino brasileiro com propulsão nuclear (SN-BR) está prevista para começar em 2022. Ao final da vida operacional do SN-BR, seu combustível nuclear retirado de bordo e ele será descomissionado. Durante o processo de descomissionamento o compartimento do reator (RC) é separado do resto do casco e enviado para uma instalação de armazenamento provisória.

Caberá à Marinha do Brasil (MB) projetar e construir uma instalação capaz de garantir o armazenamento seguro do compartimento do reator por cerca de 50 anos para permitir o decaimento dos radio nuclídeos de ativação existentes neste compartimento. O primeiro passo para a obtenção dessa instalação é selecionar o local (sítio) onde ela será construída.

Para solução deste problema esta Tese propõe um processo de seleção de sítios baseado no Processo Analítico Hierárquico (AHP) que considera a base normativa nacional (ambiental e nuclear), as especificidades dos meios navais e as restrições logísticas impostas ao transporte do compartimento do reator.

A validação do processo de seleção de sítios proposto foi realizada por um estudo de caso que foi capaz de identificar seis locais que atendem aos critérios estabelecidos e de hierarquizá-los em função do seu grau de atendimento a estes critérios.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

AN APPROACH FOR THE SITE SELECTION OF AN INTERIM STORAGE FACILITY FOR THE REACTOR COMPARTMENT OF THE DECOMMISSIONED BRAZILIAN NUCLEAR SUBMARINES

Yran Leite Maia
October 2022

Advisor: Paulo Fernando Ferreira Frutuoso e Melo
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The construction of the first Brazilian Nuclear-Powered Submarine (SN-BR) is scheduled to begin in 2022. At the end of its operational life, the submarine will be defueled and decommissioned. During the decommissioning process the reactor compartment (RC) is separated from the rest of the hull and sent to a temporary storage facility.

Thus, Brazilian Navy (MB) has to design and build a facility capable of safe storing the RC for about 50 years to allow the decay of the activation radionuclides existing within this compartment. The site selection for the construction of the interim storage facility is one of the first step required to be performed.

The purpose of this thesis is to propose a site selection process for the RC interim storage facility in Brazil. This site selection process is based on an Analytic Hierarchy Process methodology that takes into account nuclear and environmental national regulations, naval and shipyard specificities, and logistics constraints.

The validation of the proposed site selection process was carried out by a case study that was able to identify six candidate sites that meet the established criteria and to rank them according to their degree of compliance with these criteria.

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LIST OF ABBREVIATIONS

AgNSNQ – Brazilian Naval Agency for Nuclear Safety and Quality (Agência Naval de Segurança Nuclear e Qualidade)
AHP - Analytic Hierarchy Process
ALARA - As Low as Reasonably Achievable
ALARP - As Low as Reasonably Practicable
AMAZUL – Amazônia Azul Defense Technologies (Amazônia Azul Tecnologias de Defesa S.A.)
ANSNQ - Brazilian Naval Authority for Nuclear Safety and Quality (Autoridade Naval de Segurança Nuclear e Qualidade).
ANDRA – French National Agency for the Management of Radioactive Waste (*Agence Nationale Pour la Gestion des Déchets Radioactifs*)
BN - Brazilian Navy
BSIM - Brazilian Navy Submarine Base on Madeira Island, in the Itaguaí municipality (Base de Submarinos da Ilha da Madeira)
CDTN - Nuclear Technology Development Center (Centro de Desenvolvimento da Tecnologia Nuclear)
CI - Consistency Index
CME - Specialized Maintenance Center (Centro de manutenção Especializada)
CNAAA – Admiral Álvaro Alberto Nuclear Power Complex, in Angra do Reis – RJ (Central Nuclear Almirante Álvaro Alberto)
CNEN - Brazilian National Commission for Nuclear Energy (Comissão Nacional de Energia Nuclear), also Brazilian Nuclear Regulatory Body
CNI - Itaguaí Naval Complex (Complexo Naval de Itaguaí)
COE - Emergency Operations Center (Centro de Operações de Emergências)
CONAMA - Brazilian National Environment Board (Conselho Nacional do Meio Ambiente).
CR - Consistency Ratio
CSN - National Steel Company (Companhia Siderúrgica Nacional)
CSS - Confederated States Ship (from US Civil War)
DPC – Brazilian Navy Directorate of Ports and Coasts (Diretoria de Portos e Costas)
DRDL - Devonport Royal Dockyard Ltd
EBN - Itaguaí Shipyard and Naval Base (Estaleiro e Base Naval de Itaguaí)

EC - Exclusion Criterion

EIA - Environmental Impact Assessment

EL - Environmental Licensing

ELECTRE - Elimination and Choice Translating Reality (*Elimination et Choix Traduisant la Realité*)

END - National Defense Strategy (Estratégia Nacional de Defesa)

EMGEPRON - Brazilian Naval Project Management Company (Empresa Gerencial de Projetos Navais)

ERA - Radio Accident Infirmary (Enfermaria de Rádioacidentados)

EW - Exempt Waste

FN - French Navy (*Marine Nationale Française* – MNF)

HEU - Highly enriched uranium

HLW - High level radioactive waste

HMS - Her Majesty's Ship

HNR - Department of Energy’s Hanford Nuclear Reservation

IAEA - International Atomic Energy Agency

IBGE - Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatistica)

IBAMA - Brazilian Institute for Environmental and Renewable Natural Resources (Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renováveis)

ICBM - Intercontinental Ballistic Missile

ICN - Itaguaí Naval Enterprises (Itaguaí Construções Navais)

ICRP - International Commission on Radiological Protection

IEN - Nuclear Engineering Institute (Instituto de Engenharia Nuclear)

ILW - Intermediate Level Radioactive Waste

IOE – Occupationally Exposed Person (Indivíduo Ocupacionalmente Exposto)

IPEN – Nuclear and Energy Research Institute (Instituto de Pesquisas Energéticas e Nucleares)

IPHAN - Institute of National Historic and Artistic Heritage (Instituto do Patrimônio Histórico e Artístico Nacional)

IRD - Institute of Radioprotection and Dosimetry (Instituto de Radioproteção e Dosimetria)

INB - Nuclear Industries of Brazil (Indústrias Nucleares do Brasil)

LABGENE - Brazilian Navy Nuclear Electric Generation Laboratory (Laboratório de Geração Nucleoelétrica)

LDC - Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, commonly called the London Dumping Convention (1972)

LEU - Low enriched uranium

LILW - Low and Intermediate Level Radioactive Waste

LLW - Low Level Radioactive Waste

LLLW – Low Level liquid Radioactive Waste

LMAR - Environmental and Radiological Monitoring Laboratory (Laboratório de Monitoração Ambiental e Radiológica)

LMR - Liquid-Metal Reactor

MADM – Multi-attribute decision making

MAPP - Methyl Acetylene Propadiene

MCDM – Multi-criteria Decision Making

MODM – Multi-objective Decision Making

NATO - North Atlantic Treaty Organization

NG – Naval Group

NIMBY - Not in my back yard

NMFA - Norwegian Ministry of Foreign Affairs

NNR - Naval Nuclear Reactor

NNPP - Naval Nuclear Power Plant

NPP - Nuclear Power Plant

NRC – United States Nuclear Regulatory Commission

NS – Nuclear-powered submarine, generic designation to Nuclear Submarine (SSN, SSBN, or SSGN)

NSSF – Near-Surface Storage Facility

NUCLEP - Nuclebrás Heavy Equipment Industrial Unit (Nuclebrás Equipamentos Pesados S.A.)

OCDE - Organisation for Economic Co-operation and Development

PAEMB - Brazilian Navy Equipment and Articulation Plan (Plano de Articulação e Equipamentos da Marinha do Brasil)

PLAN - Chinese Navy (People's Liberation Army Navy)

PNMA - Brazilian National Environmental Policy (Política Nacional de meio Ambiente)

PMC – Port of Cherbourg (*Port Militaire de Cherbourg*)

PWR - Pressurized Water Reactor

RAH - Reactor Access House

RBMN - Brazilian Low and Intermediate Level Waste Repository (Repositório Nacional de Rejeitos de Baixo e Médio Níveis de Radiação)

RC – Reactor Compartment

RCP - Real Continuous Pairwise matrix, also known as judgment matrix

RIMA - Environmental Impact Report (Relatório de Impacto sobre o Meio Ambiente - EIA/RIMA)

RFN - Russian Federation Navy (*Voyenno-Morskoi Flot* – VMF)

RI - Random Consistency Index

RN - Royal Navy (British)

RPV - Reactor Pressure Vessel

RW – Radioactive waste(s)

SBR - Brazilian Conventional Submarines (non-nuclear powered)

SCDM - Single Criteria Decision Making

SISNAMA – National System for the Environment (Sistema Nacional do Meio Ambiente)

SLCM - Submarine-launched cruise missile

SN-BR - Brazilian Nuclear-Powered Submarine

SNF - Spent Nuclear Fuel

SSBN – Nuclear-Powered Ballistic Missile Submarine

SSGN - Nuclear-Powered Cruise Missile Submarine

SSN – Nuclear-Powered Attack Submarine

TKCSA - ThyssenKrupp Steel Company (Companhia Siderúrgica do Atlântico)

UFEM – Metal Structures Manufacturing Unit (Unidade de Fabricação de Estruturas Metálicas)

UK – United Kingdom

USA - United States of America

USN - United States Navy

USS - United States Ship

USSR - Union of Soviet Socialist Republics

VLLW – Very Low Level Waste

VSLW - Very Short-Lived Waste

WGU - Weapons-grade uranium

WPM - Weighted Product Model

WSM - Weighted Sum Model

CHAPTER 1 - INTRODUCTION

The construction of the first Brazilian nuclear-powered submarine (SN-BR) is expected to begin in 2022 and at the end of its operational life it will be defueled and decommissioned.

During the SN-BR decommissioning process, its reactor compartment (RC) is cut apart from the rest of the hull and shipped to an interim storage facility[1] specifically designed to support the large and heavy RC. To safely store the RC, Brazilian Navy (BN) has to select the site for the facility construction, design and construct such storage facility.

1.1 PURPOSE

This thesis proposes a site selection process for the construction of an interim storage facility for the reactor compartment of the decommissioned Brazilian nuclear submarines in Brazil. This site selection process is based on an Analytic Hierarchy Process methodology that takes into account nuclear and environmental national regulations, naval and shipyard specificities, and logistics constraints.

1.2 RELEVANCE

Anticipate the discussion on the site selection in Brazil for the construction of an interim deposit for the reactor compartment of the decommissioned Brazilian nuclear-powered submarines (SN-BR).

Reduce the gap in the study in the area of decommissioning nuclear submarines in relation to other countries that have already decommissioned them.

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[1] The decommissioned SN-BR Reactor Compartment (RC) temporary storage is called “interim storage”. The facility that stores the SN-BR RC is called “Deposit” when there is the intention to retrieve it. It is called “Repository” when there is no intention to retrieve it (deposition).

According to the Brazilian nuclear regulations terminology, the interim storage facility located in the installation site is called “Initial Deposit” and the one located outside the site is called “intermediate Deposit”, as presented in section 2.3.2.

1.3 ORIGINALITY

So far, six countries have operated Nuclear-Powered Submarines (NS) (United States of America, Russian Federation, Great Britain, France, China and India). Soon, Brazil will be the seventh one. In this context of limited sources of information worldwide, it is important to highlight that NS have always been surrounded by a high degree of confidentiality and few information is available on open sources. This results in an extremely limited number of scientific publications on NS.

In Brazil, the number of publications on nuclear submarines is even smaller and no publication has been found on the site selection process for the construction of an interim storage facility for the reactor compartment of the decommissioned SN-BR.

To the best of the author’s knowledge, this thesis is the first open-source publication in Brazil to approach the following aspects:

a) Destination, transportation and storage of the reactor compartment of the decommissioned SN-BR;

b) Site selection for the construction of an interim storage facility for the reactor compartment (RC) of the decommissioned SN-BR; and

c) Application of a multicriteria decision analysis methodology to support decision making on the site selection process based on the nuclear and environmental national regulations, naval and shipyard specificities, and logistics constraints.

1.4 MOTIVATION

To contribute to the adequacy of the ongoing project of the Itaguaí Naval Complex (CNI) to the demands of the SN-BR Decommissioning Process.

To contribute to the preparation of the SN-BR Preliminary Decommissioning Plan, which must be submitted to the Brazilian Naval Agency for Nuclear Safety and Quality (AgNSNQ) as part of the requirements for obtaining the submarine Commissioning License[2].

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[2] Commissioning License – It is the license required to begin the Naval Nuclear Propulsion Plant set to work and should be obtained before the core loading authorization. It is part of the SN-BR licensing process according to Brazilian naval nuclear regulations (ANSNQ-101).

1.5 ASSUMPTIONS

This thesis is limited to the information available on open sources and it is postulated that:

Assumption 1 the nuclear submarine decommissioning process adopted in this thesis is the one proposed by Maia (2015), which is similar to the ones adopted by the American, Russian and French navies (USN, RFN and FN, respectively);

Assumption 2 all activated materials in the SN-BR are confined within the reactor compartment (RC), as it has been done with the submarines of the USN, RFN, RN and FN, as presented in section 2.2.2. Thus, no radioactive material should be present in the rest of the submarine (aft and forward sections);

Assumption 3 the SN-BR reactor compartment, after its defueling, decontamination and hull cutting for RC removal, is classified as a low and intermediate level radioactive waste (LILW Class 2.1, according to CNEN-NN-8.01 - Art. 4º). This RC radioactive waste classification allows its storage in near-surface facilities and it is consistent with the ones reported by USN, RFN and RN, as presented in section 2.2.2; and

Assumption 4 The radiation level on the external surface of the metallic container that will contain the removed SN-BR RC is lower than 0.01 mSv/h. This external radiation level is consistent with the ones reported by USN, RFN and RN, as presented in section 3.3.1.

1.6 EXCLUSIONS AND LIMITATIONS

This thesis adopts the following exclusions and limitations:

1. SN-BR and its reactor compartment interim storage facility security-related aspects will not be considered and aspects related to nuclear safety will be limited strictly to the necessary for the development of this thesis.
2. The analyzed solutions (selected sites) do not consider the road infrastructure construction, demolition and/or reconstruction to allow the reactor compartment land transportation (logistic restriction); and

3. The results achieved (site selected) should be understood as a possible solution to the reactor compartment interim storage problem, only if, in the 2060s, the use of the currently available technologies be justified.

CHAPTER 2 - LITERATURE REVIEW

As previously mentioned, no open source information has been found on the site selection process for the construction of an interim deposit for the reactor compartment (RC) of the decommissioned SN-BR.

The information presented in this thesis is an account of the available relevant data found in 163 publications and documents, cited as references, which have been divided in eight main subjects to allow an overview of the research carried out. Table 1 presents the distribution of these references by subject. It is important to highlight that some references approach more than one subject.

Table 1 - References distribution by subject

	Subject	Qtt	Observations
1	Nuclear-powered submarines (NS)	16	From the NS berth to a brief description of its naval nuclear power plant.
2	NS decommissioning process	35	From the prospects of nuclear decommissioning in Brazil to the extensive foreign experience on NS decommissioning, dismantling included.
3	NS radioactive waste (RW) storage	6	From a brief description of the RW arising from the NS decommissioning to the successful foreign experience on the NS reactor compartment storage.
4	Nuclear installations decommissioning	5	Brief description of the process, focused on national and international regulations and on Brazilian decommissioning experience.
5	RW storage and management	33	Focused on Low and intermediate level radioactive waste (LILW).
6	Brazilian regulations	35	Environmental and nuclear Laws, Decrees and regulations.
7	Site selection process	12	Focused on near-surface LILW interim storage facilities.
8	MCDM and AHP	38	Multi-criteria Decision Making (MCDM) and the Analytic Hierarchy Process (AHP).

Captions: QTT – Quantity

2.1 NUCLEAR SUBMARINES

2.1.1 Nuclear-Powered Submarines

In 1954, the United States of America (USA) launched the USS Nautilus (SSN-571), the world's first operational nuclear-powered submarine (NS) and the first submarine to complete a submerged transit of the North Pole on 3 August 1958. She was capable of sustaining speeds of about 23 knots and staying submerged for months without the need to resupply (USN, 2015).

In 1959, the USA launched the USS George Washington (SSBN-598), the first NS capable of deploying nuclear ballistic missiles. From that point on, Nuclear-Powered Ballistic Missile Submarine (SSBN) became the primary deterrent element in modern warfare (USN, 2015).

The Soviet Union (USSR), United Kingdom (UK), France, China and India launched their first NS in 1959, 1963, 1971, 1974 and 2013, respectively. Table 2 lists the first NS built per nation and the year of its commissioning and decommissioning.

Table 2 - Commissioning and inactivation of the first nuclear-powered submarine per nation.

Nation	**Submarine**	**Commis.**	**Inact.**	**Operational Life (years)**
USA	SSN (USS-571) Nautilus	1954	1980	26
USSR	SSN (K-3) Leninsky Komsomol	1959	1988	29
UK	SSN (S-101) Dreadnought	1963	1980	17
France	SSBN (S-611) Le Redoutable	1971	1991	20
China	SSBN (401) Han “Long March”	1974	2005	31
India	SSBN (80) Arihant	2016	-	-
Average operational life			24.6 years	

Source: Jane’s Fighting Ships 2017 - 2018

Captions:

Comis. – Year of commissioning	SSN – Nuclear-Powered Attack Submarine
Inact. - Year of inactivation (withdrawn from operational service)	SSBN – Nuclear-Powered Ballistic Missile Submarine

Nuclear-powered submarines (NS) are divided into two large groups according to their main task, to launch nuclear weapons or to destroy submarines capable of doing so. The first group of submarines, those capable of deploying ballistic missiles with nuclear war heads, receive the designation SSBN (ballistic missile submarine). SSBNs are usually called boomers. The second group of submarines, SSN (attack submarine), are designed to destroy the first and prevent the ballistic missile launch. Subsequently, another group of submarines, SSGN (cruise missile submarine), emerged capable of launching cruise missiles (SLCMs and anti-ship missiles)[3] and hunting the boomers.

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[3] **SLCM** (submarine-launched cruise missile) is a cruise missile that is launched from a submarine (especially a SSG or SSGN).

In this thesis, nuclear-powered submarines are generically described as Nuclear Submarines (NS), limiting the use of NATO (North Atlantic Treaty Organization) general designation (SSBN, SSGN, SSN and others)[4] to pin-point details. On the other hand, Brazilian submarines are referred to as SN-BR (Brazilian nuclear-powered submarines) and as SBR (Brazilian Conventional Submarines – non nuclear-powered).

Information on nuclear-powered submarines (NS), their reactors and fuels is limited to the necessary to present the submarine decommissioning process. It is also limited to the extent of the information already made available on open sources and shall be updated as new information is released.

2.1.2 Naval Nuclear Power Plant

Nuclear-powered submarines are provided with naval nuclear power plants (NNPP). The majority of submarine NNPP are equipped with one rugged and compact pressurized water reactor (PWR) designed to withstand severe power transients and battle shock. Newer reactor designs have integrated steam generators and are capable of operating in natural circulation mode (with reactor cooling pumps shutdown) at lower speeds for silent operation.

All but one of the American submarines have been provided with one reactor. The same is true for the British and French NS and, according to available information, also for the Chinese submarines. However, most Russian nuclear submarines have been provided with two reactors, housed in separate rooms, but in the same compartment. (KOPTE, 1997). Only about a quarter of Russian submarines have been equipped with one reactor (MAIA, 2015).

The safety requirements applied to NS and its NNPP are much more stringent than those applied to land based nuclear power plants (NPP). NPP must comply with the nuclear safety requirements established by their national regulatory base. On the other hand, NS must comply with the naval safety and nuclear safety requirements simultaneously.

Nuclear safety requirements are, in general, the combination of requirements common to all industrial installations (reliability, availability, maintainability and

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[4] NATO general designation (SSBN, SSGN, SSN and others) comes from the union of "SS" (abbreviation for "submersible ship", which denotes a submarine) with the "N" (nuclear propulsion), plus another letter such as "B" (ballistic missile), which denotes the ability to launch ballistic missiles, or "G" (guided missile), which denotes the ability to launch cruise missiles.

industrial safety) with specific safety requirements to nuclear installations[5] (GUIMARÃES, 1999).

Naval security requirements are the combination of maritime safety requirements (safety of navigation and human life safeguard at sea), common to all vessels and specific military requirements (ability to survive attacks - survivability), required for combat conditions (GUIMARÃES, 1999).

The nuclear safety of the naval propulsion reactor safety is subordinated to the naval safety of the submarine because the loss of the submarine implies the loss of the reactor and the opposite is not necessarily true. Naval safety permeates and overlaps nuclear safety without, however, imposing relaxation on it.

A naval nuclear propulsion plant is divided into primary circuit and secondary circuit. The primary circuit generates heat through nuclear fission. It contains the naval nuclear reactor with its high-strength steel reactor vessel, steam generator(s) and associated piping, pumps, and valves. It is mostly contained in the Reactor compartment. The Secondary Circuit converts heat into electricity and propulsion power. It contains the turbines, generators and other equipment. It is mostly contained out of the reactor compartment.

The reactor compartment is the section of the submarine that houses the naval nuclear reactor. It consists of a part of the resistant hull limited by two rugged bulkheads and contains the primary circuit of the NNPP. It is shielded with over 100 tons of lead and is equivalent to the 3rd contention barrier in a nuclear power plant (NPP).

The thermal power of the NNPP varies from 20 MW, in older submarine classes, to 200 MW in the newer ones. In most cases, it varies from 50 MW to 90 MW (KOPTE, 1997; JMFA, 2006).

The naval reactors power level is primarily set by propulsion needs, and not by the submarine’s other service needs, which are also powered by the reactor but require a small fraction of the power required for propulsion (JMFA, 2006). NS usually moves slow and quietly, consuming just a fraction of their full rated power. In contrast, commercial reactors normally operate near full power (JMFA, 2006; BBC NEWS UK, 2019).

The NNPP normal reactivity control does not uses soluble boron due to the limited amount of demineralized water that can be stored aboard (DOE, 2019a).

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[5] In this thesis, the terms Nuclear Installation and Nuclear Power Plant are used as synonyms, in compliance with the definition adopted in the INFCIRC/449 - Convention on Nuclear Safety (Art. 2 - i).

The naval nuclear fuel is different from the one used in nuclear power plants. They are different in size, enrichment, type (metallic, ceramic and dispersion), design (rods or plates) and have much more stringent design specifications to withstand battle shock loads (DOE, 2019b; JMFA, 2006).

Nuclear submarines (NS) normally use a metallic or dispersion plate fuel far more highly enriched than that the ceramic pellets used in NPP, which is only about 4%. Depending on the type of reactor, the level of U^{235} enrichment varies from less than 10% to more than 90% (IPPOLITO, 1990). USN and RN submarine reactors are typically fueled with 97.3% weapon-grade uranium (WGU)[6]. RFN NS are typically fueled with 20% to 45% highly enriched uranium (HEU)[7], but newer ones are enriched up to 90% (MAERLI, 2002). FN NS are typically fueled with 7.5% low enriched uranium (LEU)[8] (COSTA, 2017). Indian Navy and Chinese Navy (PLAN) NS are likely to be fueled with 40% and 3% to 5% enriched uranium respectively (COSTA, 2017) (HUI, 2017).

The enrichment level of the naval nuclear fuel dictates the refueling frequency and the total amount of spent fuel elements generated throughout the submarine operational life (usually expressed in terms of the reactor core).

The NS estimated reactor core lifetime (refueling frequency) varies greatly in the considered navies. For example, the USN Virginia Class SSN has a 33 years core lifetime (without refueling) (DOE, 2014). The FN Barracuda Class SSN has a 10 years core lifetime, longer than its predecessor, the Rubis Class SSN, which has a 7 years core lifetime (COSTA, 2017). The PLAN Type 094 Jin class SSBN has a 10 years core lifetime (HUI, 2017).

The Naval Nuclear Propulsion Plants (NNPP) are different from the ones used in nuclear power plants. They are different in size, component arrangements, thermal power, average power level, and operational profile, among others. The NNPP usually accounts for 20-30% of the total weight of the submarine (COSTA, 2017). This thesis considers that the whole reactor compartment with equipment and shielding accounts for nearly 20% of the total weight.

Nuclear submarines do not store spent nuclear fuel (SNF) and wastes onboard. These radioactive materials are removed from the submarine and stored in SNF pools and in repositories on the ground support facilities.

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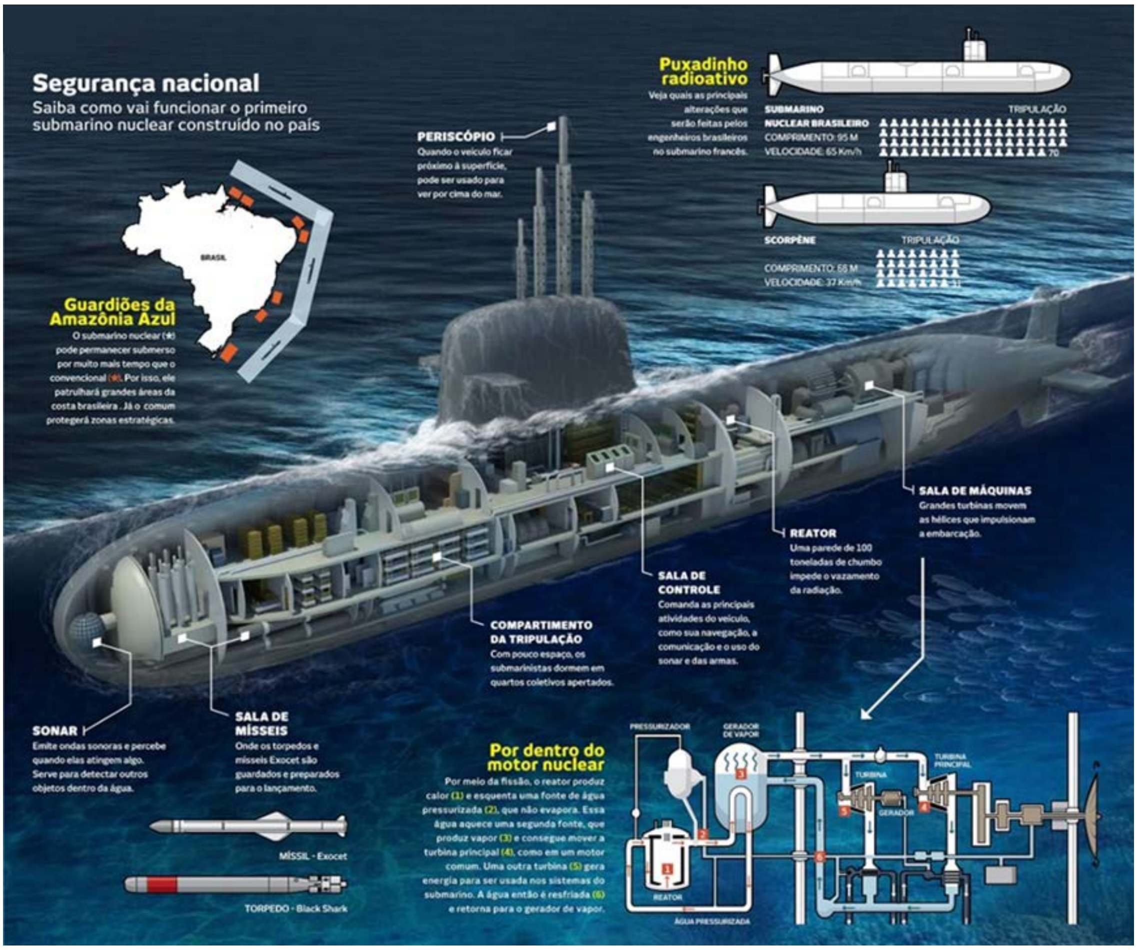
[6] **WGU** - Weapons-grade uranium, is the uranium that has a U^{235} content greater than 90% by mass.
[7] **HEU** - Highly enriched uranium, is the uranium that has a U^{235} content greater than 20% by mass.
[8] **LEU** - Low enriched uranium, is the uranium that has a U^{235} content of up to 20% by mass.

2.1.3 Brazilian Nuclear-Powered Submarine (SN-BR)

The first Brazilian nuclear submarine (SN-BR) “Álvaro Alberto” is a nuclear-powered attack submarine (SSN) that is going to be constructed by the Itaguaí Construções Navais (ICN). Figure 1 presents an artistic view of the SN-BR.

The SN-BR construction is part of the strategic partnership signed between France and Brazil in 2008, which also includes the transfer of technology and support for the construction of four enlarged conventionally powered Scorpène class submarines (SBR). The SN-BR NNPP was designed and constructed in Brazil without any transfer of technology and support from the French part.



Source: https://tecnodefesa.com.br/ihm-stefanini-participa-da-construcao-do-primeiro-submarino-nuclear-do-brasil/

Figure 1 Brazilian Nuclear-Powered Submarine (SN-BR)

The namesake of the submarine will be a tribute to the Brazilian Navy Vice Admiral and scientist Álvaro Alberto da Mota e Silva, one of the leading pioneers in nuclear energy in Brazil. He is primarily responsible for the implementation of the Brazilian Nuclear Program. He was also Brazil's representative in the UN Atomic

Energy Commission (UNAEC) and President of the Brazilian Academy of Sciences for two terms (1935–1937 and 1949–1951).

The SN-BR construction is scheduled to start in 2022 at the Itaguaí Naval Complex (CNI) Shipyard in the Itaguaí municipality - RJ. The submarine is planned to be launched in 2030 and commissioned in 2032 (PODER NAVAL, 2018). It will be the first of six SN-BR planned to be built according to the National Defense Strategy (Law 6.703/2008) and to the Brazilian Navy Equipment and Articulation Plan (PAEMB).

The SN-BR will have a length of 100 m (328 ft. 1 in), a beam of 9.8 m (32 ft. 2 in) and a displacement of 6,000 tons. It will have a 48 MW PWR that will power a (64,000 hp) turbo-electric propulsion system, performing a maximum speed of 24 to 26 knots, and will have a maximum operational depth of 350 m. The submarine will have six torpedo tubes and will be able to carry F21 torpedoes, SM39 Exocet anti-ship missiles, and naval mines (PODER NAVAL, 2020; PODER NAVAL, 2018; PADILHA, 2012b).

2.2 NUCLEAR SUBMARINES DECOMISSIONING

2.2.1 Nuclear Decommissioning Process

All power plants, coal, gas and nuclear, have a finite life beyond which it is not economically feasible to be operated. At the end of the life of any power plant, it needs to be decommissioned, cleaned up and dismantled so that the site is made available for other uses.

Early nuclear power plants were designed for a life of about 30 years (generally speaking), though with refurbishment, some have proved capable of continuing well beyond it. Newer plants have been designed for a 40 to 60 year operating life (WNA, 2020). Beyond this point, as a rule of thumb, the nuclear power plant (NPP) has to be decommissioned or to have a life extension granted.

Nuclear-powered submarine (NS) operational life (lifespan) ranges from 20 to 30 years because its operational life ends when the submarine's military capability does not justify the cost of continued operation (USN, 2019). So, despite the rugged naval nuclear reactors (NNR) be normally in very good condition at their final shutdown, no life extension is foreseen for NNR.

The purpose of decommissioning a nuclear installation is to allow the facility[9] and its site to be released of all or some of the regulatory controls so that it can be available for other uses (IAEA-GSR Part 6, 2014). The decommissioning usually takes place at the end of the life of the installation. However, it may be anticipated due to accidents (IAEA-GSR Part 6, 2014; CNEN-NN-9.01, 2012).

The International Atomic Energy Agency (IAEA) proposes two generally adopted strategies for decommissioning, in principle, applicable to all facilities. These two strategies are “immediate dismantling” and “deferred dismantling” (IAEA-GSR Part 6, 2014).

Different nations adopt different decommissioning normative bases, as no globally consolidated normative base is available. Despite the mentioned differences, the Brazilian normative base (CNEN[10] regulations) is consistent with internationally accepted practices (IAEA and NRC).

Up to May 2020, about 100 mines, 115 nuclear power plants (NPP), 48 experimental reactors or prototypes, more than 250 research reactors and a series of fuel cycle installations have been decommissioned. Of these reactors, at least 17 have been fully dismantled, over 50 are being dismantled, over 50 are in safe storage (deferred dismantling), and 3 reactors have been encapsulated in resistant structures like “sarcophagus” (entombed) showing that considerable experience has been gained so far in the decommissioning of various types of nuclear facilities (WNA, 2020).

In Brazil, the main decommissioning experiences are the Santo Amaro Plant (USAM-INB[11]) in 1993, the Poços de Caldas Industrial Complex (CIPC-INB) in 1996 and the INB Uranium Hexafluoride Plant in 2004. There is no national experience in decommissioning nuclear power plants (NPP) so far.

Brazilian NPP in Angra do Reis – RJ (CNAAA)[12] will adopt the deferred dismantling decommissioning strategy. Thus, at the end of Angra 1 useful life, the defueled unit will be kept intact awaiting its activated materials radioactive decay.

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[9] According to IAEA, ‘facility’ means buildings, and their associated land and equipment, in which radioactive material was or still is produced, processed, used, handled or stored on a scale with such a degree of hazard and risk that consideration of protection and safety is required (IAEA-GSR Part 6, 2014).

[10] CNEN (Comissão Nacional de Energia Nuclear) - Brazilian National Commission for Nuclear Energy. It was created in 1956 by Decree 40.110 of 1956.

[11] INB - Nuclear Industries of Brazil (Indústrias Nucleares do Brasil).

[12] CNAAA (Central Nuclear Almirante Álvaro Alberto) – Admiral Álvaro Alberto Nuclear Power Complex, commonly called Angra NPP. CNAAA currently has two nuclear power plants in operation (Angra 1,640 MWe gross/610 MWe net, and Angra 2,1345 MWe gross /1,275MWe net), and one under construction (Angra 3,1351 MWe gross/1,275 MW net). Angra 1, 2 and 3 are located at a common site, near the city of Angra dos Reis, about 130 km from Rio de Janeiro.

Likewise, at the end of Angra 2 useful life, the unit will be kept intact. When Angra 3, now under construction, reaches the end of its useful life in the 2060s, the three units will be dismantled in sequence (Angra 1, 2 and 3) (SEGABINAZE, 2015)[13].

2.2.2 Nuclear-Powered Submarines Decommissioning Process

As previously mentioned, NS are withdrawn from operational service (inactivated) when their military capability does not justify the cost of continued operation, when necessary to comply with treaty requirements that limit ballistic missile capacity, or when the ships are no longer needed (USN, 2019).

The NS decommissioning process is different from those adopted for decommissioning land based nuclear installations. The most basic and obvious difference among them is the absence of a site to be taken out of regulatory control and released for use. Thus, the desired final state to be achieved at the end of the NS decommissioning process is the release of NS constituent materials from the regulatory control.

Up to now, there is no international regulations for NS decommissioning and each country should develop its own regulations. Despite that, national regulations follow strict safety standards (nuclear and military) and adopt practices consolidated for more than four decades. Table 3 presents the estimated number of inactivated nuclear submarines at different stages of the decommissioning process from the 1980s up to 2018.

The U.S. Navy (USN), Russian Federation Navy (RFN) and French Navy (FN) decommissioning processes involve defueling the reactor(s), removing the reactor compartment for land disposal, recycling the remainder of the vessel to the maximum practical extent, and disposing of the remaining non-recyclable materials. Those decommissioning processes are detailed respectively at USN (USN, 2019), RFN (DIAKOV, KOROBOV and MIASNIKOV, 1996; SNELL, 2000; NILSEN, KUDRIK and NIKITIN, 2006; KALISTRATOV, 2011) and FN (MINISTERE DE LA DEFENSE, 2013; DIRECTION GENERALE DE L'ARMEMENT, 2010).

The NS decommissioning process adopted by the British Royal Navy (RN) differs from the aforementioned ones. Instead of removing the reactor compartment, the upper

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[13] Engineer Roberto de Oliveira Segabinaze, Fuel and Nuclear Safety Superintendence, Eletrobras Eletronuclear, interview at Eletronuclear, Rio de Janeiro, on March 2, 2015 (personal communication).

part of the hull is cut to allow access for the removal of the radioactive equipment inside[14] (MINISTRY OF DEFENCE, 2019, 2011and 2007). The technical options for removing activated materials from British NS are summarized in Appendix A of Maia (2015).

Maia presents a synthetic analysis of the four above mentioned decommissioning processes (MAIA, 2015). No open source information was gathered about the Chinese Navy (PLAN - People's Liberation Army Navy) NS decommissioning process, so it will not be considered, and no Indian Navy NS is expected to be decommissioned in the next decade.

The decommissioning strategy adopted by the USN, RFN, FN and RN is the Deferred Dismantling. PLAN decommissioning strategy seems to adopt the same[15], despite the lack of information.

The defueling is the single most important safety-related event in the entire decommissioning process. After that, the core becomes a “passive” element, without the risk of a nuclear accident. The remaining radioactive material on board is limited to activated materials contained in the reactor compartment. Its total activity is reduced to about 1% of the previously existing one (USN, 2019; DAVIS e Van DYKE, 1990). The definition of Activated Materials is presented in section 2.2.3.2.

During the naval SNF removal from the submarines, each removed assembly is placed in SNF casks and put on secure transportation for disposal at long-term waste storage and/or reprocessing plant.

The USA disposes its naval SNF in the Naval Reactor Facility at the sprawling Idaho National Laboratory (USN, 2019). Russian Federation disposes its naval SNF in the Mayak plutonium production and reprocessing plant in Siberia (MARKS, 2015). The United Kingdom disposes its naval SNF in Sellafield (Wet Inlet Facility), near the village of Seascale in Cumbria (MINISTRY OF DEFENCE, 2019). France disposes its naval SNF in the Cascade Storage Facility, in Cadarache (HØIBRÅTEN et al., 2007).

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[14] The United Kingdom decided to dispose their radioactive material and waste arising from NS in a geologic repository. Therefore, RN will remove the radioactive material in the reactor compartment and send it to a geologic repository instead of removing the whole reactor compartment and store it in an interim repository (MAIA, 2015).

[15] The first Chinese NS SSN 401 - CNS Long March-1 (type 091 – NATO Han-class) was decommissioned in 2000. She had its nuclear parts removed in accordance to international standards, and was transformed into a museum-ship (ZHAO, 2016). This process indicates the adoption of the deferred dismantling strategy. She is currently berthed at Chinese Navy Museum in Qingdao, on exhibit.

After defueling, the remaining radioactive materials in the submarine are the activation products within the reactor compartment (RC). The removed RC is a Low and Intermediate Level Radioactive Waste (LILW) (USN, 2019; BUKHARIN and HANDLER, 1995; MARKS, 2015; DIRECTION GENERALE DE L'ARMEMENT, 2010; MINISTRY OF DEFENCE, 2019). No radioactive material should be present in the rest of the submarine (aft and forward sections) (USN, 2019).

As previously mentioned, British NS reactor compartments will not be cut apart from submarines hulls (MINISTRY OF DEFENCE, 2019; MINISTRY OF DEFENCE, 2014a). The radioactive components of the primary circuit, once removed, are Intermediate Level Radioactive Waste (ILW) (MINISTRY OF DEFENCE, 2007).

The total number of inactivated submarines that are being or have been decommissioned, dismantled and disposed is not certain. It is probably around 390 NS (nearly 70% of the more than 530 NS already built) (Jane´s Fighting Ships 2017-2018; Bellona Foundation Report nr 2:96; USN, 2019; MINISTRY OF DEFENCE, 2019; DIGGES, 2017). The considerable number of dismantled and disposed NS shows that the current NS decommissioning process is a safety-proven technology. The SN-BR decommissioning process is presented in section 3.3. Table 3 presents the estimated number of inactivated NS at different stages of the decommissioning process.

Table 3 - Estimated number of nuclear submarines built, operational, inactivated and at different stages of the decommissioning process.

Country	Built (Until 2018)	Operational (at 2018)	Inactivated (Until 2018)	Decommissioned (Until 2018)
Russia	262	35	227	186[1]
USA	205	71	134	116
UK	31	11	20	2
France	18	12	6	6
China	20[1]	16[1]	3	1
India	2	2[2]	0	0
TOTAL	537	147	390	311

Adapted from Jane’s Fighting Ships and other publications[3]

Captions:

Decommissioned – NS dismantled or at different stages of the decommissioning process.

[1] The figures presented in different references are conflicting;

[2] The INS Arighat, the second Indian SSBN, is in the testing phase, but was counted as operational in this table; and

[3] Jane´s Fighting Ships 2017-2018; Bellona Foundation Report nr 2:96; USN, 2019; MINISTRY OF DEFENCE, 2019; and DIGGES, 2017.

2.2.3 Radioactive Waste arising from Nuclear Submarine Decommissioning

Until the 1980s, radioactive waste was deliberately disposed at sea. At the time, this procedure (dumping) was seen as an acceptable low-cost solution. The practice of dumping was banned in 1975 when the London Dumping Convention (LDC)[16] was enforced (UNITED NATIONS ORGANIZATION, 1977). The estimated amount of radioactive waste dumped by the various countries over the years is reported by the International Atomic Energy Agency (IAEA-TECDOC-1105, 1999).

National sovereignty issues granted immunity to nuclear-powered vessels, delaying the adoption of LDC practices and allowing radioactive waste dumping for at least two more decades. Based on this positioning, unserviceable NS, naval nuclear reactors and radioactive waste arising from NS have been dumped (EPA, 1984; KOPTE, 1997).

As an example, a 2019 study conducted by a consortium including the British nuclear safety firm Nuvia updated the Norwegian radiation authorities report about the found 18,000 radioactive objects in the Arctic Ocean, among them 19 vessels, 14 nuclear reactors, including five that still contain spent nuclear fuel, and 735 other pieces of radioactively contaminated heavy machinery (LUHN, 2020; DIGGES, 2017).

The need to safely dispose the increasing number of unserviceable NS and the public concern on environmental pollution and on radioactive waste management have led the NS operating navies to implement safe NS decommissioning and waste management processes.

In 2020, Russian President Vladimir Putin set a decree to put in motion an initiative to lift two Soviet nuclear submarines (K-27 and k-159)[17] and four reactor compartments from the bottom, reducing the amount of radioactive material in the Arctic Ocean by 90% (LUHN, 2020).

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[16] The 1972 London Convention regulates the disposal of waste and other materials in the sea (dumping) to the prevention of marine pollution. It is commonly called the London Dumping Convention (LDC).

[17] The K-159 was a SSN (NATO report name - November class) decommissioned on 30 May 1989 and kept afloat with the aid of pressurized pontoons (floats). It was not defueled and received little or no maintenance for 14 years. On 28 August 2003, the K-159 sank in Arctic waters, at the depth of 238 m, drowning nine crewmembers and caring 800 kg of SNF. At the time, it was under tow from the Gremikha naval installation near Arkhangelsk to the Nerpa shipyard on the Kola Peninsula for dismantlement (DIGGES, 2017).

The K-27 was a prototype SSN (Project 645) and the only one constructed with a pair of experimental VT-1 liquid Metal Reactors (eutectic lead-bismuth). It suffered a series of accidents throughout its operational life. The last one was a liquid Metal coolant leak accident caused by uneven coolant flows that damaged one-fifth of the reactor core and killed nine. In 1981, it was deliberately sunk (dumped) in the shallows off the Novaya Zemlya Archipelago (DIGGES, 2017).

Radioactive waste arising from nuclear submarines decommissioning process is basically originated from two main sources: 1 - the reactor defueling; and 2 – the management of the activated materials in the RC.

The radioactive waste (RW) classification is presented in section 2.3.1. The RW arising from these two main sources are presented in sections 2.2.3.1 and 2.2.3.2, respectively. A synthetic overview of the types of RW arising from nuclear submarines decommissioning is presented in Table 4.

Table 4 – Types of radioactive wastes arising from NS decommissioning

	NNR Defueling	NNPP Decont.	RC Removal	RC Dismantling
HL SNF[18]	X			
ILW and IL activated materials	X			X
LLLW (Coolant)	X			
LLLW	X	X	X	X
VLLW	X	X	X	X

Captions:

HL SNF - High level activity used naval nuclear fuel (spent nuclear fuel - SNF)
IL – Intermediate Level
ILW – Intermediate Level Waste
LLLW – Low Level liquid Waste
VLLW – Very Low Level Waste
NNR - Naval Nuclear Reactor
NNPP - Naval Nuclear Power Plant
RC – Reactor Compartment
Decont. – Decontamination

2.2.3.1 Radioactive waste arising from the Naval Nuclear Reactor defueling

Radioactive waste arising from the naval nuclear reactor defueling is basically composed of:

a) high level activity spent nuclear fuel (SNF);
b) intermediate level activity ion-exchange resins;
c) low level activity liquids removed from the primary circuit (coolant included); and
d) lightly-contaminated items like tools and work clothing resulting from the defueling operation (classified as Very Low Level Waste – VLLW).

The High level activity used naval nuclear fuel (SNF) is the most radioactive item in the reactor. The removal of all SNF (defueling) removes over 99% of the radioactivity in the RC (USN, 2019; DAVIS and Van DYKE, 1990).

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[18] SNF is not necessarily classified as radioactive waste. It varies from country to country, according to national regulations

Ion-exchange resins, used for purification of water within the reactor, are Intermediate level activity. The resins removal is a routine activity and is not necessarily associated to the reactor defueling. The type and amount of resins in the RC varies greatly in different classes of submarines and will not be addressed in this thesis.

Low level activity liquids removed from the primary circuit (coolant included) would be either demineralized water or a solution of demineralized water and a corrosion inhibitor (potassium chromate in the USN) (USN, 2019).

In the USN, the radioactive potassium chromate liquid solution is removed from naval nuclear reactors, processed (filtered) to remove radioactivity[19], and either recycled into other Navy nuclear ships or, if not needed, treated and disposed of in accordance to applicable national and local (state) regulations. After filtration, the chromate solution is evaporated to reduce volume, processed to reduce hexavalent chromium to trivalent chromium, and the residual liquid is immobilized (solidification to an end product for disposal) as a low level RW (USN, 2012).

The reactor coolant also contains short-lived radionuclides with half-lives of seconds to hours. Their highest concentrations in reactor coolant are from N^{16} (7 second half-life), N^{13} (10 minute half-life), F^{18} (1.8 hour half-life), Ar^{41} (1.8 hour half-life), and Mn^{56} (2.6 hour half-life). The concentration of these radionuclides is reduced to one-thousandth one day after its discharge and reduced to one-millionth two days after its discharge. Consequently, these short-lived radionuclides are not important for liquid release considerations (NAVAL NUCLEAR PROPULSION PROGRAM, 2019).

2.2.3.2 Radioactive waste arising from the Naval Nuclear Propulsion Plant decontamination, the Reactor Compartment removal and its dismantling

Radioactive waste arising from the NNPP decontamination is basically composed of:

a) Low level activity liquids removed from the primary circuit resulting from the decontamination activities; and

b) Lightly-contaminated items like tools and work clothing resulting from the decontamination activities (usually classified as VLLW).

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[19] The radioactive liquid processing system consists of particulate filters, activated carbon bed filters, tied hydrogen hydroxil resin and colloidal removal resin beds. This filtration process reduces radioactivity in the liquid to about 10-8 μCi/ml (USN, 2012).

Radioactive waste arising from the reactor compartment removal and its dismantling is basically composed of:

a) low and intermediate level activity metal structures and equipment that have been exposed to the reactor neutron flux (activated materials);
b) low-level activity liquids resulting from additional decontamination activities; and
c) lightly-contaminated items like tools and work clothing resulting from additional decontamination activities (usually classified as VLLW).

Activated materials are originally non-radioactive materials (target nuclei) containing radioactive isotopes formed by the interaction of neutrons with nuclei. When neutrons interact with target nuclei, through shock and/or capture, give rise to highly excited nuclei. These nuclei lose their energy through various decay processes, emitting particles and/or radiation until they reach stability again. The type of particle and/or radiation emitted depends on the energy of the incident neutrons and the target nuclei. Most decay processes result in the emission of gamma radiation. Activated items contain:

a) radioactive isotopes within their constituent materials; and may also contain,
b) layers of activated corrosion products deposited on their surfaces.

The first cannot be removed by chemical or mechanical processes and does not generate contamination.

The low and intermediate level wastes might include primary circuit equipment and steel components inside the RC, used filters and some effluents from reprocessing (WNA, 2017). They correspond to nearly 1% of the previously existing radioactivity. Approximately 99.8 % of this radioactive material is an integral part of the structural metals forming the plant components. The remaining 0.2 % is radioactive corrosion and wear products which have been deposited on the inside of piping systems (USN, 2019; DAVIS and Van DYKE, 1990).

The primary source of radiation in the structural metals forming the Naval Nuclear Propulsion Plant is Co^{60} that emits gamma radiation (half-life of 5.27 years). Among the activation products in steel there are many gamma rays emitting highly radioactive isotopes such as Fe^{55}, Fe^{59} and Zn^{65} (half-life of 2.7 years, 45 days, 5.3 years, 245 days respectively) (USN, 2019; WNA, 2020).

During the first 20 years, the induced activity is dominated by the decay of the radioisotopes Fe^{55} and CO^{60}. During the next 800 years Ni^{63} is the most important and after that Ni^{59} is dominating (KOPTE, 1997).

Cobalt 60 is also the dominant residual corrosion and wear product of radioactive nuclide (USN, 2019). The radioactive corrosion and wear products are contained within two boundaries, the first being the sealed piping systems, and the second one the welded hull and package containment structure which makes up the completed RC disposal package (USN, 2019).

Radioactive contamination of the reactor circuit due to the release of fission products from the fuel is usually negligible. However, if the fuel has been damaged in an accident, the situation may be different (KOPTE, 1997).

During the RC dismantling, gases and dust containing radioisotopes may be carried by the wind or the rain, increasing the risk of radiological contamination.

2.2.4 Reactor Compartment Interim Storage

The removed RC is classified LILW, as presented in section 2.2.2. United States Navy (USN), Russian Federation Navy (RFN) and French Navy (FN) store their removed reactor compartment (RC) in different types of near-surface facilities. The temporary storage of LILW and the near-surface facilities are presented in sections 2.3.2 and 2.3.3, respectively.

The USN stores the removed RC in a burial trench (near the surface facility) at Department of Energy’s Hanford Nuclear Reservation (HNR) on burial ground 218-E-12B in the 200 East Area (USN, 2019). As of January 2019, there were USN 133 reactor compartments disposed at HNR, originated from 116 submarines and 8 cruisers (USN, 2019). Figure 2 shows the HNR burial ground (near-surface facility) in November 2009.

Once full, the trench will be filled with dirt and buried. The compartments are expected to retain their integrity for more than 600 years. The use of the thick steel submarine hull as a disposal provides extra isolation between the environment and the low-level waste and hazardous lead that remain after the spent nuclear fuel has been removed (USN, 2019).

Source: United States Navy (2012)

Figure 2 - Department of Energy’s Hanford Nuclear Reservation burial ground

The Russian Federation Navy (RFN) stores the removed reactor compartment in several near-surface facilities such as the long-term storage facility at Cape Ustrichiny in Primorsky and the interim repositories at Razboynik bay and at Sayda Bay (BUKHARIN and HANDLER, 1995; BELLONA FOUNDATION, 2013). The RFN no longer has reactor compartments stored afloat (NILSEN, 2019). Figure 3 shows the last of 120 RC from Cold War submarines, previously stored afloat, safely stored on a Concrete deck near-surface facility in Sayda Bay, on the Kola Peninsula, August 8th 2020.

Source: https://thebarentsobserver.com/en/ecology/2019/08/last-cold-war-reactor-lifted-water

Figure 3 - Reactor compartments on interim repositories at Sayda Bay

The French Navy (FN) stores the removed RC in a warehouse-like near-surface facility at Homet in Cherbourg for 15–20 years[20] (DIRECTION GENERALE DE L'ARMEMENT, 2010; KOPTE, 1997). This facility is shown in Figure 4.

Source: Demantelement des Sous-Marins et Gestion des Dechets, (2006)

Figure 4 - French reactor compartment at Homet

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[20] The RC of the Le Redoutable (first FN decommissioned NS) has already been stored for 29 years.

As previously mentioned, Royal Navy (RN) reactor compartments (RC) will not be cut apart from their submarines hulls (MINISTRY OF DEFENCE, 2014a). They will be removed and then transported to URENCO Nuclear Stewardship (interim storage facility) in Capenhurst, Cheshire, until the Geological Disposal Facility becomes available (MINISTRY OF DEFENCE, 2019). Scraped components of the primary circuit are ILW (MINISTRY OF DEFENCE, 2019 and 2014b).

The main characteristics of the RC near-surface storage facilities (NSSF) adopted by USN, RFN and FN are presented in Table 5.

Table 5 - Main characteristics of the USN, RFN and FN RC NSSF

	NSSF	Depth	Container	Facility Type	Quantity
USN[1]	X	Approximately 20 m [4]	yes	Trench	133 RC
RFN[2]	X	Surface	yes	Concrete deck	120 RC
FN[3]	X	Surface		Warehouse	6 RC

Captions:

NSSF – Near-Surface Storage Facility
RC - Reactor Compartment
[1] DOE Hanford Nuclear Reservation burial ground
[2] Russian RC store facility at Sayda Bay
[3] French RC store facility at Homet
[4] Estimated based in Figure 2

No information is available on the SN-BR RC characteristics, but its beam. Table 6 presents some RC characteristics.

Table 6 - Reactor Compartment main characteristics.

	Submarine			Reactor Compartment		Reactor	NS Class
	D	L	B	L	Weight		
USN[1]	6927 ton	110 m	10 m	8.9 m	NA	1 PWR GE S6G,	Los Angeles SSN
	7800 ton	115 m	10 m	9.4 m	NA	1 PWR GE S9G 40,000 SHP	Virginia SSN
RFN[2]	9300 ton	123 m	11.6 m	NA	NA	2 PWR, OK-700, 90 MWt	Yankee SSBN
FN[3]	8080 ton	128 m	10.6 m	12 m	1100 ton	1 PWR PAAR K15 - 150 MWt	Le Redoutable SSBN
	5100 ton	99.5 m	8.8 m	10 m	750 ton	1 PWR K15 150 MWt	Barracuda SSN
RN[4]	4060 ton	81 m	9.5 m	9 m	850 ton	1 PWR S5W 78 MWt	Dreadnought SSN
	7400 ton	97 m	11.3 m	9.8 m	NA	1 RR PWR2 145 MWt	Astute SSN

Captions:
D – Displacement
L – Length
B - Beam
NA - Information not available

[1] https://www.globalsecurity.org/military/systems
[2] https://fas.org/nuke/guide/russia/slbm/667A.htm
[3] Ministere de La Defense, (2006)
[4] Ministry of Defence, (2011); KOPTE, (1997)

2.3 LOW AND INTERMEDIATE LEVEL RADIOACTIVE WASTE STORAGE

In Brazil, the main guidelines for radioactive waste (RW) classification, management, storage and transportation are set by Federal Law 10.308/2001, nuclear regulations (CNEN-NN-3.01, 2014; CENEN-NE-5.01, 2021; CNEN-NN-8.01, 2014; and CNEN-NN-8.02, 2014), naval nuclear regulation (ANSNQ-112, 2019), which is specific for nuclear-powered vessels, and Standards (ABNT NBR 10.004, 2004).

2.3.1 Low and Intermediate Level Radioactive Waste

Industrial, medical and research installations generate waste that must be properly managed. In the nuclear field, the waste containing radionuclides is named radioactive waste. IAEA has classified radioactive waste in six classes (IAEA GSG-1), as follows:

a) exempt waste (EW);
b) very short-lived waste (VSLW);
c) very low level waste (VLLW);
d) low level waste (LLW);
e) intermediate level waste (ILW); and
f) high level waste (HLW).

In Brazil, CNEN has grouped radioactive wastes (RW) in classes according to their activity levels, the nature of radiation and their half-lives (CNEN-NN-8.01, 2014). Brazilian naval nuclear regulation on RW (ANSNQ-112) follows the same classification.

CNEN Low and Intermediate Level Waste (LILW) definition is:

> Low and Intermediate Level Waste (LILW): “Wastes with a half-life longer than VSLW, with activity or concentration levels above clearance levels and thermal powers below 2 kW/m^3.” (CNEN-NN-8.01, Class 2 RW).

CNEN RW classification is summarized in Figure 5.

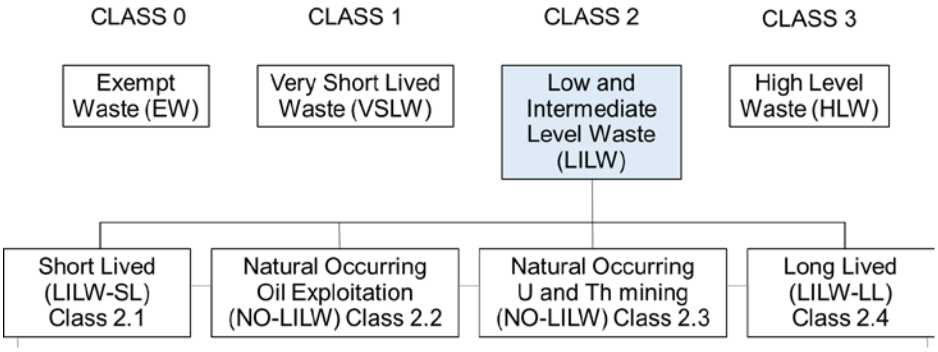

Figure 5 - CNEN radioactive waste classification

The main guidelines for RW classification, management, storage and transportation in Brazil are set in Law nº 10.308/2001, Brazilian regulation NBR 10.004, Brazilian nuclear regulations (CNEN-NN-3.01, CNEN-NN-5.01, CNEN-NN-8.01 and CNEN-NN-8.02). Additional guidance is provided by IAEA Technical Reports and Safety Guides.

LILW is often separated into short-lived and long-lived waste. The term ‘long lived’ refers to radionuclides with half-lives usually greater than 30 years (IAEA GSG-1 and CNEN-NN-8.01).

The boundary between short-lived and long-lived wastes cannot be specified in a universal manner with respect to concentration levels for radioactive waste disposal. These boundary limits depend on the actual radioactive waste management option and the properties of the individual radionuclides (IAEA GSG-1).

Generally speaking, the LILW in Brazil comes from: two nuclear power plants; one facility for processing monazite sands; several mining and milling facilities of conventional ores associated with uranium and thorium; the use of radioisotopes in medicine, industry, research; and from the decontamination work performed in Goiânia following the radiological accident that occurred in 1987 (HEILBRON et al., 2014).

According to IAEA, at least 95% of all radioactive waste generated is low and intermediate level waste (IAEA-TRS-390, 1998).

2.3.2 Low and Intermediate Level Radioactive Waste Storage Facilities

Radioactive waste storage is the waste retention in a facility or a location with the intention of retrieving it (IAEA-SSR-5, 2011). Storage is by definition an interim measure (temporary) that requires further action, such as waste conditioning, packaging or, ultimately, its disposal, when there is no intention of retrieving the wastes (IAEA Glossary, 2018; CNEN Glossary, 2020).

The term interim storage refers only to short term temporary storage solution, planned for a period that ranges from several years to about 50 years (IAEA-TRS-390, 1998). The interim storage plays a central role in the management of radioactive waste (RW) (IAEA, 2003). Radioactive wastes are stored not only to allow them to cool (decay), but also as an interim solution pending the definition of the final destination (IAEA-TRS-390, 1998).

The main functions of a storage facility for conditioned radioactive waste are to provide safe custody of the waste packages[21] and to protect operators and the general public from any radiological hazards associated with radioactive waste. The design of storage facilities will have to meet the national regulatory standards and basic safety principles (IAEA-SS-115, 1996).

According to Law 10.308/2001 and CNEN regulations (CNEN-NN-8.01, 2014), there are four types of radioactive waste storage facilities: 1 – Initial storage (inside the site); 2 – Intermediate storage (outside the site); 3 – Final repository (when there is no intention of wastes retrieving); and 4 – Temporary storage (for wastes arising from nuclear or radiological accidents). The first two types are suitable for the interim storage of the RC.

Storage and disposal facilities are designed to contain radioactive waste and to isolate it from the accessible biosphere[22] to the extent necessary (IAEA, 1997; IAEA-SSR-5, 2011). Different types of radioactive waste may require different storage and disposal facilities designs. According to the IAEA, the waste disposal facilities belong to two main categories[23] (IAEA-TECDOC-653, 2006): Near-Surface Repository[24]; and Geologic Repository. These categories are presented in Table 7.

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[21] Waste Package is a waste conditioning product that includes the waste form and any containers and internal barriers (e.g. absorbing materials and liner). It is prepared in accordance with requirements for handling, transport, storage and/or disposal (IAEA Glossary, 2018). The Waste in its physical and chemical form after treatment and/or conditioning (resulting in a solid product) prior to packaging (IAEA Glossary, 2018).

[22] The biosphere is the part of the environment that is normally inhabited by living organisms, including groundwater, surface water and marine resources that are used by people or accessible to people (IAEA, 2011).

[23] Additionally, very low level radioactive waste (VLLW) may be disposed in a facility similar to a conventional landfill facility for industrial refuse. Typical waste disposed of in a facility of this type may include soil and rubble arising from decommissioning activities.

[24] The term near-surface disposal replaces the terms 'shallow land' and 'ground disposal', but these older terms are still sometimes used when referring to this option.

Table 7 – IAEA main categories of disposal facilities

Categories	Description
Near-Surface	Disposal facility consisting of engineered trenches or vaults, usually made of concrete, constructed on the ground surface or up to a few meters below ground level (not greater than 30 meters - 100 ft.).
Geologic	Disposal facility constructed in tunnels, vaults or silos in a particular geological formation at least a few hundred meters below surface.

Brazilian nuclear regulations allow LILW interim storage in both categories of disposal facilities (CNEN-NN-8.01 - Art. 4º), as follows:

a) near-surface facilities to store or dispose Class 2.1 LILW; and
b) geologic facilities to store or dispose Class 2.4 LILW.

In Brazil, the storage or disposal of LILW in a near-surface facility depends on the amount of long-lived radioisotopes contained. This amount is limited to a maximum of 3700 kBq/kg in individual volumes and to an average value of 370 kBq/kg for the set of volumes (CNEN-NN-8.01, 2014).

According to IAEA, the current practice in various Member States limits the amount of long-lived radioisotopes to a maximum of 4000 kBq/kg in individual volumes and to an average value of 400 kBq/kg for the set of volumes (IAEA-TRS-390, 1998).

2.3.3 Near-Surface Storage Facilities

The term “near-surface disposal” refers to a range of disposal methods, such as the emplacement of solid radioactive waste in: 1 - earthen trenches, above ground engineered structures; 2 - engineered structures just below the ground surface; and 3 - rock caverns, silos and tunnels excavated at depths of up to a few tens of meters underground (IAEA-SSR-5, 2011).

Near-surface disposal facilities (NSDF) are currently in operation in many countries for the safe disposal of their LILW (IAEA-SSR-5, 2011; WNA, 2018). Among them are Brazil, Canada (IRUS), England (DRIGG), Finland (Olkiluoto and Loviisa), France (La Manche and Centre de L’aube), Japan (ROKKASHO), Russia (Ozersk, Tomsk, Novouralsk and Sosnovy Bor), South Korea (Wolseong), Spain (El Cabril), Sweden (Oskarshamn) and USA (Barnwell, Clive, Oak Ridge and Richland) (HEILBRON et al., 2014; WNA, 2018).

In Brazil NSSF are currently used to store or dispose LILW as follows:

a) RW generated by the uranium mine and milling facilities – these wastes, although significant in volume, are kept at the respective sites, in dams specially built for this purpose. There are, presently, about 600 metric tons of mesothorium[25] with an estimated Ra^{228} activity of 1.85 TBq (50 Ci) stored by INB in a trench and 0.2 TBq (6 Ci) stored in a shed (78 m^3). The by-product containing uranium and thorium from monazite processing, although not formally classified as waste, has been under storage for decades in many installations in Brazil. This material was sold by INB to China and will be gradually transferred to that country (HEILBRON et al., 2014).

b) RW generated by the Goiânia accident[26] - these wastes were generated from the cleanup of the Cs^{137} contaminated areas. It generated about 3500 m^3 of solid radioactive waste totaling some 6000 tons of material. The waste was disposed of in two near-surface LILW repositories built in reinforced concrete (HEILBRON et al., 2002; IAEA STI/PUB/815, 1988; PASCHOA et al., 1993). The repository is located in the city of Abadia – state of Goiás;

c) LILW generated by the Angra nuclear power plants is stored in sheds on the site (HEILBRON et al., 2014).

d) LILW generated by the medical and industrial applications and by the research facilities that cannot reach clearance levels are mainly stored in CNEN Research Institutes. These institutes are: the Nuclear Technology Development Center (CDTN), in the city of Belo Horizonte; the Institute of Radioprotection and Dosimetry (IRD) and the Nuclear Engineering Institute (IEN), in the city of Rio de Janeiro; and the Nuclear and Energy Research Institute (IPEN), in the city of São Paulo (HEILBRON et al., 2014; ZANCHETA et al, 2009).

Other Brazilian LILW NSSF are currently in different phases of their design and licensing process, as for example:

a) Brazilian low and intermediate level waste repository (RBMN) – it is a surface repository that will receive LILW (CNEN class 2.1) from the national initial, intermediate and provisory deposits. RBMN is equipped with a multiple barriers

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[25] Mesothorium is either of two decay products of thorium or a mixture of the two products. It is usually obtained from thorium minerals (as monazite sand). Mesothorium I is an isotope of radium (MsTh1 or Ra^{228}) and mesothorium II is an isotope of actinium (MsTh2 or Ac^{228}).

[26] The Goiânia accident was a radioactive contamination accident occurred on September 13, 1987, in Goiânia, in the state of Goiás – Brazil. The accident was caused by a forgotten cesium chloride (CsCl) radiotherapy source taken from an abandoned hospital site (about 50 TBq of Cs^{137}), subsequently handled by many people, resulting in four deaths.

deposition system. It will ensure institutional custody for these wastes for 300 years (TELLO, 2019). RBMN receives technical advice from the French National Agency for the Management of Radioactive Waste (ANDRA) since 2015; and

b) EBN LILW initial deposit – It will be built in the Specialized Maintenance Center (CME) in the EBN site to store the LILW generated during the SN-BR operational life. This deposit will not be approached in this thesis.

According to IAEA near-surface storage and disposal facilities may be constructed, with or without engineered barriers, in two ways (IAEA-TRS-390, 1998; IAEA-SSR-5, 2011):

a) near-surface disposal facilities at ground level. These facilities are on or below the surface where the protective covering is of the order of a few meters thick. Waste containers are placed in constructed vaults and, when full, the vaults are backfilled. Eventually, they will be covered and capped with an impermeable membrane and topsoil. These facilities may incorporate some form of drainage and possibly a gas venting system.

b) near-surface disposal facilities in caverns below ground level. Unlike near-surface disposal at ground level, where the excavations are conducted from the surface, shallow disposal requires underground excavation of caverns. The facility is at a depth of several tens of meters below the Earth's surface and accessed through a drift.

An engineered storage facility for LILW with low contact dose rates may be of simple construction, for example an inflatable building on an asphalt base pad. Alternatively a warehouse-like construction with no arrangements for package handling, heating or ventilation is widely used (IAEA-TRS-390, 1998).

In Brazil, the design, construction and operation of the Initial Deposit are the responsibility of the operator. CNEN has the same responsibilities for the Intermediate Deposit and Final Repository (Law 10.308/2001 and CNEN-NN-8.02, 2014).

2.3.4 Safety Considerations for Near-Surface Storage Facilities

The IAEA fundamental safety objective, which applies to the storage and management of radioactive waste, is to protect people and the environment from the harmful effects of ionizing radiation (IAEA-TECDOC-653, 2006). To achieve this objective, radioactive waste has to be contained and isolated from the accessible biosphere to the extent that this is necessary (CNEN-NN-8.01 and IAEA SSR-5).

During the facility operational period the radiation safety requirements and the related safety criteria are the same as those for any nuclear facility or activity involving radioactive material and are established in the International Basic Safety Standards (IAEA Safety Series N° 115). The primary goal is to ensure that radiation doses are as low as reasonably achievable and within the applicable system of dose limitation (IAEA SSR-5).

The dose limit for members of the public is an effective dose of 1 mSv in a year (CNEN-NN-3.01; IAEA Safety Series N° 115). To comply with this dose limit, a disposal facility (considered as a single source) is so designed that the calculated dose or risk to the representative person does not exceed a dose constraint of 0.3 mSv in a year (IAEA-SSR-5).

The dose limit for occupationally exposed persons (IOE) is an effective dose of 20 mSv in a year[27] (CNEN-NN-3.01, 2014).

In relation to the effects of inadvertent human intrusion after facility closure, if such intrusion is expected to lead to an annual dose to those living around the site of the magnitude of:

a) less than 1 mSv, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted;

b) in the range 1–20 mSv, then reasonable efforts are warranted to reduce the probability of intrusion or to limit its consequences through optimization of the facility's design; and

c) more than 20 mSv, then alternative options for waste disposal are to be considered, for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.

Safety in the operation of radioactive waste disposal facilities has to be achieved through a variety of engineered and operational controls similar to those used in other facilities in which radioactive material is handled, used, stored or processed. These include the containment and shielding for the radioactive waste and operational control over time of exposure and proximity to the waste. Protection of the public is provided for by preventing or controlling releases from the facility and by controlling access to the site (IAEA-SSR-5, 2011).

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[27] Arithmetic average over 5 consecutive years, provided it does not exceed 50 mSv in any year (amended by CNEN Resolution 114/2011).

2.4 ENVIRONMENTAL AND NUCLEAR LICENSING OF RADIOACTIVE WASTE STORAGE FACILITIES IN BRAZIL

Brazilian National Environmental Policy (Política Nacional de Meio Ambiente - PNMA) was established in 1981 to preserve, improve and recover environmental quality, ensuring the conditions for social and economic development and the protection of human dignity (Law nº 6.938/1981).

The PNMA established the National System for the Environment (Sistema Nacional do Meio Ambiente - SISNAMA), which is composed of the Brazilian National Environment Board (Conselho Nacional do Meio Ambiente - CONAMA) and executive agencies at the federal, state and municipal levels (Law 6.938/1981, Supplementary Law nº 140/2011, CONAMA Resolutions 001/1986 and 237/1997, IBAMA Normative Instruction 184/2008 and Rio de Janeiro State Decree 134/1975).

In Brazil, activities and enterprises with significant environmental impact, including nuclear undertakings and activities, have to be submitted to environmental licensing by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) (Law nº 7.804/1989).

The Environmental Licensing in Brazil is:

> "Administrative procedure by which the competent environmental agency licenses the location, installation, expansion and operation of enterprises and activities that use environmental resources considered effective or potentially polluting or those that, in any form, may cause environmental degradation, considering the legal and regulatory provisions and technical standards applicable to the case." (CONAMA Resolution nº 237/1997)

Nuclear installations have to be submitted to environmental licensing by IBAMA and to nuclear licensing by CNEN, without prejudice to other legally required licenses (Art. 10, Law 10.308/2001). The licensing of nuclear installations and their safety, safeguards and security is the responsibility of the Brazilian National Nuclear Safety Authority (ANSN) (Law 14.222/2021). The environmental licensing and the nuclear licensing processes are independent, parallel, and complementary acts.

The basic criterion concerning the impact of introducing a new industrial installation in a given site is that it should have minimal adverse effects on individuals, society and the environment. For a nuclear power plant, the major impact is associated to the potential of radioactive releases, in normal operation or accidental conditions.

The environmental licensing requires the development of an Environmental Impact Study (EIA) and the preparation of an Environmental Impact Report (RIMA) before site approval. The various definitions, responsibilities, criteria and guidelines for EIA are established by CONAMA resolution nº 001/1986.

2.4.1 Environmental Licensing of Ships and Military Facilities in Brazil

Brazilian Navy ships and military facilities have to comply with Brazilian environmental regulations and with international regulations for the prevention of pollution on the sea. However, military facilities related to the use and preparation of the Armed Forces have a specific environmental licensing process (Supplementary Law nº 97/1999 and CONAMA Resolution nº 237/1997). This different approach aims to prevent the disclosure of information related to the defense and national sovereignty.

The CNI and the military facilities within[28] are exempt from IBAMA environmental licensing (IBAMA, 2018). The authority with environmental responsibility for the BN facilities is the Brazilian Navy Directorate of Ports and Coasts (DPC). Thus the SN-BR construction, the activities related to the RC removal, the dismantling of submarine remaining parts and the construction of the RC interim storage facility are exempt of the IBAMA environmental licensing process. If the RC interim storage facility is located outside the CNI site it will have to be submitted to IBAMA environmental licensing.

2.4.2 Nuclear Licensing of Ships and Military Facilities in Brazil

Nuclear facilities operated by Brazilian Armed Forces have to be submitted to a nuclear licensing process (Law nº 7.781/1989). A different licensing process applies to the Brazilian nuclear-powered ships and to the Military land based nuclear facilities.

a) Brazilian nuclear-powered ships are licensed by the Brazilian Naval Authority for Nuclear Safety and Quality (ANSNQ) (Law nº 1.3976/2020 and Provisional Measure nº 1.049/2021); and

b) Military land based nuclear facilities are licensed by CNEN (Law nº 7.781/1989).

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[28] The facilities of the Itaguaí Naval Complex (CNI) that are exempt of IBAMA environmental licensing are: the Brazilian Navy Submarine Base (Base de Submarinos da Ilha da Madeira - BSIM), shipyard, ship elevator (Shiplift), dry-docks and berths.

2.4.2.1 Licensing of Nuclear-Powered Ships in Brazil

As previously mentioned, Brazilian nuclear-powered ships are licensed by the Brazilian Naval Authority for Nuclear Safety and Quality (ANSNQ) (Law nº 13.976/2020 and Ministerial Ordinance 120/MB).

> “Navy Command is required to promote the licensing and inspection of ships, their naval nuclear propulsion plants and the transportation of its nuclear fuel, by an independent specific military organization for that purpose." (Law nº 13.976/2020).

ANSNQ is the Brazilian naval regulatory authority (Ministerial Ordinance nº 332/MB, 2020). The Brazilian Naval Agency for Nuclear Safety and Quality (AgNSNQ) is the naval regulatory body for the SN-BR design, construction operation and decommissioning (Ministerial Ordinance nº 120/MB, 2017).

AgNSNQ is responsible for the SN-BR licensing and decommissioning process and for the activities related to the RC removal and to the dismantling of submarine remaining parts. The SN-BR decommissioning process is presented in section 3.3.

The nuclear regulations applied to the SN-BR licensing and decommissioning process are the ANSNQ regulations complemented by CNEN and United States Nuclear Regulatory Commission (NRC) regulations, if necessary to fill any current gap on Brazilian naval nuclear regulations.

Brazilian naval nuclear regulations (ANSNQ regulations) are compliant with Brazilian nuclear regulations (CNEN regulations). ANSNQ regulations will ensure that naval nuclear power plants be, at least, as safe as nuclear power plants.

As an example, the naval nuclear-powered vessels licensing regulations (ANSNQ-101) is, in essence, the national nuclear installations licensing regulations (CNEN-NE-1.04) adjusted to encompass the naval nuclear propulsion plants specificities.

It is important to highlight that CNEN regulations for licensing (CNEN-NE-1.04, 2002) and for decommissioning (CNEN-NN-9.01, 2012) do not apply to naval nuclear propulsion plants (CNEN-NE-1.04, section 1.2.1.1).

> “1.2.1.1 - Activities related to nuclear reactors used as an energy source for transport means, as propulsion or other uses, are excluded.” (CNEN-NE-1.04, 2002).

2.4.2.2 Licensing of Military Land Based Nuclear Facilities in Brazil

As previously mentioned, land-based nuclear installations (military installations included) are licensed by CNEN (Law nº 7.781/1989). However, this licensing process is about to be handover to the recently created Brazilian National Nuclear Safety Authority (ANSN) (Provisional Measure nº 1.049/2021).

ANSN was created with the purpose to separate nuclear activities related to regulation from those related to research. ANSN will be responsible for regulation, inspection and licensing, and CNEN will carry out research and development work in the nuclear sector. No significant change in the Brazilian regulatory process is expected to arise from alteration in the Brazilian nuclear regulatory structure.

The licensing of the SN-BR RC near-surface storage facility (NSSF), the CNI nuclear facilities and its dry-docks will be carried out by ANSN.

Table 8 presents the Regulatory Authorities responsible for the environmental and nuclear licensing of the SN-BR and its RC interim storage facility.

Table 8 - Regulatory Authorities responsible for the environmental and nuclear licensing

	REGULATORY AUTHORITY	
Vessel / Facility	Environmental Licensing	Nuclear Licensing
SN-BR decommissioning	exempt	AgNSNQ
RC Initial Deposit	DPC	CNEN
RC Intermediate Deposit	IBAMA	CNEN

2.5 SITE SELECTION OF LILW STORAGE FACILITIES

Near-surface disposal facilities (NSDF) are in operation in many countries[29] since the last century (IAEA-SSR-5, 2011; HEILBRON et al., 2014; WNA, 2018). Their site selection process is regulated by AIEA, NRC and various national regulatory bodies. Appendix B lists the relevant nuclear regulations on site selection of radioactive waste storage and disposal facilities (CNEN Regulations and related IAEA Regulations).

Generally speaking, the operator has to evaluate the candidate sites and select one of them for the construction of the interim storage facility. To accomplish this task, IAEA proposes the combined use of a siting process and a site evaluation process (IAEA-SSG-35, 2015).

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[29] The main LILW near-surface storage facilities in Brazil and abroad are listed in section 2.3.3.

The siting process consists of surveying and selecting a suitable site for a nuclear installation. The site evaluation process consists of the analysis of the factors that could affect the safety of a facility or of an activity throughout its operational life (IAEA-SSG-35, 2015). The two processes comprise five different stages, as follows:

1. site survey stage;
2. site selection stage;
3. site characterization stage (site verification and site confirmation);
4. pre-operational stage; and
5. operational stage.

The siting process consists of the first two stages, i.e. site survey and site selection (see Figure 6). In the site survey stage, large regions are investigated to find potential sites. In the site selection stage unsuitable sites are discarded and the remaining ones are screened based on safety and other considerations.

The site evaluation process consists of the last four stages. It comprises: (a) the site selection stage (last stage of the siting process); (b) the site characterization stage, responsible for the confirmation of the selected site suitability, its characterization and its derivation from the nuclear installation design basis; (c) the pre-operational stage, responsible for the confirmation and completion of the pre-operational stage assessment; and finally (d) the operational stage, responsible for the installation periodic safety review (IAEA-SSG-35, 2015).

Figure 6 presents the five stages of the siting process and site evaluation process. This thesis is limited to the site selection stage (circled in red).

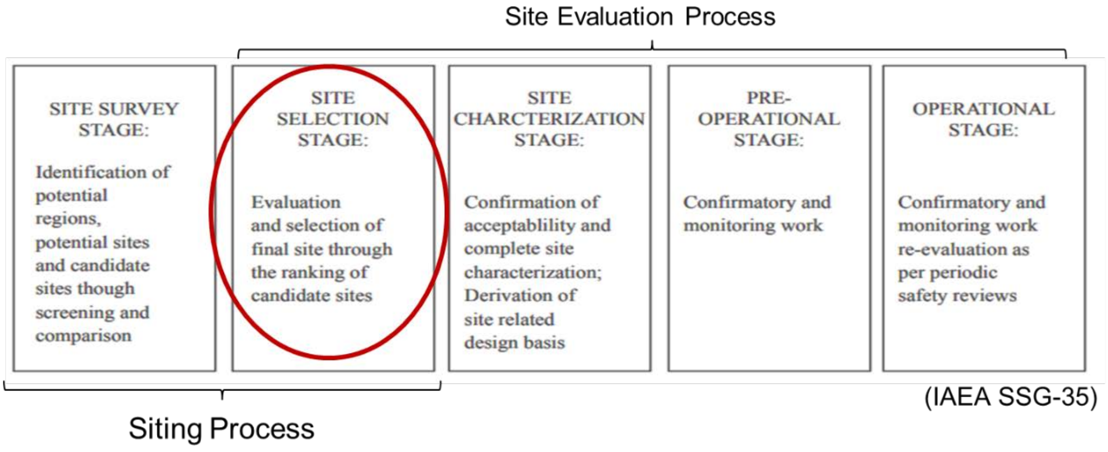

Figure 6 - Stages of the siting process and site evaluation process

2.5.1 Site Selection of LILW Storage Facilities in Brazil

According to CNEN regulations (CNEN-NE-6.06, 1989) near-surface storage and disposal facilities have to ensure long-term protection:

a) to men, his goods and to the environment against the release of radioactive material and or radiation;
b) to inadvertent intrusion of individuals and animals; and
c) to maintain the repository sealing stability.

In Brazil, the site selection process is regulated by Law 10.308/2001 and CNEN (CNEN-NE-6.06, 1989) which complies with IAEA regulations. Due to the SN-BR RC specificities, these regulations have been complemented by the Brazilian Naval Authority for Nuclear Safety and Quality (ANSNQ) regulations when necessary.

CNEN regulations (CNEN-NE-6.06, 1989) divide the site survey stage into four steps of successive technical analyses of increasing complexity. The difference between the steps lies mostly in the complexity level of the studies. These steps are presented in Table 9.

Table 9 – CNEN Site Selection Steps

Step		Description
1	Regions of Interest	Territorial spaces initially identified in the selection process, at the regional level. Studies are performed on regional scale (less than 1:100,000)
2	Preliminary Areas	Areas identified within the region of interest and selected to be investigated to identify potential areas. Studies are performed on regional scale (less than 1:100,000)
3	Potential Areas	Areas contained in the preliminary area, identified as potentially satisfactory to receive a deposit of radioactive waste, through the application of restrictive technical criteria and specific technical studies. Studies are performed on semi-detailed scale (between 1:10,000 and 1:100,000)
4	Candidate Sites	Favorable locations selected among the potential areas, through the application of technical studies of increasing depth concerning those previously applied. One of the candidate sites will be the site selected by the proper authority. Studies are performed in detail scale (greater than 1:10,000).

CNEN regulations establish four fundamental factors that must be taken into account to identify critical parameters that could limit or prevent the use of a location (CNEN-NE-6.06, 1989). These four factors are presented in Table 10.

Table 10 – CNEN Fundamental Factors for Site Selection

Factors		Description
1	Ecological Factors	• Terrestrial and aquatic ecology survey and study of regional flora and fauna; • Environmental impact survey and study, considering the estimation of potential effects caused by the repository on the area; and • Forecast of environmental impacts caused by the implementation and operation of the repository.
2	Socio-economic Factors	• Demography survey and study of its projection. • Union and state lands survey; • Land and water survey of current and future use; • Agropastoral activities survey and evaluation given their contribution for the local, state and federal economy; • Industrial activities survey and evaluation of existing industrial and commercial activities; • Ways and means of transport survey; and • Survey on direct and indirect benefits to the surrounding population.
3	Geological Factors	• Regional hydrography survey, considering meteorological and climatological aspects; • Hydrogeology and Hydrology survey and study of the surface and groundwater; • Geological survey and study of the main structural and tectonic features; • Geomorphology survey of the terrain forms. • Pedology survey and study of the soil nature and properties. • Seismology survey of earthquake information and historical records. • Lithology survey and study of the mineralogical and chemical analysis of rocks.
4	Physiographic Factors	• Hydrography survey at regional and local level, of surface water characteristics; and • Meteorology and climatology survey and study of the meteorological and climatological conditions, through the interpretation of historical and forecast records.

The identification of the candidate sites (4th step) requires, at least, the development of the following surveys and studies (CNEN-NE-6.06, 1989): 1 - Geophysical, Geotechnical and Geochemistry surveys; 2 - Planimetric survey; 3 - Pedological survey; 4 - Meteorological measurements; 5 - Hydrological and hydrogeological studies; 6 - Ecological studies; and 7 - Radiometric survey.

Additionally, candidate sites should also (CNEN-NE-6.06, 1989):

a) be located on land belonging to either municipalities, state or Federal Government (private owned lands should be expropriated before the construction begins);

b) be well drained and have no surface water (not subject to flooding); and

c) prevent or delay the radiation exposure as a result of surface transport of radionuclides; erosion processes; and dispersion caused by the intrusion of man, animal or deep root plants.

The first site selection studies for LILW deposition in Brazil were conducted by CNEN in the late 1970s and early 1980s (RADUAN, 1994). These studies suggest that surface repository would be the most convenient alternative for the deposition of LILW in Brazil (CASTELO, DORNELLES and BARRETO, 1986).

Surface storage facilities are more susceptible to the adverse effects of the natural processes and to human intrusion when compared to other disposal systems, such as disposal below the surface or geological disposal (RADUAN; 1994).

The first final repository in Brazil is the Abadia repository[30], completed in 1997 (PEREIRA, 2005). Its site selection process followed the four steps established in CNEN-NE-6.06 (CNEN Resolution 3, 1993; CDTN, 1991).

Experience to date, in Brazil and abroad, suggests that technical issues are not the main challenge in the site selection process of disposal facilities (RADUAN, 1994; IAEA-SSR-5, 2011). The main challenge is often related to the political approach required to encompass the demands of the different segments of society. Among these demands are: the public opinion; the environmental impacts in the area; and the socio-economic impacts on the local communities (RADUAN; 1994).

Public opinion constantly opposes the construction of radioactive wastes deposits in their surroundings. This is due to the local community's attitude to take risks

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[30] The Abadia repository is the final repository for the radioactive waste generated by the Goiânia accident involving Cs ^{137}.

despite the proposed socio-economic benefits. This opposition is known as NIMBY, “Not in my backyard” syndrome[31] (PEREIRA, 2005).

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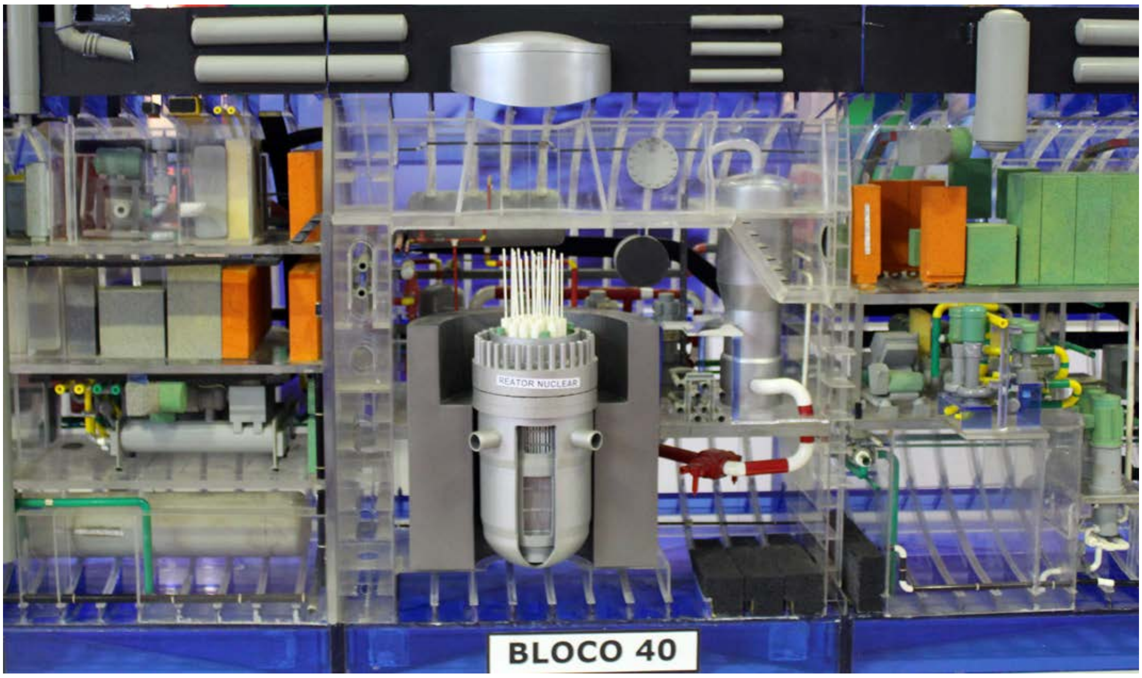
[31] NIMBY, an acronym for the phrase "not in my back yard". It is a characterization of opposition by residents to proposed enterprises in their local area. The word appears in a June 1980 newspaper article "No One Wants Backyard Nuclear Dump" (Gates, Ernie. Daily Press. 29 jun. 1980).

CHAPTER 3 - THEORETICAL FOUNDATION

3.1 SN-BR REACTOR COMPARTMENT AND ITS CONTAINER

3.1.1 SN-BR Reactor Compartment

The SN-BR Naval Nuclear Power Plant (NNPP) and its reactor compartment (RC) have always been surrounded by a high degree of confidentiality and little information is available on open sources. Figure 7 shows a possible RC configuration in an SN-BR model (WILTGEN, 2018).



Source: Wiltgen (2018)

Figure 7 - SN-BR model with visible RC

Due to the lack of open source information, this thesis adopts:

a) SN-BR RC main characteristics as presented in Table 11;

b) SN-BR RC is classified as a low and intermediate level radioactive waste (LILW) (Assumption 2). Its LILW is Class 2.1 RW and may be stored in near-surface storage facilities (CNEN-NN-8.01, 2014) as the American, Russian and French removed RC (section 2.2.4).

c) SN-BR RC metallic container main characteristics as presented in Table 12;

d) the external radiation levels on the surface of the metallic container of the SN-BR RC is lower than 0.01 mSv/h (Assumption 4). These external radiation levels are consistent with the ones reported by USN, RFN and RN, as per section 3.3.1.

Table 11 - SN-BR Reactor Compartment main characteristics

SN-BR RC		Observations
Length	13 m	This length was estimated by the comparison of the SN-BR and the submarine model shown by Wiltgen (2018). It comprises the length of the RC and two cofferdams.
Diameter	9.8 m	It is the SN-BR beam (PADILHA, 2012b).
Weight	1200 ton	It was estimated as 20% of the SN-BR total weight (section 2.1.2). It comprises the hull section, the two cofferdams, the shielding and all the equipment within.

As previously mentioned, the RC is the section of the submarine that houses the naval nuclear reactor. The RC is a watertight structure that is expected to retain its integrity for more than 600 years (USN, 2019). A brief description of the NNPP and their RC is presented in section 2.1.2. The RC removal process (hull cutting) and the SN-BR decommissioning process are presented in section 3.3 and Appendix A.

The radioactive materials in the RC are activation products that are immobilized within the RC, as presented in section 2.2.3.2. These radioactive materials are not subjected to water transportation because: 1 - they are immobilized in the RC constituent materials; and 2 - the RC is a watertight structure that confines these materials and limits the possibility of their release to the environment (USN, 2019). The RC is equivalent to the 3rd contention barrier in a nuclear power plant. Additionally, the RC is to be encapsulated within a metallic container, which is an external barrier enforcing radiologic safety.

3.1.2 SN-BR Reactor Compartment Metallic Container

The SN-BR metallic container is the vessel into which the RC is placed. It is an external barrier responsible to ensure the safe RC handling, transporting and interim storage. The encapsulated RC defines the activated materials waste package (WP) to be stored (CNEN-NN-8.01 and IAEA SSR-5).

The SN-BR RC metallic container has a very stringent design to properly support the loads imposed by the RC and to retain its integrity in an accident scenario (IAEA-SS-115, 1996), in order to effectively protect the public and the environment. This hypothetical condition considers heat, cold, pressure, vibration, drop, puncture and sinking in the event of transportation on a barge.

The Brazilian Navy adopts conservative design criteria for the SN-BR and shall do so in the design of the metallic container. Additionally, its design has to comply with CNEN radioactive material transport regulations (CNEN-NE-5.01, 2021). The metallic container construction has to be preceded by CNEN licensing (CNEN-NN-8.01, 2014). SN-BR RC metallic container main characteristics adopted in this thesis are presented in Table 12.

Table 12 - SN-BR reactor compartment metallic container main characteristics

SN-BR RC Metallic Container		Observations
Length	14 m	The SN-BR hull cut is made several feet forward and aft of the shielded RC, as per Appendix A.
Diameter	12 m	It considers the installation of the tracks and the cradles required to insert and retrieve the RC in/from the metallic container.
Weight	200 ton	
External Radiation Level	lower than 0.01 mSv/h	It is the radiation level on the surface of the container
TOTAL WEIGHT	1400 ton	It is the RC waste package total weight (RC and metallic container)

3.1.3 SN-BR reactor compartment and Waste package Transportation

The SN-BR reactor compartment and Waste package transportation may be performed by two transport options (land or sea transportation). Both options have to consider the limitations (logistics constraints) imposed by the waste package weight and dimensions.

Land transportation is carried out by transport vehicles (transporters) capable of jacking the waste package. As an example, Figure 8 presents the transporters and the cradles adopted for the French NS class “Le Redoutable” RC transportation.

In this option, the waste package will be attached to the transporter using welded attachments, and raised off the support columns using jacking features built into the transport vehicle. At the arrival, the transporter is maneuvered into an off-loading area, the RC waste package welded attachments are cut free from the transporter, the package is jacked and offloaded into a system of high capacity tracks and rollers.

Source: Demantelement des Sous-Marins et Gestion des Dechets, (2006)

Figure 8 - French NS class “Le Redoutable” reactor compartment transportation

Sea transportation is carried out by a special floating device (barge) capable of compensating the vertical misalignment resulting from the loaded transporter displacement. In the sea transport option, the transporter is then driven from the Main Hall to the Shiplift[32] to be loaded in the barge. Welded attachments connect the transporter to the barge. At the arrival, these attachments are cut free for the transporter load-out.

3.2 REACTOR COMPARTMENT INTERIM STORAGE IN BRAZIL

3.2.1 The SN-BR Reactor Compartment Near-Surface Storage Facility

The SN-BR RC should be stored in a near-surface storage facility (NSSF) just as it is done by the American, Russian and French Navies (section 2.2.4). Three different

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[32] Shiplift – Ship elevator, the name refers to the main manufacturer of these elevators.

types of NSSF have been adopted by these three navies. USN stores their RC in a trench in the desert, RFN stores in a seaside concrete deck and FN stores in a warehouse-like NSSF as per Table 5.

This thesis considers four types of facilities for the construction of the SN-BR RC interim storage. They are a tunnel drilled in the rocks at ground level and the three above mentioned facilities (trench, concrete deck and warehouse). These different types of facilities may be more adequate to certain locations (site) than to others.

The interim storage site selection, design, construction and operation are the operator's responsibility (Law nº 10.308/2001 and CNEN-NN-8.01, 2014). If the storage facility is located inside the CNI site, those activities are BN responsibility. Otherwise, if located outside, they are the responsibility of the Brazilian National Nuclear Safety Authority (ANSN) (Law nº 13976/2020 and Provisional Measure nº 1049/2021).

Brazilian National Commission for Nuclear Energy (CNEN) regulations allow four types of LILW near-surface storage facilities (CNEN-NN-8.01, 2014): 1 – Initial storage (inside the site); 2 – Intermediate storage (outside the site); 3 – Final repository (when there is no intention of wastes retrieving); and 4 – Temporary storage (for wastes arising from nuclear or radiological accidents). The first two types of NSSF are suitable for the interim storage of the RC waste package.

For each of these types of LILW near-surface storage facilities three types of structures may be constructed for LILW storage and disposal (CNEN-NN-8.01, 2014; CNEN-NE-6.06, 1989 and IAEA-SSR-5, 2011). They are: 1 – earthen trenches, above ground engineered structures; 2 - engineered structures just below the ground surface; and 3 – rock caverns, silos and tunnels excavated at depths of up to a few tens of meters underground. The different types of NSSF adopted by USN, RFN and FN RC are presented in section 2.2.4.

The RC storage facility has to be approached as a system to ensure its safe performance. This system consists of three major components: the site (location); the deposit (facility) and the waste package. This concept of system implies that a less favorable characteristic of one of the components must be compensated by a better performance of another component.

The SN-BR reactor compartment interim storage period is not available in open-sources. According to the IAEA the interim storage period ranges from several years up to about 50 years (IAEA-TRS-390, 1998). The RC interim storage period of the USN, RFN and FN ranges from 30 to 60 years. However, longer storage periods have been reported, as no RC has been dismantled so far (USN, 2019; NILSEN, KUDRIK and NIKITIN, 2006; KALISTRATOV, 2011). Thus, a conservative interim storage period of 60 years for the SN-BR RC is advisable, as presented in section 3.3.1.

3.2.2 Space Required for the Storage of the Reactor Compartment Waste Package

No open source information was found on the space required by the BN for the storage of the SN-BR waste packages (reactor compartment and its metallic container). Thus, as a conservative approach, this thesis considers the minimum space required because it will lead to a greater number of candidate sites.

The minimum SN-BR RC NSSF area of 2030 m^2 was estimated considering:

a) individual waste package area of 168 m^2 (12 m x 14 m), as per Table 12;

b) individual waste package storage area of 255 m^2 (15 m x 17 m) considering a minimum distance of 3 m between each waste package (estimated from Figure 2);

c) minimum storage of 6 waste packages (6 SN-BR);

d) minimum area of 1530 m^2 (6 x 255 m^2) for 6 waste package storage; and

e) minimum off-loading and maneuver area of 500 m^2 to unload the waste package from the transporter.

Additional space provisions should be made to fulfill security requirements. This area will not be considered in this thesis.

3.3 SN-BR DECOMMISSIONING PROCESS

So far, the Brazilian Navy (BN) has no officially approved decommissioning process for the SN-BR. Thus, this thesis adopts the SN-BR decommissioning process proposed by Maia (2015), which is similar to the ones adopted by the American, Russian and French navies (Assumption 1). This Decommissioning process complies with Brazilian nuclear regulations (ANSNQ-112 and CNEN-NN-9.01).

The proposed SN-BR decommissioning process should be performed at the CNI site (RC disposal excluded). This approach does not require the construction of additional facilities (cost-effectiveness) and prevents disclosure of sensitive information during the RC and submarine dismantling.

According to Maia (2015), the nuclear submarine decommissioning is the set of activities to be carried out at the end of the submarine operational life to ensure that the submarine constituent materials pose no risk to the public and to the environment.

The desired final state to be achieved at the end of the SN-BR decommissioning process is the release of the submarine constituent materials from the regulatory control to recycling or to disposal (MAIA, 2015).

The SN-BR decommissioning process will adopt the deferred dismantling strategy. Deferred dismantling is the strategy in which, after the removal of the nuclear fuel from the SN-BR, the part of the submarine containing radioactive material is either processed or placed in such a condition that it can be put in safe storage until it is subsequently decontaminated and/or dismantled (Adapted from ANSNQ-112, CNEN-NN-9.01 and IAEA GSR Part 6).

The proposed SN-BR decommissioning process is divided into five phases, as follows:

1 – Preparatory Phase;
2 - Fuel and Waste Removal Phase;
3 - Fuel and Waste Management Phase;
4 - Activated Material Management Phase; and
5 - Hull Dismantling Phase.

BN estimate for the SN-BR decommissioning duration is not available in open sources. However, considering foreign experience, it is likely to take at least three years[33] (not considering the RC dismantling).

Appendix A presents the description of the proposed SN-BR decommissioning process, allowing us to focus on the Activated Material Management Phase (Phase 5).

3.3.1 SN-BR Activated Material Management Phase

The Activated Material Management Phase main objective is to reduce the risk of radiological contamination from activated materials arising from the RC. To do so,

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[33] The time required to perform the preparatory activities (i.e. those comprised from the NS withdrawn from operational service to the end of the pre-defueling) is more than one year, typically from one to three years (HØIBRÅTEN et al., 2007). The time consumed in the next activities should not be less than two years. The USN decommissioning process, from fuel removal to hull dismantling, takes an average of two years (RAGHEB, 2010).

the RC is cut and separated from the rest of the submarine to segregate the activated materials therein. This phase starts after formal authorization for the SN-BR decommissioning, which is granted by the Brazilian Naval Authority for Nuclear Safety and Quality (ANSNQ). It finishes with the disposal/recycling of the activated materials within the RC. The SN-BR decommissioning process formally starts in this phase and ends when ANSNQ no longer controls the materials within the reactor compartment.

As previously mentioned, this thesis postulates that: 1 – the RC is a low and intermediate level activity radioactive waste (LILW) (Assumption 3); and 2 - all activated materials in the SN-BR are confined within the RC (Assumption 2). Thus, no radioactive material should be present in the rest of the submarine (aft and forward sections).

The SN-BR hull cut should be performed at the CNI shipyard Main Hall facilities. To do so, the defueled submarine is moved from the dry docks to the Shiplift, where the SN-BR is raised from the sea to the submarine maintenance area (MAIA and ALVIM, 2019).

Before the SN-BR hull cut, all internal structures connected to the rest of the submarine or crossing the reactor compartment (piping and cables) are set loose. All primary circuit equipment and piping inside the RC are open to allow the drainage of all the fluids inside them, and its decontamination.

The SN-BR will be cut when the RC is decontaminated and the hull is the only connection to the RC and to the submarine fore and aft sections. The removal of the RC removes all the remaining radioactivity in the submarine (USN, 2019).

After the RC is separated from the rest of the hull, two actions should be taken to improve safety: 1 – containment bulkheads are welded to both ends of the RC; and 2 - the RC is placed inside a metallic container (RC encapsulation).

The main advantages of SN-BR hull cut at the CNI Main Hall facilities are (MAIA and ALVIM, 2019): 1 - Cost-effectiveness, no additional facilities construction is required; 2 - Easier transportation, the cut hull sections are on the ground (maintenance deck level) and their transportation to the dismantling installations is simpler; and 3 - Dry dock free, CNI dry docks are not required and may be used to support other NS.

The reactor compartment encapsulation aims to enforce its radiologic safety. The proposed encapsulation process consists of: 1 – Construction of a resistant metallic container capable of housing the removed RC; 2 – Application of a resin protective layer on the RC; and 3 – Injection of expansive resin inside the primary circuit piping to ensure that no leak will take place in the event of a pipe break.

The reported external radiation levels on the surface of the reactor compartment container are: usually below 10 μSv/h in USN submarines (USN, 2019); below 12 μSv/h in number 625 "Victor II" RFN NS (ENVIROS, 2004); and about 5 μSv/h on the HMS DREADNOUGHT (HØIBRÅTEN et al., 2007). According to Enviros[34] the highest reported dose inside the reactor compartment of the number 625 "Victor II" Class RFN NS is 40 μSv/h[35].

A Russian worker spending 500 hours, three working months (estimated dismantling period is about three months) in such a dose rate could receive 6 mSv, 30% of the occupational dose limit of 20 mSv (ENVIROS, 2004). A more typical, but still conservative, 'average' dose rate around the main cutting points would be around 0.1–0.2 μSv/h (ENVIROS, 2004). This corresponds to only about 0.05 to 0.1 mSv in the three working months assumed for dismantling.

The informed workers' occupational exposure at Puget Sound dry docks is 130 mSv (RAGHEB, 2010). The expected workers' occupational exposure at CNI is thought to be lower than 130 mSv[36].

3.4 ANALYTIC HIERARCHY PROCESS (AHP)

3.4.1 Decision Making Methodologies

How to make the optimal decision in a given situation is probably one of the oldest intellectual challenges in science and engineering. Ancient civilizations tried to solve complex and risky decision problems by seeking advice from knowledgeable individuals, oracles, priests, etc. More recently, old methods have been replaced by methodological approaches with increasing science and technology support (TRIANTAPHYLLOU, 2000).

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[34] Enviros Consulting Ltd, contracted by Norwegian Ministry of Foreign Affairs (NMFA) for the decommissioning of two "Victor II" Class nuclear-powered submarines from the Russian Federation's Northern Fleet, identified as numbers 625 and 627. The two submarines are being dismantled, respectively, by the Nerpa ship repair plant north of Murmansk on the Kola Peninsula, and by the Zvezdochka ship repair plant at Severodvinsk, near Archangelsky.

[35] This is a single point in the hull of the number 625 RFN "Victor II" Class nuclear-powered submarine (highly localised maximum dose) not representative of the average dose (ENVIROS, 2004).

[36] This assumption is based on: 1 - the fact that induced activity depends on the power level, on the design and on the operational history of the reactor (various data agree reasonably well); and 2 - SN-BR has lower fuel enrichment and lower reactor power, when compared to the USN Los Angeles class NS.

A decision making methodology is a set of systematic procedures for analyzing complex decision problems, including dividing decision problems into smaller and more understandable parts, analyzing each part, and integrating the parts logically to produce a solution (RAMOS, 2000).

The methodological approaches for decision making evolved from the quest for the optimal decision (solution) by the optimization of a single criterion (Single Criteria Decision Making - SCDM) to much more complex and risky decisions that consider multiple criteria (Multi-criteria Decision Making - MCDM). MCDM frequently involves conflicting objectives (OLSON, 1995).

3.4.2 Multi-criteria Decision Making Methodologies

Multi-criteria decision making (MCDM) is one of the most well-known branches of decision making. MCDM is divided into multi-objective decision making (MODM) and multi-attribute decision making (MADM) (ZIMMERMANN, 1996).

MCDM methods may also be classified according to the number of decision makers involved in the decision process (single or group decision maker) and to the type of used data (deterministic, stochastic, or fuzzy).

MODM studies decision problems in which the decision space is continuous. On the other hand, MADM concentrates on problems with discrete decision spaces. In these problems the set of decision alternatives has been predetermined.

There is a large number of MCDM methods in use today. Among them, the most popular ones are: the weighted sum model (WSM) (FISHBURN, 1967), the weighted product model (WPM) (MILLER and STARR, 1969), the analytic hierarchy process (AHP) with some of its variants (SAATY, 1977 and 1980), the ELECTRE[37] (BENAYOUN, et al., 1966) and the TOPSIS[38] (HWANG and YOON, 1981).

The common challenge derived from this large number of available MCDM techniques and approaches is the optimal methodology definition. So far, there seems to be no universal methodology to be applied to all decision aiding processes (AL

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[37] **ELECTRE** - Elimination and Choice Translating Reality (*Elimination et Choix Traduisant la Realité*).
[38] **TOPSIS** - Technique for Order Preference by Similarity to Ideal Solution, was developed by Hwang and Yoon (1981) as an alternative to the ELECTRE method and can be considered as one of its most widely accepted variants. The basic concept of this method is that the selected alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution in some geometrical sense (TRIANTAPHYLLOU, 2000).

KHALIL, 2002; GAL et al., 1999; VAIDYA and KUMAR, 2006). Thus, the methodology definition is up to the decision-maker.

In 2015, Mardani approached the problem of the optimal methodology definition by a quantitative perspective[39]. His quantitative approach showed that the AHP is the mostly used decision-aid methodology, as it was used in nearly 33% of the 393 MCDM articles reviewed from 2000 to 2014 (MARDANI et al., 2015), as presented in Table 13.

Table 13 – Summary of applications of the decision-making techniques.

Decision Making techniques	Frequency of application	Percentage
AHP	128	32.57
ELECTRE	34	8.65
DEMATEL	7	1.78
PROMETHEE	26	6.62
TOPSIS	45	11.4
ANP	29	7.38
Aggregation DM methods	46	11.70
Hybrid MCDM	64	16.28
VIKOR	14	3.56
Total	393	100.00

(MARDANI et al., 2015)

MCDM-MADM is a process of selecting a single alternative from a set of alternatives in a systematic and logical way (TRIANTAPHYLLOU, 2000). In MADM methods, alternatives represent the different choices of action available to the decision maker. Attributes represent the different dimensions from which the alternatives can be viewed. Attributes are also referred to as "goals" or “decision criteria".

The basic step by step process involved in decision making is called a decision making process.

The MCDM-MADM main steps are:

1. Define the decision problem (objective);
2. Define the criteria;
3. Identify alternatives;
4. Allocate importance weights to each criterion;

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[39] Mardani’s findings were based on an extensive review of the literature regarding the decision-aid techniques. He reviewed 393 MCDM articles published from 2000 to 2014 and grouped them by the adopted decision making technique. The following techniques have been considered: AHP, ELECTRE, DEMATEL, PROMETHEE, TOPSIS, ANP, Aggregation DM methods, Hybrid MCDM and VIKOR

5. Score the criteria for each of the alternatives;
6. Apply the decision rules;
7. Evaluate alternatives against criteria; and
8. Identify the best alternative.

According to Ramos, there is no consensual method to define the relative importance of the criteria (criteria weight) (RAMOS, 2000), but several proposed weights definition procedures can be found in the literature (von WINTERFELTDT and EDWARDS, 1986).

Criteria weights definition methods can be grouped into four categories: criteria ordering based methods (STILLWELL et al., 1981), point scales based methods (OSGOOD et al., 1957), point distribution based methods (EASTON, 1973) and pairwise comparison methods.

Fechner (1860) introduced the pairwise comparison method and Thurstone (1927) developed it. Saaty (1977) proposed the AHP, which is based on the pairwise comparison.

3.4.3 Analytic Hierarchy Process (AHP) Methodology

Analytic Hierarchy Process (AHP) was developed in 1970 by Thomas L. Saaty, an American mathematician at the University of Pittsburgh. The AHP is a technique for converting subjective assessments of relative importance into a set of weights through pairwise comparisons and relies on the judgments of experts to derive priority scales (SAATY, 1977) (OLSON, 1995).

The AHP decomposes a complex MCDM problem into a system of hierarchies. The final step in the AHP deals with the structure of an m x n matrix (where m is the number of alternatives and n is the number of criteria). The matrix is constructed by using the relative importance of the alternatives in terms of each criterion (SAATY, 1977 and 1980). AHP derives the criteria weights from the subjective assessments of relative importance through pairwise comparisons. Both qualitative and quantitative factors may be used to derive the relative weights (SAATY, 1980; OLSON, 1995; ISHIZAKA and LABIB, 2011).

Over the last decade, the AHP has emerged as one of the most important decision support method due to its wide use in several areas of knowledge (ASADABADI et al

2019; DARKO et al 2019; EMROUZNEJAD and MARRA, 2017; JURENKA et al, 2019; MARDANI et al., 2015).

The first step in any MCDM problem, including the AHP, is to define the set of alternatives and the set of decision criteria that the alternatives need to be evaluated with (TRIANTAPHYLLOU, 2000). The definition of the set of criteria (exclusion and decision criteria) is presented in section 4.2.2.

Defined the set of alternatives and decision criteria, the next step is the determination of the relative importance of each alternative in terms of each criterion. It is necessary to evaluate individual alternatives, deriving weights for the criteria, constructing the overall rating of the alternatives to identify the best one. AHP adopts pairwise comparisons to do so (SAATY, 1977 and 1980).

3.4.3.1 Pairwise Comparisons

In the pairwise comparison method, criteria and alternatives (candidate sites) are presented in pairs to one or more referees (e.g. experts or decision makers).

The pairwise comparisons may use both qualitative and quantitative values. Qualitative pairwise comparisons can be obtained from subjective opinion such as preferences. Quantitative pairwise comparisons can be obtained from actual measurements such as price, weight, etc.

Qualitative pairwise comparisons are quantified by using a scale of discrete linguistic choices (Saaty scale) (SAATY, 1980). Quantitative pairwise comparisons are quantified by using an adequately constructed scale that encompasses the whole range of numeric values.

These two types of scales (Qualitative and Quantitative scales) are nothing but an one-to-one mapping between: 1 - the set of discrete linguistic choices available to the decision maker; and 2 - a discrete set of numbers which represent the importance, or weight, of the previous linguistic choices (TRIANTAPHYLLOU, 2000). Table 14 presents the Saaty scale that is defined on the interval 9 to 1/9 and is adopted for pairwise comparisons in this thesis.

The results of the pairwise comparisons (relative importance of each alternative in terms of each criterion) are assembled in reciprocal matrices called judgment matrices (SAATY, 1980), presented in section 3.4.3.2. After the judgment matrices assembling, it becomes an eigenvector problem (TRIANTAPHYLLOU, 2000).

Table 14 – Saaty’s scale for pairwise comparisons

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one activity over another.
5	Strong importance	Experience and judgment strongly favor one activity over another.
7	Very strong importance	Experience and judgment highly favor one activity over another, demonstrating great dominance in practice.
9	Extreme importance	Experience and judgment favor one activity over another on the utmost possible degree.
2, 4, 6, 8	Intermediate values between two adjacent judgments	When compromise is needed.
Reciprocals of above non-zero numbers		If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.

Adapted from Saaty (1980)

Odd values are traditionally adopted for use in pairwise comparisons (TRIANTAPHYLLOU, 2000). In this thesis, even values (intermediate values) will be adopted when there is more than one evaluator and there is no consensus between them.

In complex MCDM problems the effort required to collect pairwise comparisons becomes impracticable when the number of alternatives or criteria is large (TRIANTAPHYLLOU, 2000)[40]. Note that the number of judgment matrices required to assemble the pairwise comparisons is equal to the number of criteria and the matrices size (order n) is equal to the number of alternatives.

A procedure based on the transitivity of the AHP verbal scale (Saaty scale) may be used to reduce this effort and/or to bring logical consistency to incomplete evaluations (GAVIÃO, LIMA and GARCIA, 2021).

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[40] For instance, If the number of alternatives or criteria (n) is 100, the number of pairwise comparisons (N) the decision maker would have to make is 4.950, as $N = (n^2 - n)/2$.

3.4.3.2 Judgment Matrix

Judgment matrices, also known as Real Continuous Pairwise matrices (RCP), were introduced by Saaty (1980) as a tool for extracting qualitative information from a decision maker. They proved to be of easy applicability in real world MCDM problems, receiving wide acceptance (CHU, et al., 1979; HIHN and JOHNSON, 1988; LOOTSMA, et al., 1990; TRIANTAPHYLLOU, 2000).

The judgment matrix $A = \left[a_{ij}\right]$ represents the value of the pairwise comparison (judgment) of the i-th alternative (or criterion) with the j-th entity. The entry a_{ij} represents the intensity of the experts (or decision makers) preference between individual pairs of alternatives (relative importance of element A_i when it is compared with element A_j, for all i , j = 1, 2, … ,n). Alternatives are denoted by $\{A_1, A_2, \cdots, A_n\}$ and n is the number of compared alternatives. As judgment matrices are reciprocal matrices, $a_{ii} = 1$ and $a_{ij} = {}^{1}\!/_{a_{ji}}$.

$$A = \left(a_{ij}\right) = \begin{vmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{vmatrix} \tag{1}$$

The judgment matrices required to assemble the pairwise comparisons in a MCDM-MADM with three alternatives (matrices order of n = 3) is denoted by

$$\mathbf{A} = \begin{vmatrix} 1 & a_{12} & a_{13} \\ \dfrac{1}{a_{12}} & 1 & a_{23} \\ \dfrac{1}{a_{13}} & \dfrac{1}{a_{23}} & 1 \end{vmatrix} \tag{2}$$

3.4.3.3 Calculation of the relative weights of importance

After the assembling of the judgment matrices, one has to determine the relative weights of importance of a collection of alternatives to be studied in terms of a single decision criterion.

In the judgment matrices the entry a_{ij} also represents the ratios ${}^{w_i}\!/_{w_j}$ where W is the vector of current weights $\{w_1, w_2, \cdots, w_n\}$ of the alternative (which is our goal). As judgment matrices are reciprocal matrices, $a_{ii} = {}^{w_i}\!/_{w_i} = 1$ and $a_{ij} = {}^{1}\!/_{a_{ji}}$.

The matrix of the ratios of all weights is denoted by

$$W = \left({}^{w_i}/_{w_j} \right) = \begin{vmatrix} 1 & {}^{w_1}/_{w_2} \cdots & {}^{w_1}/_{w_n} \\ {}^{w_2}/_{w_1} & 1 \quad \cdots & {}^{w_2}/_{w_n} \\ \vdots & \vdots \quad \cdots & \vdots \\ {}^{w_n}/_{w_1} & {}^{w_n}/_{w_2} \cdots & 1 \end{vmatrix} \tag{3}$$

There is no correct way to determine the relative weights of importance of the pairwise comparisons and each one of them implies some estimation error that arises from human inconsistency in judgment (OLSON, 1995). The assessment of the inconsistency in judgment is presented in section 3.4.3.4.

The relative weights of importance (scale of importance) can be obtained by different approaches, among which are: 1 - normalizing columns, which is probably the simplest method, but relatively unstable; 2 - obtaining the geometric mean, which presents some theoretical advantages: 3 - obtaining the principal eigenvectors (eigenvector method proposed by Saaty in 1980), which provides a robust estimator and an assessment of the overall consistency; and 4 – use of the logarithmic regression method proposed by Lootsma (1988, 1991). This thesis adopts the eigenvector methodology to derive the relative weights of importance from paired comparisons and their consistency ratio.

The eigenvector method, applied in AHP, derives ratio scales from principal eigenvectors (SAATY, 1980). The principal eigenvector is a representation of the priorities derived from a positive reciprocal pairwise comparison judgment matrix $A = [a_{ij}]$ when A is a small perturbation of a consistent matrix and W is the vector of current weights $\{w_1, w_2, \cdots, w_n\}$ of the alternative (which is our goal) (SAATY, 2002).

The principal eigenvalue is obtained from the summation of products between each element of the eigenvector and the sum of columns of the reciprocal matrix W (SAATY, 1980).

The calculation of the eigenvector (w_i) is presented in Equation (4),

$$w_i = \left(\prod_{j=1}^{n} w_{ij} \right)^{1/n} \tag{4}$$

The eigenvector normalization makes it possible to compare criteria and alternatives. The normalized principal eigenvector is also called priority vector. The priority vector is the eigenvector of the matrix W (Eq. (3)). Since it is normalized, the sum of all elements in the priority vector is 1. The priority vector shows relative weights among the things we compare.

The eigenvector normalization is presented in Equation (5),

$$\text{Ʈ}= \left|\frac{w_1}{\sum w_i} : \frac{w_2}{\sum w_i} : \frac{w_3}{\sum w_i}\right| \tag{5}$$

Saaty proposed to estimate the value of the maximum eigenvalue of the matrix $\lambda_{\max}$ by adding the columns of matrix A and then multiplying the resulting vector with the vector W, as shown in equation (6),

$$\lambda_{\max} = \text{Ʈ x w} \tag{6}$$

3.4.3.4 Consistency measure

AHP allows some small inconsistency in judgment because humans are not always consistent. The ratio scales are derived from principal eigenvectors and the consistence ratio is derived from the principal eigenvectors.

Aside from relative weights, we can check the consistency of the judge’s answer. To do that, we need the principal eigenvalue. According to Saaty, in a consistent reciprocal matrix, the largest eigenvalue is equal to the size of the comparison, or $\lambda_{\max} = n$. It gives a measure of consistency (called Consistency Index - CI) as a deviation or degree of consistency.

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{(n-1)} \tag{7}$$

The consistency ratio (CR) allows to evaluate the inconsistency due to the order (n) of the judgment matrix. CR is obtained by dividing the Consistency Index (CI) by the Random Consistency Index (RI). If the CR is 10% or less, the inconsistency is acceptable. Otherwise, review the model and or judgments (SAATY, 1977 and 1980).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{8}$$

The RI is an average random consistency index derived from a sample of size 500 of randomly generated reciprocal matrices with entries from the set (9, 8, 7, ... , 2, 1, 1/2, ... , 1/7, 1/8, 1/9) (SAATY, 1977 and 1980). Table 15 presents the RI Values of Sets of Different Order n.

Table 15 - Random consistency index (RI)

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

An overview of the AHP process and its equations is presented in Table 16.

Table 16 - AHP process and its equations

Step		Equation	Notes
1	Eq. 1	$A = \begin{vmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{vmatrix}$	**Judgment matrices assembly.** AHP derives the relative performance of the alternatives or the criteria from paired comparisons. Each entry at the judgment matrices (reciprocal matrices) expresses the experts (or decision makers) preference between individual pairs of alternatives (SAATY, 1980; GOMES, ARAYA and CARIGNANO, 2004)
2	Eq. 4	$w_i = \left(\prod_{j=1}^{n} w_{ij}\right)^{1/n}$	**Calculation of the eigenvector (w_i).** It consists of ordering the priorities or hierarchies of the studied characteristics.
3	Eq. 5	$\text{Ʈ}= \left\lvert \frac{w_1}{\sum w_i} : \frac{w_2}{\sum w_i} : \frac{w_3}{\sum w_i} \right\rvert$	**Eigenvector normalization** Eigenvector normalization makes it possible to compare criteria and alternatives. These values are estimates of the relative magnitudes (or weights) of the importance of the entities which are compared in terms of a common characteristic they all share.
4	Eq. 6	$\lambda_{\max} = \text{Ʈ} \text{ x w}$	**Maximum eigenvalue of the matrix $\lambda_{\max}$** Index that lists the criteria of the consistency matrix and the weights of the criteria $\lambda_{\max}$ is the maximum eigenvalue of the matrix with the pairwise comparisons
5	Eq. 7	$\text{CI} = \frac{\lambda_{\max} - n}{(\text{n} - 1)}$	**Consistency index (CI)** Expresses the inconsistency of a pairwise comparison matrix.
6	Eq. 8	$\text{CR} = \frac{\text{CI}}{\text{RI}}$	**Consistency ratio (CR)** It allows to evaluate the inconsistency due to the order of the judgment matrix. If the value is greater than 0.1, review the model and or judgments.

CHAPTER 4 - METHODOLOGY

The evaluation (ranking) of the candidate sites is a multicriteria decision-making problem (MCDM). This thesis proposes a site selection process based on the AHP methodology that comprises the activities (stages) presented in Table 17 and Figure 9.

The use of the AHP methodology to support the multicriteria decision-making on site selection was adopted because: 1 – AHP is a versatile and wide accepted MCDM methodology (ASADABADI et al 2019; DARKO et al 2019; EMROUZNEJAD and MARRA, 2017; JURENKA et al, 2019; MARDANI et al., 2015); 2 - AHP may use both qualitative and quantitative factors to derive the relative weights (SAATY, 1980; TRIANTAPHYLLOU, 2000); and 3 – AHP accepts small inconsistencies in the experts' evaluations and provides a tool to assess them (SAATY, 1980; TRIANTAPHYLLOU, 2000; ASADABADI et al, 2019).

Table 17 - Proposed site selection process

Stage		Description
1	Survey stage	Composed of four steps of successive technical analyses of increasing complexity that move the siting process from the regional level to the local level. At the end of this stage the whole set of available sites is identified and listed.
2	Screening stage	Consists of the discard of the unacceptable sites as a result of the exclusion criteria application to the available sites. It comprises the research (data collection) and definition of the whole set of criteria (decision and exclusion criteria). At the end of this stage the list of candidate sites is available.
3	Evaluation stage	Consists of the evaluation (ranking) of the candidate sites and the type of storage facility definition. It comprises the following activities: 1 – criteria and sub-criteria importance weights definition; 2 – consistency of the evaluations assessment; 3 - alternatives scoring; and 4 – importance weights application.
4	Site selection stage	Consists of the definition of the best site and type of storage facility to be built. These definitions are presented in a ranked list, from the best alternative (highest score) to the worst.

This site selection process was used in a case study presented in Chapter 5 (MAIA et al., 2022). Its objective is to identify the best site for the construction of the reactor compartment near-surface storage facility in Brazil.

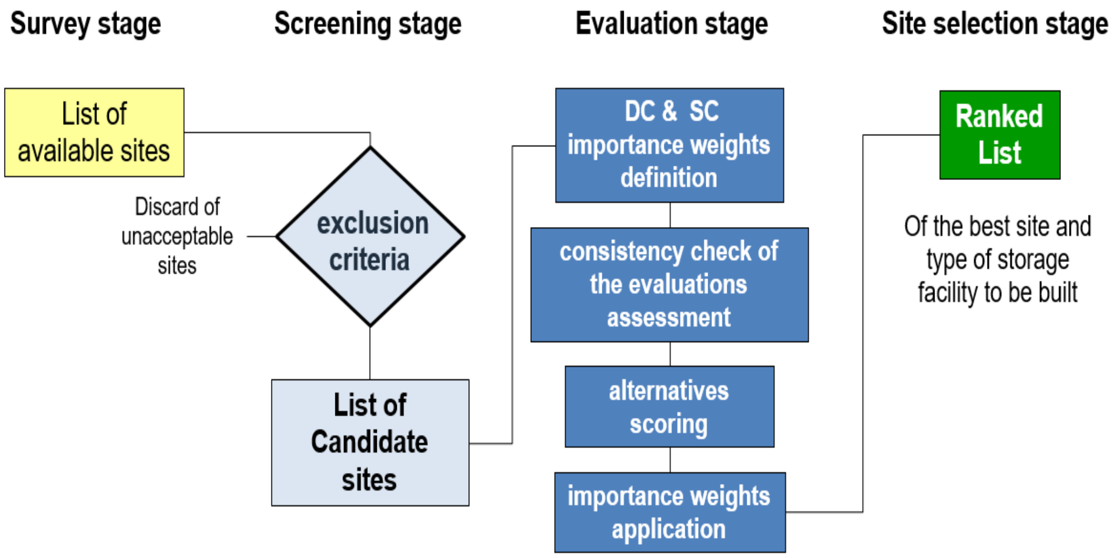

Figure 9 - Proposed four stages site selection process

4.1 SURVEY STAGE

In the site survey stage, large regions are investigated in four steps of successive technical analyses to find potential sites. The list of sites identified at the end of the local level siting process has to be submitted to the exclusion criteria at the screening stage.

4.2 SCREENING STAGE

As previously mentioned, the site screening stage consists of the application of the exclusion criteria to discard of the unacceptable sites. The whole set of criteria (decision and exclusion criteria) is defined in this stage.

In this proposed site selection process, the definition of the whole set of criteria is based on the research (data collection) carried out during the screening stage. It took into account: 1 – relevant Brazilian laws, regulations and standards[41], as recommended by Malczewski (1999); 2 - factors influencing decision-making on this site selection process, presented in section 4.5; 3 – naval and shipyard specificities; and 4 – logistics constraints imposed by the WP transportation.

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[41] Malczewski (1999) proposed the definition of the decision criteria (criteria and sub-criteria) based on the examination of the relevant literature, mostly agencies and government documents. Among them are: Law 10.308/2001; CNEN regulations (CNEN-NN-3.01, CNEN-NE-5.01, CNEN-NN-8.01, CNEN-NN-8.02); ANSNQ-112; and ABNT-NBR-10.004.

4.2.1 Exclusion Criteria Definition

Several exclusion criteria (EC) may be established based on siting regulations presented in section 2.5.1 and on the technical analyses previously performed.

In this case study, two exclusion criteria have been defined to discard sites that cannot be used due to legal or logistics constraints. The exclusion criteria are presented in Table 18.

The unacceptable are discarded at the end of the local level siting process (survey stage), before the candidate site list becomes available. The exclusion criteria EC2 - Logistics Constraints proved to be more restrictive, as it was responsible for discarding most of the unacceptable sites.

If the number of remaining sites (candidate sites) is large, sites with similar characteristics may be grouped in blocks, thus reducing the total number of sites to be evaluated.

Table 18 – Exclusion Criteria

Exclusion Criteria		Description
EC1	Location Restriction	Discard areas designated by law for environmental protection, natural reserves, archaeological sites, national historic and artistic heritage preservation (IPHAN)[42], lands occupied by native people and Contaminant Deposition Unities (Geobags) (CNEN-NE-6.06, 1989).
EC2	Logistic Restriction	Discard areas that are inaccessible to the RC transporter due to the dimensions and weight of the RC (waste package).

Captions: EC - Exclusion Criterion

If the number of remaining sites (candidate sites) is large, sites with similar characteristics may be grouped in blocks, thus reducing the total number of sites to be evaluated.

As previously mentioned, the RC and its metallic container are watertight structures. This thesis considers that this characteristic mitigates the risk of radionuclides water transportation. Thus, the presence of surface water is not considered an exclusion criterion (Hydrologic Restriction), but a constraint to be overcome.

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[42] IPHAN - Institute of National Historic and Artistic Heritage (Instituto do Patrimônio Histórico e Artístico Nacional).

4.2.2 Criteria and Sub-criteria Definition

Decision criteria (criteria and sub-criteria) represent the different dimensions from which the alternatives (candidate sites) should be viewed by the referees. They are used to evaluate candidate sites and to define the most adequate one for the construction of the RC NSSF. Decision criteria are also referred to as "goals" or “attributes" (TRIANTAPHYLLOU, 2000).

Four decision criteria (DC) and seven sub-criteria (SC) have been defined to evaluate the candidate sites. The list of candidate sites achieved at the end of the screening stage represents the alternatives and is the starting point to the evaluation stage.

4.2.2.1 Decision Criteria Definition

The definition of the four decision criteria (DC) presented in Table 19 is based on the research (data collection) carried out during the screening stage. These DC are consistent with the ones adopted in the following site selection studies in Brazil.

Table 19 – Decision Criteria

Decision Criterion		Description
DC1	Long Term Safety	It considers the overall impact in the facility long term safety arising from the site geology (SC1), hydrogeology (SC2), and the industrialization of the facility (SC7)
DC2	Socio-Economic and Environ-mental Feasibility	It considers the overall socio-economic and environmental impact arising from the site geology (SC1), hydrogeology (SC2), land use and cove-rage (SC3), Demography (SC4) and economic aspects (SC5).
DC3	Technical Viability	It considers the overall technical complexity of the design, construction and safe operation of the facility throughout its life-cycle. It encompasses the impact arising from site geology (SC1), hydrogeology (SC2), WP transportation (SC6) and industrialization of the facility (SC7).
DC4	Cost Effectiveness	It considers the overall cost impact arising from the site geology (SC1), hydrogeology (SC2), land use and coverage (SC3), WP transportation (SC6) and the industrialization of the facility (SC7).

Captions: DC - decision criteria SC - sub-criteria

Martins site selection study for SNF disposal in geological repositories in Brazil proposed the following criteria: 1 - Long Term Safety; 2 - Socio-Economic and Environmental Feasibility; and 3 - Technical Feasibility (MARTINS, 2009).

Raduan site selection study for LILW final disposal in surface repositories in Brazil proposed the use of the following classes of criteria: 1 - Safety Criteria; 2 - Feasibility Criteria; 3 - Technical Criteria; and 4 - Financial Criteria (RADUAN; 1994).

For each of the decision criteria, a set of sub-criteria has been defined. The sub-criteria are the attributes that have the ability to measure (indicate) the suitability of the candidate sites (alternatives) in relation to the decision criteria under analysis. The relationship between the criteria and sub-criteria is presented in Table 21.

4.2.2.2 Sub-Criteria Definition

The seven sub-criteria (attributes) have been established considering: 1 - the four CNEN fundamental factors for site selection (Table 10); 2 – the reactor compartment WP characteristics (Table 12); and 3 - The adequacy of the facility types (trenches, engineered structures and tunnels) to the specificities of the candidate site. Table 20 presents the seven sub-criteria and their attributes.

Table 20 – Sub-Criteria

Sub-Criterion		Attributes
SC1	Geology	• Reliefs and terrain forms (plains or hills); • Soils nature (rocky, gley, planosols or cambisols); • Soil permeability; and • Rocks (sedimentary, metamorphic or fiery).
SC2	Hydro-geology	• Distance to surface water (rivers, mangroves and sea); • Distance to ground and surface water; • Water Quality (fresh, brackish or salty); • Rainfall and the risk of flooding; and • RW water transportation risk.
SC3	Land use and coverage	• Land use (industrial, commercial, agro-pastoral or not currently in use); • Land ownership (private, municipality, state and federal government); • Coverage type (forests, wetlands, grass and impervious surfaces); and • Landslide risk.
SC4	Demography	• Local population density and its growth projection; and • Distance to local community.
SC5	Socio-economic impact	• Distance to local community, surface and ground water; • Economic contribution to local, state and federal economy; • Local work positions creation; • Land scape impact; and • Land expropriation impact.

SC6	WP Transportation	• Type of WP transportation required (land and/or sea); • WP transportation distance; and • WP transportation cost.
SC7	Industrialization of the Facility	• Facility design and construction technical complexity (considering the need of additional containment barriers, groundwater insulation, and additional security); • Required additional site infrastructure (considering the need of site elevation to 5.6 m, additional drainage systems, slope contention and reforestation; and • Facility ownership cost (considering the construction, operation, decommissioning and additional infrastructure costs).

Local features and attributes that are equally effective to all sites (Non-differential) have been disregarded as they do not differentiate one site from another.

In this thesis, the following features and attributes have been considered non-differential and disregarded: seismological aspects, geological aspects (structural and tectonic features, fractures and cracks), meteorological and climatological aspects, natural occurring events (earthquakes, torrential rain, strong winds and tornadoes, and movements of the sea such as waves and tsunamis), nuclear licensing, naval and nuclear engineering design demands to the RC and its metallic container. Public opinion has also been disregarded as no pool was performed in support of this thesis.

Table 21 – Criteria and Sub-Criteria Relationship

Sub-criterion		DC1	DC2	DC3	DC4
SC1	Geology	X	X	X	X
SC2	Hydrogeology	X	X	X	X
SC3	Land use and coverage		X		X
SC4	Demography		X		
SC5	Socio-economic impact		X		
SC6	Waste package transportation			X	X
SC7	Industrialization of the Facility	X		X	X

Captions:
DC – Decision Criterion
DC1- Long-Term Safety criterion
DC2 - Socio-Economic and Environmental Feasibility criterion
DC3 - Technical Viability criterion
DC4 – Cost-Effectiveness criterion
SC – Sub-criterion

4.3 EVALUATION STAGE

As previously mentioned, the evaluation stage consists of the candidate sites evaluation (ranking). It comprises the criteria importance weights definition, the assessment of the evaluations consistency, the score of the alternatives and the importance weights application. The evaluation of the best type of storage facility to be built in each candidate site is also performed in this stage.

4.3.1 Relative Importance Weights Definition

The relative importance of the criteria and sub-criteria is determined by the experts' judgments throughout pairwise comparisons. In the pairwise comparison, criteria and alternatives are presented in pairs to the experts and the results of the comparisons are assembled in judgment matrices.

The judgment matrices are reciprocal matrices (Eq. (1)) which integrate the qualitative and quantitative aspects and are used to derive the relative weights of importance. After the judgment matrices assembling, it becomes an eigenvector problem as the principal eigenvector represents the relative weights (SAATY, 1980; TRIANTAPHYLLOU, 2000; ASADABADI et al, 2019). The eigenvector calculation is presented in section 3.4.3.3.

As soon as the criteria and sub-criteria relative weights are defined, they should be presented to the decision-maker and validated.

4.3.2 Consistency of the Evaluations

The experts' evaluations are not always consistent. Their judgment implies estimation and some judgment error may arise (human inconsistency in judgment) (OLSON, 1995). Thus these inconsistencies have to be assessed. If the inconsistencies are small, they can be accept by the AHP methodology. Otherwise, the judgments should be reviewed (SAATY, 1980; TRIANTAPHYLLOU, 2000; ASADABADI et al, 2019; DARKO et al 2019).

The consistency of the judgment matrix is assessed by the consistency ratio (CR). The CR is the ratio of the Consistency Index (CI) over the Random Consistency Index (RI), which is presented in Table 15. If the CR is 10% or less, the inconsistency is acceptable (SAATY, 1980). The determination of the evaluation’s consistency is presented in section 3.4.3.4.

4.3.3 Score of the Alternatives

After the definition of the criteria and sub-criteria relative importance weights, the alternatives have to be scored. To do so, the candidate sites features and characteristics are quantified in terms of each sub-criterion. It allows to measure (indicate) the suitability of the alternatives (candidate sites and the type of facility) in relation to the decision criteria under analysis.

4.4 SITE SELECTION STAGE

As previously mentioned, the site selection stage consists of the definition of the best candidate site and type of storage facility to be built. To do so, the set of scored alternatives arising from the evaluation stage have to be ranked and presented to the decision-maker in a ranked list, from the best alternative (highest score) to the worst one.

4.5 FACTORS INFLUENCING DECISION-MAKING ON THE SITE SELECTION PROCESS

4.5.1 Transportation Factors

These factors represent the logistics challenges and constraints resulting from the SN-BR and WP transportation. The total transport distance, the transport options (land or sea transportation) and the limitations (logistics constraints) imposed by the waste package weight and dimensions should be considered. These factors influence the Technical Viability criteria (DC3) and the Cost-Effectiveness criteria (DC4).

The SN-BR transportation from the dry dock to the Main Hall, for hull cutting and dismantling, can be carried out in the CNI using the available infrastructure. The challenge lies in the WP transportation.

The WP transportation comprises the following transport actions: 1 – from the CNI to the NSSF for interim storage; 2 – from the NSSF to the RC dismantling facility; and 3 – from the dismantling facility to RBMN for final deposition of the packages containing scraped activated materials (MAIA and ALVIM, 2019).

These transportations are complex activities, as the WP transporter is required to move on a previously existing road infrastructure not designed to support the WP loads and height. Sea transportation may also be required to overcome blocking points such as bridges and overpasses, or to allow longer distance transportations.

4.5.2 Cost and Expense Factors

Brazilian nuclear power plants are required to make provisions to cover their own decommissioning costs (CNEN-NN-9.02, 2016). To do so, part of the electrical revenues are segregated in a decommissioning fund.

NS have no revenues. Thus, no provisions are made and the Federal Government should bear with all decommissioning and storage costs (CNEN-NN-9.02, 2016). The required funding has to be requested to the Federal Government within two years in advance (Law 10.308, 2001). BN SN-BR estimate decommissioning cost is not available in open-sources.

The Federal Government should also bear with the RC NSSF life cycle cost. It has not been estimated yet as it depends on several aspects related to its siting, design, construction, operation (operational and pre-operational costs) and decommissioning.

The required funding should be requested within two years in advance by the operator (BN or ANSN) (Law 10.308, 2001) according to the NSSF siting.

Additionally, the depositor (BN) has to:

a) provide monthly financial compensation to the municipalities that house waste deposits (Law 10.308, 2001); and

b) provide waste storage service costs compensation to ANSN (storage and disposal fees) at the intermediate and the final deposit (Law 10.308, 2001).

The methodology for the compensation costs calculation is established by CNEN Technical Note nº 01/2003 (HEILBRON, 2003). The WP transportation costs (direct and indirect expenses included) from the CNI to the NSSF, for interim storage, and back, for the RC dismantling, should be covered by BN. The same transportation costs from the interim storage or dismantling facility to the final repository should be covered by ANSN (Law 10.308, 2001).These cost factors influence the Cost-Effectiveness criteria (DC4).

4.5.3 Timing Factors

The beginning of the SN-BR decommissioning process is set by the provision of the required funding. To get it, BN has to inform the Federal Government and ANSNQ of its intention to withdraw the SN-BR from active duty and decommission it. The funding has to be requested at least two years in advance.

As previously mentioned, the duration of the SN-BR decommissioning process (RC interim storage and dismantling excluded) is likely to take more than three years.

Its beginning date is reasonably foreseeable if no decommissioning anticipation is imposed by an accident. In this accidental scenario, the anticipation of the site selection process would be an advisable practice.

4.5.4 Siting Factors

The whole SN-BR decommissioning process is likely to take place in the CNI site. This approach does not require the construction of additional facilities (cost-effectiveness) and prevents disclosure of sensitive information during the RC and submarine dismantling.

As previously mentioned, the site for the WP NSSF construction has not been established yet. If it is located nearby the CNI, the RC dismantling process is likely to take place at the CNI site. Otherwise, the selection of an alternative RC dismantling facility should be considered.

The definition of the type of near-surface storage facility (trenches, concrete deck, warehouse and tunnels) depends directly on the site selected. This definition affects the facility design and construction costs. It may require additional engineered barriers to enhance the facility’s long-term safety. The definition of the type and siting of the facility influences the Cost-Effectiveness criteria (DC4).

4.5.5 Factors Related to the Design and Operation of the Storage Facility

The operations to be carried out in a storage facility are essentially passive and limited to the receipt, emplacement, integrity control[43], retrieval and preparation for waste packages dispatch (IAEA-TRS-390, 1998). To carry out these operations, provisions should be taken to ensure that the facility design criteria should take into

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[43] The integrity control consists of the inspection and the monitoring of the waste package (WP) storage during the storage phase. Its purpose is to avoid the WP deterioration and to ensure that contamination has not occurred (IAEA-TRS-390, 1998).

account: 1- requirements imposed by the facility type and siting (e.g. space required, floor loadings, waste type and natural occurring events); 2 - naval engineering requirements; and 3 – the need for additional containment barriers.

4.5.6 Naval Engineering Requirements

As previously mentioned, the Brazilian Navy adopts conservative design criteria for the SN-BR and shall do so in the design of the metallic container. The main naval engineering requirements refers to: 1 - structural reinforcement of the RC to ensure the waste package safety during storage and transportation; 2 - Containment bulkheads attachment at both ends of the removed RC to ensure the confinement of the existing radioisotopes; 3 - design of the RC metallic container to meet the demands of CNEN radioactive materials transport regulations (CNEN-NE-5.01, 2021); 4 – design of cradles for the WP transportation, storage and retrieval; and 5 - design of barge transportation devices for the WP shipment, load in and load out (offloading slip).

4.5.7 Additional Containment Barriers Considerations

Containment barriers are divided into two distinct groups that comprise natural barriers and artificial barriers (engineering barriers) (IAEA-SSG-29, 2014 and IAEA-SSR-5, 2011).

Natural barriers are the site characteristics that isolate radionuclides from the biosphere, such as the types of rocks (geology) and types of soil (pedology).

Engineering barriers are the deposit characteristic designed to provide or enhance isolation.

Additional Containment Barriers are engineering barriers added to the deposit design to improve safety (IAEA-SSG-29, 2014). These barriers mainly consist of the waste immobilization matrix, the container or packaging, the materials used to fill the gaps between the packages, and the deposit layout (floors and walls that provide additional containment) (IAEA-SSG-29, 2014).

The following additional containment barriers (engineering barriers) are considered for the RC interim storage facility: 1 - surface coverage with low permeability materials, to minimize water intrusion; 2 - water drainage systems; and 3 - sealing the deposit floors with low permeability materials. These barriers are commonly made of concrete, clay, bituminous materials, minerals and polymers (RADUAN; 1994).

The engineering barriers considered to be added to the different types of facilities (NSSF) are presented in Table 22. These engineering barriers influence the Cost-Effectiveness criteria (DC4).

Table 22 – Types of Engineering Barriers to be added to the RC NSSF

Facility Type	Low Permeability Surface Coverage	Water Drainage Systems	Floors Sealing	Additional Floors and Walls
Trench	X	X	X	
Concrete deck		X	X	
Warehouse		X	X	
Tunnel		X	X	X

CHAPTER 5 - CASE STUDY

This case study objective is to identify the best site for the construction of the reactor compartment near-surface storage facility in Brazil. The site selection process adopted is based on the AHP methodology presented in chapter 4. The definition of the importance weights was derived from the combined evaluations of 18 experts selected to properly encompass the required knowledge and experience.

The site selection of an interim storage facility for the SN-BR reactor compartments is a “real problem” and, despite the academic approach of this case study, the results achieved represent a possible solution of a defense issue. To prevent the disclosure of the defense sites’ location, the survey stage is not presented, the screening stage is partially presented and the candidate sites are described but not identified.

This chapter is organized as follows: section 5.1 presents the experts profile; section 5.2 presents the list of candidate sites (screening stage); section 5.3 presents the criteria and sub-criteria importance weights definition; section 5.4 presents the candidate sites ranking (evaluation stage); section 5.5 presents the storage facility type definition (evaluation stage); section 5.6 presents the candidate sites and type of facility definition (site selection stage).

5.1 EXPERTS PROFILE

The experts are the referees who determine the relative importance of each alternative in terms of each criterion. Due to the lack of previous Brazilian experience on NS decommissioning and on RC interim storage facility design, there is no Brazilian expert on these subjects. Thus, the experts’ selection has been based on personal qualification, experience and knowledge on the evaluated criterion (expertise).

It is important to highlight that there are experts with experience in more than one area (nuclear, regulatory and managerial, for example). Experts’ names are not provided but their employer affiliations are[44]. The experts’ profiles are presented in Table 23.

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[44] Notes on affiliation: 1 – AMAZUL, Amazônia Azul Defense Technologies, is a government defense company focused on strategic programs; 2 – EMGEPRON, Naval Project Management Company, is a naval construction bureau focused on Brazilian Navy ships construction; and 3 - ELETRONUCLEAR, is the operator of the Brazilian NPP.

Table 23 - Experts' profiles

Area of Knowledge (Number of Experts)				
Nuclear Engineering	2	Automation & Control Engineering		1
Naval Engineering	2			
Mechanical Engineering	3	Environmental Engineering		1
Electronic Engineering	3	Economy		1
Civil Engineering	1	Physicist		2
Chemical Engineering	1	Biologist		1
Academic Qualification		Work Experience	Years	
PhD / D.Sc.	10	Nuclear Area	0 - 10	4
Master	7		10 - 20	5
Bachelor	1		20 +	2
Affiliation		Naval Area	0 - 10	1
BRAZILIAN NAVY	6		10 - 20	3
AMAZUL	2		20 +	3
EMGEPRON	4	Management Area	0 - 10	4
ELETRONUCLEAR	3		10 - 20	5
IAEA	1		20 +	3
CNEN	1	Regulatory Area	0 - 10	2
AgNSNQ	1		10 - 20	1
			Total Number of Experts	18

(MAIA et al., 2022)

5.2 LIST OF CANDIDATE SITES (SCREENING STAGE)

The list of candidate sites is the screening stage main output. This list presents the sites that have been submitted to the exclusion criteria and accepted.

In this case study, two Exclusion Criteria[45] have been applied to the sites selected during the Survey stage in order to discard the unacceptable ones. Most of the unacceptable sites have been discarded by Logistic Restriction (EC2) as they proved to be inaccessible to the WP. As a result, six candidate sites (CS1 to CS6) have been defined (MAIA et al., 2022). Table 24 presents the list of candidate sites and their main features.

Table 24 – List of Candidate Sites

Candidate Sites Features	
CS1	Federal Government owned site, on a hill side area with metamorphic rocky ground (granitoids), apart from local population, surface and ground water, covered with grass. No significant environmental impact is foreseen and slope containment is advisable. The WP access is through land transportation.

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[45] The two exclusion criteria are Location Restriction (EC1) and Logistic Restriction (EC2). In this thesis, the presence of surface water is not considered an exclusion criterion (Hydrologic Restriction) but a constraint to be overcome. It is considered that the presence of watertight structures (RC and its metallic container) mitigates the risk of radionuclides water transportation.

CS2	Federal Government owned site, on a plain area of gley soil, with the nearest population (village) within a distance of 2 km (1.2 mile). It is apart from surface and ground water and covered with grass. No significant environmental impact is foreseen. The WP access is through land transportation.
CS3	Municipality owned site, on a plain area of planosols soil with presence of ground water, within a distance of 2 km (1.2 mile) of mangroves and sea, but apart from local populations. It is covered with grass and the WP access is through land and sea transportation. No significant environmental impact is foreseen.
CS4	Municipality owned site, on a plain area of planosols soil apart from surface and ground water. It is covered with grass and the nearest population (district) is within a distance of 1.6 km (1 mile). No significant environmental impact is foreseen. The WP access is through land and sea transportation. CS4 and CS5 are sites alike and within a short distance from each other.
CS5	Federal Government owned site, on a plain area of planosols soil apart from surface and ground water. It is covered with grass and the nearest population (district) is within a distance of 2 km (1.2 mile). The WP access is through land and sea transportation. No significant environmental impact is foreseen.
CS6	Private owned site (industry), on a plain area of planosols soil within 800 m (0.5 mile) of nearest river. It is covered with grass and the nearest population (district) is within a distance of 2.5 km (1.6 mile). The WP access is through land and sea transportation. No significant environmental impact is foreseen.

(MAIA et al., 2022)

A comparation of the candidate sites' main features is presented in Table 25.

Table 25 - Candidate Sites Features

	CS1	CS2	CS3	CS4	CS5	CS6
Ownership	Federal Gov.	Federal Gov.	Municipality	Municipality	Federal Gov.	private
Geomorphology	hill side	plain area	plain area	plain area	plain area	plain area
Pedology	granitoids	gley	planosols	planosols	planosols	planosols
Vegetation	bushes	grass	grass	grass	grass	grass
Demography	away	2 km	2 km	1,6 km	2 km	2,5 km
Hydrogeology	away	away	1,6 km ground Water	away	away	800 m river
Transportation	land	land	land and sea	land and sea	land and sea	land and sea

5.3 CRITERIA AND SUB-CRITERIA IMPORTANCE WEIGHTS DEFINITION

As previously mentioned, the criteria and sub-criteria importance weights definition derive from the experts’ assessments through pairwise comparisons. The results of the pairwise comparisons are assembled in judgment matrices (Eq. (1)). The matrix normalized principal eigenvector (Ʈ) represents the relative importance weights (Eq. (5)) and the matrix maximum eigenvalue (λ_{max}) allows to assess the consistency of the judgment (Eq. (6)) (SAATY, 1980).

Before the weights definition, each judgment matrix consistency should be assessed. To do so, the consistency ratio (CR) has to be determined with Eqs. 7 and 8. If the CR is less than 10%, the inconsistency is acceptable. Otherwise, the judgment has to be revised (SAATY, 1980).

5.3.1 Decision Criteria Importance Weights Definition

The judgment matrix used to derive the decision criteria importance weights is presented in Figure 10 (MAIA et al., 2022). It also presents the importance weights defined by its normalized principal eigenvector (Ʈ) and its consistency ratio (CR).

$$\begin{array}{c|cccc|} & DC1 & DC2 & DC3 & DC4 \\ DC1 & 1 & 5 & 5 & 7 \\ DC2 & 1/5 & 1 & 3 & 3 \\ DC3 & 1/5 & 1/3 & 1 & 1 \\ DC4 & 1/7 & 1/3 & 1 & 1 \end{array} \qquad Ʈ = \begin{vmatrix} 0.62 \\ 0.21 \\ 0.09 \\ 0.08 \end{vmatrix} \qquad \begin{array}{rl} \lambda_{max} = & 4.225044092 \\ CI = & 0.075014697 \\ CR = & 0.083349664 \\ RI = & 0.9 \end{array}$$

Relative	DC1	DC2	DC3	DC4
Weights	62%	21%	9%	8%

(MAIA et al., 2022)

Captions:
DC1- Long-Term Safety criterion
DC2 - Socio-Economic and Environmental Feasibility criterion
DC3 - Technical Viability criterion
DC4 – Cost-Effectiveness criterion

Figure 10 Decision criteria relative importance weights

5.3.2 Sub-criteria Importance Weights Definition

The sub-criteria are the attributes used to qualify the decision criteria. According to the relationship between the decision criteria and the sub-criteria, different importance weights are derived. Figure 11 presents the relationship between criteria and sub-criteria. This relationship is represented by the connecting lines.

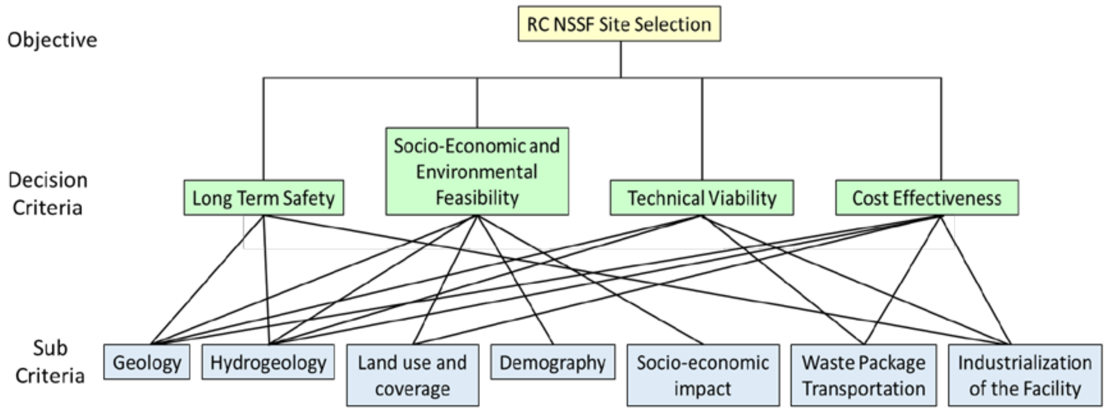

Figure 11 Criteria and sub-criteria relationship

The judgment matrices used to derive the sub-criteria importance weights to each decision criteria are not presented. Table 26 Table 24 presents sub-criteria importance weights.

Table 26 – Sub-criteria importance weights

		Criterion			
Sub-criterion		DC1	DC2	DC3	DC4
SC1	Geology	0.33	0.14	0.25	0.16
SC2	Hydrogeology	0.29	0.17	0.22	0.18
SC3	Land use and coverage		0.14		0.15
SC4	Demography		0.24		
SC5	Socio-economic impact		0.31		
SC6	Waste Package Transportation			0.26	0.22
SC7	Industrialization of the Facility	0.38		0.27	0.30
	CR =	0.0069	0.0047	0.0086	0.0076

(MAIA et al., 2022)

Captions:
DC – Decision Criterion
DC1- Long-Term Safety criterion
DC2 - Socio-Economic and Environmental Feasibility criterion
DC3 - Technical Viability criterion
DC4 – Cost-Effectiveness criterion

In this case study, the defined criteria and sub-criteria relative weights have not been presented to the decision-maker and validated because there is no such person due to its academic approach.

5.4 CANDIDATE SITES RANKING (EVALUATION STAGE)

The candidate sites ranking consists of the quantification and the application of the due importance weights. To do so, candidate sites' features are quantified in relation to the attributes presented in Table 20. The results achieved are presented in Table 27.

Table 27 - Candidate sites' features quantification

	CS1	CS2	CS3	CS4	CS5	CS6
SC1	0.24	0.20	0.12	0.15	0.15	0.15
SC2	0.37	0.23	0.03	0.16	0.16	0.04
SC3	0.15	0.15	0.16	0.18	0.21	0.15
SC4	0.44	0.33	0.07	0.07	0.04	0.04
SC5	0.27	0.26	0.09	0.12	0.16	0.09
SC6	0.44	0.41	0.06	0.03	0.05	0.01
SC7	0.10	0.24	0.11	0.18	0.18	0.18

(MAIA et al., 2022)

After the quantification, the results are first multiplied by the sub-criteria importance weights (presented in Table 26) and assembled in Matrix A. Then, the matrix is multiplied by the criteria importance weights (Ʈ) (presented in Figure 10) and ranked. The candidate sites ranking (importance assessment) is presented in Figure 12 (MAIA et al., 2022).

Matrix A

$$\text{Ʈ} = \begin{vmatrix} 0.49 \\ 0.24 \\ 0.18 \\ 0.09 \end{vmatrix} \qquad \begin{array}{c|cccccc|} & CS1 & CS2 & CS3 & CS4 & CS5 & CS6 \\ DC1 & 0.23 & 0.23 & 0.09 & 0.16 & 0.17 & 0.13 \\ DC2 & 0.31 & 0.25 & 0.09 & 0.13 & 0.12 & 0.11 \\ DC3 & 0.29 & 0.27 & 0.08 & 0.13 & 0.13 & 0.10 \\ DC4 & 0.25 & 0.26 & 0.09 & 0.14 & 0.15 & 0.11 \end{array}$$

$$CR = 0.0239$$

$$\begin{array}{c|cccccc|} & CS1 & CS2 & CS3 & CS4 & CS5 & CS6 \\ & 0.11 & 0.11 & 0.04 & 0.08 & 0.08 & 0.06 \\ \text{Weighted Evaluation} & 0.07 & 0.06 & 0.02 & 0.03 & 0.03 & 0.03 \\ & 0.05 & 0.05 & 0.01 & 0.02 & 0.02 & 0.02 \\ & 0.02 & 0.02 & 0.01 & 0.01 & 0.01 & 0.01 \end{array}$$

$$\begin{array}{ccccccc} \text{CS ranking (importance assessment)} & 0.26 & 0.24 & 0.09 & 0.15 & 0.15 & 0.12 \end{array}$$

Captions:

CR - Consistency Ratio
DC – Decision Criteria
CS – Candidate Site
Ʈ - Normalized Principal Eigenvector

Figure 12 – Candidate sites ranking

5.5 STORAGE FACILITY TYPE DEFINITION (EVALUATION STAGE)

The purpose of this section is to support the decision-making on the best type of facility to be built in the selected candidate site. The four considered types of near-surface storage facilities are Trench, Concrete deck, Warehouse and Tunnel, as presented in section 2.3.3.

As experts' evaluation equally valued the facility types (no preferences among them), they all have the same importance weight (one) and the facility type definition relays on the ranking of their attributes.

The following attributes have been used to quantify the features of each type of facility: Life Cycle Cost (design, construction, operation and decommissioning), additional safety requirements (e.g. engineered containment barriers, drainage systems and groundwater insulation), additional security requirements, slope contention, and reforestation.

The case study assessment on the best type of facility to be built in the candidate site is a warehouse like NSSF for CS2 to CS6 and a tunnel for CS1. Table 28 presents the quantification of the facilities' features for each candidate site. The highest score represents the best option per candidate site. The blank cells in Table 28 represent unacceptable facility types of a given candidate site.

Table 28 - Facilities' features quantification

Type of Facility	CS1	CS2	CS3	CS4	CS5	CS6
Trench		1.47	0.54	0.84	0.89	0.84
Concrete deck		1.47	0.68	1.05	1.10	1.05
Warehouse		1.69	0.79	1.21	1.27	1.21
Tunnel	0.72					

5.6 CANDIDATE SITES AND TYPE OF FACILITY DEFINITION (SITE SELECTION STAGE

The case study assessment is to select the candidate site one (CS1) (MAIA et al., 2022) and to construct a tunnel type NSSF in its hill side area. The remaining candidate sites ranking is (CS2, CS5, CS4, CS6 and CS3) (MAIA et al., 2022) and, to all of them, the construction of a warehouse-like NSSF is the most advisable option. Table 29 presents the candidate sites relative importance and its CR. This assessment is based on the results presented in Figure 12 and Table 28.

Table 29 – Assessment on candidate site selection for the construction of a reactor compartment interim storage facility in Brazil

Rank	1	2	3	4	5	6	CR
	CS1	CS2	CS5	CS4	CS6	CS3	0.0239
	0.26	0.24	0.15	0.15	0.12	0.09	

(MAIA et al., 2022)

CHAPTER 6 - RESULTS AND DISCUSSION

The case study assessment is to select the candidate site one (CS1) (MAIA et al., 2022) and to construct a tunnel type NSSF in its hill side area. The proposed site selection process has successfully ranked the six candidate sites (CS1, CS2, CS5, CS4, CS6 and CS3), from the best alternative (highest score) to the worst, and defined the most advisable type of interim storage facility to be built in each of the candidate sites, as presented in section 5.6.

The comparison of the AHP results (Figure 12) with sites' features (Table 24) suggests the consistency of the assessment and the effectiveness of the proposed site selection process. The highlights of this comparison are as follows:

1 – The ranked list of candidate sites presented in Table 29 reflects the higher relative importance weights given by the experts to aspects related to the long-term safety and the socio-economic and environment (62% and 21%, respectively);

2 - The CS1 highest score reflects its site attributes (granitoides rocks, apart from local population, surface and ground water) enforcing its long-term safety. It is expected to result in a facility with lower radioactive wastes contamination risk;

3 - In general, candidate sites CS1 and CS2 seem to be far better alternatives than the other CS, as their individual scores nearly double the ones of the third and fourth position (CS5 and CS4). The gap between CS1-CS2 and the other positions reflects the absence of ground water in the sites and the distance to population; and

4 - The candidate sites CS5 and CS4 have technically even scores. This is due to their similarity and proximity.

Additionally, each of the 18 experts' evaluations have been used to derive individual solutions (non-combined assessments) (MAIA et al., 2022), which are presented in Table 30.

Table 30 – Experts' individual assessments on candidate sites selection

Exp	CS1	CS2	CS3	CS4	CS5	CS6	CR
1	0.26	0.23	0.10	0.14	0.14	0.13	0.0526
2	0.25	0.21	0.10	0.15	0.15	0.13	0.0000
3	0.26	0.23	0.10	0.14	0.15	0.13	0.0917
4	0.29	0.25	0.08	0.14	0.14	0.11	0.0833
5	0.28	0.23	0.08	0.15	0.15	0.11	0.0618
6	0.28	0.23	0.08	0.15	0.15	0.11	0.0701
7	0.24	0.26	0.09	0.14	0.15	0.12	0.0162

8	0.29	0.23	0.08	0.15	0.15	0.11	0.0870
9	0.22	0.24	0.10	0.15	0.15	0.13	0.0591
10	0.28	0.23	0.08	0.15	0.15	0.11	0.0870
11	0.22	0.25	0.10	0.15	0.16	0.13	0.0654
12	0.26	0.24	0.08	0.15	0.15	0.11	0.0434
13	0.25	0.24	0.10	0.14	0.14	0.13	0.0185
14	0.28	0.25	0.09	0.14	0.14	0.12	0.0185
15	0.24	0.26	0.09	0.14	0.15	0.12	0.0000
16	0.26	0.24	0.09	0.15	0.15	0.12	0.0278
17	0.31	0.25	0.08	0.13	0.14	0.09	0.0244
18	0.27	0.23	0.09	0.15	0.15	0.12	0.0954

(MAIA et al., 2022)

Captions:
Exp – Expert Assessment Number CR - Consistency Ratio

The comparison of these individual assessments shows that they match the case study assessment in 14 of the assessments (78%). In the four other assessments CS2 is the highest score site (highlighted in blue). This comparison suggests the accuracy of the case study assessment and the experts' adequate understanding of the problem.

The expert # 13, from CNEN, is likely to be the most experienced expert in RW management. His assessment matches the case study assessment, enforcing the case study accuracy.

Figure 13 presents the range of variation and the standard deviation of the experts' individual assessments. The low standard deviation indicates that it approaches the case study assessment, thus enforcing its accuracy.

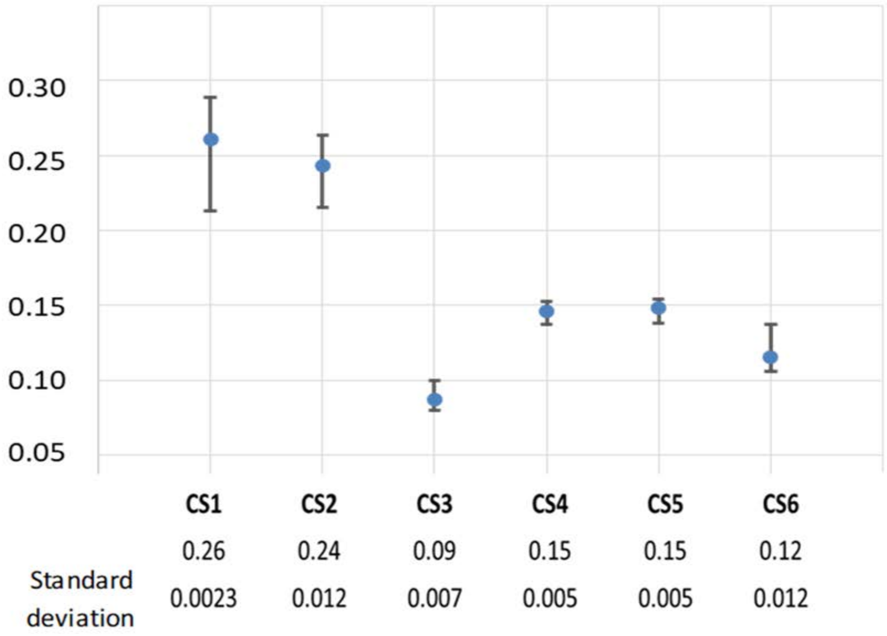

Figure 13 – Experts' individual assessments standard deviation

In this case study, the AHP based approach was able to encompass the various demands imposed on the candidate sites in order to support the decision-making process.

The AHP pairwise comparison methodology is practical and of simple application by the experts. Experts had to deal with qualitative and quantitative factors to derive the relative weights and to rank the alternatives.

Qualitative factors were used to assess the relative importance of each decision criteria to the site selection problem and to assess the relative importance of the sub-criteria to each criterion.

Quantitative factors were used to assess how much a candidate site complies with the sub-criteria. It was based on an adequately constructed scale that encompasses the whole range of numeric values.

In MCDM problems with a larger number of alternatives or criteria the effort required to collect pairwise comparisons may become impracticable. In such cases, a procedure based on the transitivity of the AHP verbal scale (Saaty scale) may be used to reduce this effort or to bring logical consistency to incomplete evaluations (GAVIÃO, LIMA and GARCIA, 2021).

CHAPTER 7 - CONCLUSIONS AND RECOMMENDATIONS

This thesis proposes an AHP based site selection process to define the best site for the construction of the reactor compartment near-surface storage facility in Brazil. This site selection process was successfully adopted in a case study.

In the proposed site selection process the AHP application starts at the final phase of the survey stage when the list of candidate sites becomes available. The AHP methodology proved to be practical, of simple application by the experts and able to encompass the various demands imposed to the candidate sites in order to support the decision making process. These demands are represented by the adopted criteria.

The criteria established in the case study are consistent with the ones adopted by Martins (2009) and Raduan (1994) site selection studies for the construction of a final repository in Brazil for SNF and for LILW.

The case study assessment recommends the construction of a tunnel type LILW near-surface storage facility for the reactor compartments interim storage in the candidate site CS1. It also presents: 1 - a list of candidate site ranked from the best alternative (highest score) to the worst, as follows: CS1, CS2, CS5, CS4, CS6 and CS3; and 2 - the most advisable type of interim storage facility to be built in each of the candidate sites.

This assessment is consistent with the sites' characteristics, with the evaluation of the most experienced expert and by its match with 78% of the experts' individual evaluations. It suggests the accuracy and the effectiveness of the proposed site selection process.

It is important to highlight that the novelty is not in the methodology in itself but on how the relative weights have been derived to select the site.

This case study should be seen as an initial approach to support the Brazilian Navy decision on the site selection for the construction of the SN-BR reactor compartment interim storage facility. The SN-BR decommissioning process and reactor interim storage presented in this thesis are proposed approaches for this problem that have to be validated by BN studies before practical use.

Additionally, the case study siting process (site survey stage and site selection stage) should be validated with the use of field information and the site evaluation process has to be completed because in this thesis it has been limited to the site selection stage (i.e. the site characterization stage, the pre-operational stage and the operational stage have not been performed, as detailed in Figure 6).

Studies on the SN-BR reactor compartment decontamination and on estimates of the activation radionuclides within it should be performed by Brazilian Navy to confirm the reactor compartment classification as a low and intermediate level radioactive waste (Assumption 3) and to confirm the external radiation level lower than 0.01 mSv/h on the surface of the metallic container (Assumption 4).

The nuclear submarines decommissioning processes adopted by the USN, French Navy and Russian Federation Navy have proved to be safe solutions. These solutions may be adapted to suit the decommissioning of small modular reactors and reactors installed in floating devices. This proposition is based on the similarity between the weights and dimensions of those reactors and the naval reactors used for submarine propulsion. An in deep study is required to customize the nuclear submarines decommissioning processes to other types of small reactors.

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GLOSSARY OF NAUTICAL AND MILITARY TERMS

Bulkhead - upright wall within the hull of a ship, vertical separation that subdivides the internal space of the hull in each deck (FONSECA, 2005).

Beam - width of the cross section to which it refers (FONSECA, 2005). In submarines, it is the widest diameter of the hull.

Cofferdam – safety space or empty space between two transverse bulkheads next to each other, so that compartments on each side have no common boundary. It may be located vertically or horizontally and serves to insulate oil and water tanks, machine or boiler compartment, etc. (FONSECA, 2005).

Compartment - internal subdivision of a ship, which can be watertight or not (FONSECA, 2005).

Commissioning License – It is part of the SN-BR licensing process. It is the license required to begin the Naval Nuclear Propulsion Plant set to work and should be obtained before the core loading authorization.

Cruise missile (SLCM) - submarine-launched cruise missile, is a missile that flies on a non-ballistic trajectory, from extremely low altitude at supersonic speeds or at high subsonic speeds. They are launched from submarines (SSG or SSGN) and carry a warhead over long distances with high precision.

Decommissioning - in this thesis, the term decommissioning, when applied to submarines, will be understood as the set of activities to be carried out at the end of the submarine operational life to ensure that the submarine's constituent materials pose no risk to the public and to the environment. The desired final state to be achieved at the end of the process is the release of the NS constituent materials from the regulatory control to recycling or to disposal.

Displacement (W) or (D) - is the weight of the water displaced by a ship floating in calm waters. According to the Archimedes Principle, the displacement is equal to the weight of the ship and everything it contains in the current flotation condition: W = weight of the ship = weight of the displaced water = immersed volume x water specific weight. The displacement is expressed in tons (thousand kilograms) in countries that adopt the metric system or in long tons (2240 pounds or 1016 kilograms) in countries that adopt the Imperial system (FONSECA, 2005).

Dismantling - in this thesis, it corresponds to the process of cutting the hull and other submarine structures for recycling or disposal.

Inactivated - withdrawn from operational service.

Intercontinental ballistic missile (ICBM) - missile launched from submarines and special vehicles with ballistic trajectory and a minimum range of 5500 km. They are designed to carry one or more nuclear warheads. Conventional, biological and chemical weapons may also be transported.

Knot – speed unit, corresponds to one nautical mile (1852 m) per hour (FONSECA, 2005).

Load In – term used in the shipbuilding industry for the transfer of heavy loads from the deck to a floating device (barge). During the transfer, as the heavy load moves, water has to be pumped in or out of the barge ballast tanks to keep the barge-deck set leveled (vertical gap within tolerance limits).

Load Out – Same as Load in but in the opposite direction (floating device to a deck).

Main Hall – CNI shipyard main building and construction facility. It integrates most of the construction workshops and it is the facility that welds the submarine's sections during the construction process.

Mobile - Mobile Confinement Unit, is an attachable device capable of coupling with NS reactor compartment through a retractable skirt. Its purpose is to grant access from the SN-BR support facilities at CNI to the interior of the reactor compartment, and vice-versa, under a controlled atmosphere condition.

NATO - North Atlantic Treaty Organization

NATO Reporting Names - they are names, easily understood by the troops, used to designate the military equipment of the USSR / Russia, Warsaw Pact countries and China. Russian nuclear submarines are usually treated by their Reporting Names, for example: Alpha, November, Typhoon, etc.

Nuclear-powered Attack Submarine (SSN) - submarine designed to destroy the SSBN and prevent the ballistic missile launch.

Nuclear-powered Ballistic Submarine (SSBN) - submarine capable of deploying ballistic missiles with nuclear warheads, usually called boomers.

Nuclear-powered Cruise Missile Submarine (SSGN) - submarine capable of launching cruise missiles (SLCMs and anti-ship missiles) and hunting the boomers.

Pontoons (Floats) - are airtight hollow structures, similar to pressure vessels, designed to provide buoyancy in water (FONSECA, 2005).

Reactor compartment - the section of the submarine that houses the Naval Nuclear Reactor. It consists of a part of the resistant hull limited by two rugged bulkheads and contains the primary circuit of the Naval Nuclear Propulsion Plant.

Shiplift – Ship elevator, the name refers to the main manufacturer of these elevators.

Soft-Patch - detachable hatch that grants access to the Reactor Compartment and other compartments, used to allow large equipment maintenance onboard submarines.

APPENDIX A - PROPOSED SN-BR DECOMMISSIONING PROCESS

The proposed SN-BR decommissioning process is based on the analysis of the successful decommissioning process adopted by the United States Navy (USN), Russian Federation Navy (RFN) and French Navy (FN). It considers the adoption of the deferred dismantling decommissioning strategy for the SN-BR (MAIA, 2015).

To implement the SN-BR deferred dismantling decommissioning strategy, the proposed SN-BR decommissioning process is divided into five phases, as follows:

1 – Preparatory Phase;
2 - Fuel and Waste Removal Phase;
3 - Fuel and Waste Management Phase;
4 - Activated Material Management Phase; and
5 - Hull Dismantling Phase.

The five phases have a proposed sequence of steps to be accomplished for the SN-BR decommissioning. The sequences of steps of each phase are approached along with its phase.

1 PREPARATORY PHASE

The Preparatory Phase main objectives are to prepare the submarine for the removal of the Spent Nuclear Fuel (SNF) and Wastes, and to reduce the risk of environmental (non-nuclear) contamination arising from the contaminants in the submarine.

This phase starts with the Brazilian Navy (BN) manifesting of the intention to withdraw the SN-BR from active duty (inactivate the submarine) to the AgNSNQ (Brazilian Naval Agency for Nuclear Safety and Quality). It finishes immediately before docking at the Itaguaí naval Complex (CNI) for SNF and waste removal, which occurs in the next phase.

After the SN-BR inactivation, BN notifies the AgNSNQ of the final submarine reactor shutdown (Notification of the end of the SN-BR reactor operation). This last notification must be made at least 30 days before the date of the SN-BR reactor end of the operation (adapted from Article 7 of CNEN-NN-9.01).

In this phase, the SN-BR is moored to the awaiting berth at the CNI, where it remains in temporary storage with its reactor in cold shutdown. All submarine nuclear systems are preserved (fully operational) and operated by its crew until the SNF is removed. The residual heat is removed by onboard safety systems.

The CNI awaiting berths provide the necessary resources to guarantee the fulfillment of the nuclear safety functions in case of SN-BR systems failure. NS at the berths are autonomous for nuclear safety purposes.

The submarine temporary storage is the period in which the submarine remains at the awaiting berth to allow the short half-life radioisotopes to decay naturally, reducing the inventory of fission products and the amount of heat to be removed from the core (residual heat).

The extent of the SN-BR temporary storage period was not found in the available literature. The extent of the temporary storage period for the American, Russian and French NS varies significantly and normally exceeds one year (MAIA, 2015).

Torpedoes, weapons, explosives, all classified materials and sensitive military equipment that pass through submarine's hatches are removed in this phase.

The proposed sequence of steps to be accomplished in this phase are:

1. Notify the regulatory body of the intention to inactivate the SN-BR and, subsequently, the final reactor shutdown (Notification of the end of the SN-BR reactor operation);
2. Inactivate the SN-BR (withdraw from operational service);
3. Remove torpedoes, weapons and explosives to reduce the explosion and fire risk;
4. Moore the submarine at the CNI awaiting berth. It remains in temporary storage with its reactor in cold shutdown;
5. Remove all classified materials and sensitive military equipment to reduce the risk of sensitive information exposure;
6. Remove spare parts, reusable ordinary equipment, technical manuals, tools, furniture and everything else that passes through the submarine hatches and can be removed to reduce fire risk without compromising the SN-BR safety;
7. Deactivate the non-nuclear SN-BR systems (maneuver, atmosphere control, propulsion, sensors, diving, weaponry, communications, etc.) to reduce the fire risk;
8. Drain and remove the fluids from the deactivated systems (lubricants, refrigerants, cold storage fluids, control hydraulics, water, wastewater,

ballast, control hydraulics, etc.) to reduce the risk of environmental (non-nuclear) contamination by onboard contaminants; and

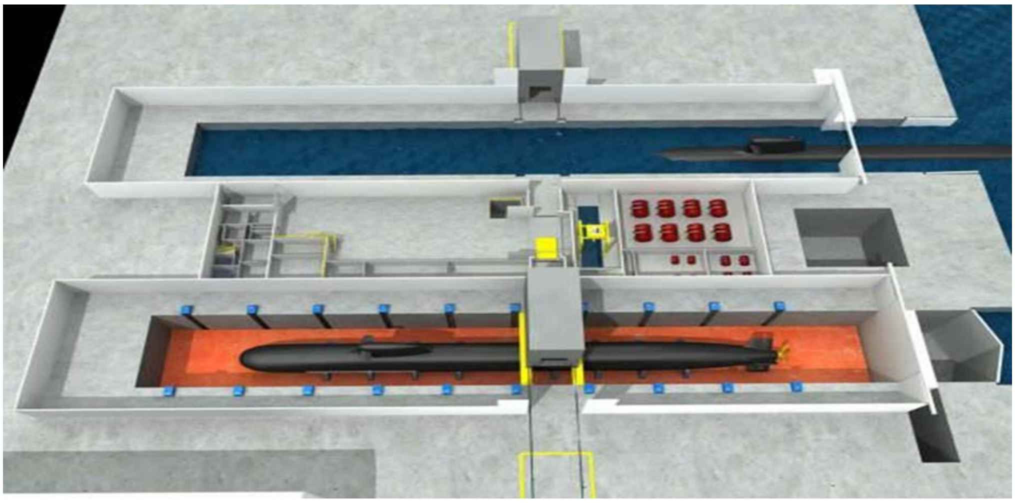
9. Preserve all support systems for the SN-BR reactor (nuclear safety systems).

2 FUEL AND WASTE REMOVAL PHASE

The Fuel and Waste Removal Phase main objective is to reduce the risk of nuclear and radiological contamination arising from the submarine by removing such materials. This phase starts with the SN-BR dry-docking for defueling and it ends with the removal of solid and liquid radioactive waste in the reactor compartment (RC), including those arising from the cleaning and decontamination processes required to allow the cut and removal of the RC, which occurs in the Activated Material Management Phase.

During the dry-docking, the submarine relays on the docks' resources to guarantee the fulfillment of the nuclear safety functions until its defueling. At the CNI dry docks, a Mobile Confinement Unit (UMC) is attached to the SN-BR RC Soft-Patch (detachable hatch that grants access to the RC for refueling or large equipment maintenance). It allows the safe removal of the SNF and radioactive waste and, after that, the final shutdown of all SN-BR nuclear systems.

The UMC is an attachable device capable of coupling with RC through a retractable skirt. Its purpose is to grant access from the SN-BR support facilities at CNI to the interior of the RC, and vice-versa, under a controlled atmosphere condition. Figure 14 shows an artistic conception of the SN-BR in the CNI dry docks with the mobile confinement unit attached.



Source: Padilha (2012a)

Figure 14 - SN-BR in the CNI dry docks with the Mobile Confinement Unit Attached

The defueling of the naval nuclear reactor is the removal of all SNF. The defueling is accomplished using the same procedures that have been used for the reactor refueling during its operational life.

The USN, FN and RN Mobiles are big devices with different design to ensure safety and to match their support facilities dimensions. For instance, the British Mobile (RAH – Reactor Access House), Figure 15, weighs 650 tons.

Source: Babcock International Group (2014).

Figure 15 - British reactor access house at HMNB Devonport.

The removal process of the SNF and the solid and the liquid radioactive wastes adopted in the decommissioning process is the same used throughout the submarine operational life and as it is not a specific decommissioning practice, it will not be addressed in this thesis.

After the final SN-BR defueling, BN notifies the AgNSNQ of the final removal of the SNF from the SN-BR reactor (adapted from Art. 7 of CNEN-NN-9.01).

At the end of this phase, the defueled submarine may be moved to a conventional (non-nuclear) installation, allowing CNI dry docks to carry out activities related to the maintenance of operational submarines.

The proposed sequence of steps to be accomplished in this phase are:

10. Prepare the SN-BR and the reactor for defueling;

11. Dock the SN-BR in the CNI dry docks;
12. Attach the mobile confinement unit to remove the SNF and wastes;
13. Remove the SNF;
14. Notify the SN-BR reactor final defueling to the AgNSNQ (Notification of definitive SNF removal of the SN-BR); and
15. Drain the SN-BR reactor and remove all solid and liquid radioactive waste, including those arising from the cleaning and decontamination processes of the reactor section.

3 FUEL AND WASTE MANAGEMENT PHASE;

The Fuel and Waste Management Phase main objective is to ensure these materials are safely transported, contained, stored and routinely disposed, in accordance with national regulation, from its removal from SN-BR to its processing and disposal. This phase starts after the fuel and waste removal and it ends when those materials are disposed in the final repository.

In this phase the proposed sequence of steps to be accomplished are:

16. Transport and store the SNF in the CNI Spent Fuel Pool (SFP);
17. Transport the radioactive waste (solid and liquid) to the processing facilities and, after that, safely contain, store and then routinely dispose of it in accordance with national regulations;
18. Request the regulatory body Authorization for Decommissioning the SN-BR;
19. Transport the SNF stored in the CNI Spent Fuel Pool (SFP) to the Interim Repository;
20. Transport the SNF and the radioactive waste from their Interim storage to the Final Repository.

The SNF removal is supposed to produce nearly 200 m^3 of radioactive liquid waste, 20 m^3 arising from the primary circuit, 4 m^3 from the filters, 170 m^3 from the shielding tanks in the RC and the rest from various smaller equipment (SNELL, 2000). The decontamination of the primary circuit produces about additional 100 m^3 of liquid waste with an activity of up to 100 Ci / l (SNELL, 2000).

BN will require the Authorization for the Decommissioning of the SN-BR to the regulatory body after the confirmation that all nuclear material previously existing in the submarine have been safely transferred to another licensed facility (adapted from Paragraph 2 of Article 8 of CNEN-NN-9.01).

The SNF and the radioactive wastes transportation and storage process adopted in the decommissioning process is the same used throughout the submarine operational life and as it is not a specific decommissioning practice, it will not be addressed in this thesis.

4 ACTIVATED MATERIAL MANAGEMENT PHASE

The Activated Material Management Phase main objective is to reduce the risk of radiological contamination from activated materials arising from the RC. To do so, the RC is cut and separated from the rest of the submarine in order to segregate the activated materials therein. This phase starts with the regulatory body authorization for the SN-BR decommissioning and it finishes with the SN-BR RC dismantling and the disposal/recycling of the activated materials contained therein.

The SN-BR decommissioning process formally starts in this phase and ends when the regulatory body no longer controls the constituent materials of the SN-BR reactor section.

The adoption of the proposed deferred dismantling decommissioning strategy implies in the removed RC interim storage. The constituent materials of the rest of the submarine (submarine fore and aft sections) have no activated materials therein and must be recycled or disposed in compliance with national environmental regulations. The removal of the RC removes all the remaining radioactivity in the submarine (USN, 2019).

Before the submarine hull is cut, all internal structures connected to the rest of the submarine or crossing the RC (piping and cables) are set loose. All primary circuit equipment and piping inside the RC are open to allow the drainage of all the fluids inside them and its decontamination. The SN-BR will be cut when the RC is decontaminated and the hull is the only connection between the RC and the submarine fore and aft sections.

The Naval Nuclear Propulsion Plant decontamination process consists of: 1 - the drainage and removal of all fluids in the reactor compartment, 2 - the decontamination of the equipment (inside the reactor compartment) and of the piping that crosses the reactor compartment bulkheads.

During the decontamination, the pressure vessel, piping, tanks, and fluid system components that remain in the RC are drained to the maximum practical extent. Absorbent is added to absorb the residual liquid that may be present (USN, 2019). According to USN, the system draining procedures remove nearly all (over 98 %) of the liquid originally present. Only a small amount of liquid remains trapped in discrete locations such as pockets in valves, pumps, tanks, vessels, and other inaccessible piping system components (USN, 2019).

The RC removal process consists of the hull cut (made several feet forward and aft of the shielded reactor compartment) and its slid, after the removal of all interferences, such as structures attached to the reactor compartment bulkheads, piping, electrical cabling, and other components that penetrate the reactor compartment bulkheads (USN, 2019).

The RC removal and the disposal of the remaining parts of the NS do not involve any sophisticated technology, but common industrial practices well within the capability of a large shipyard.

This thesis proposes the SN-BR hull cut at the CNI shipyard Main Hall facilities. To do so, the defueled submarine is moved from the dry docks to the Shiplift. At the Shiplift, the SN-BR is raised from the sea to the submarine maintenance deck.

The SN-BR hull cut at the CNI Main Hall facilities main advantages are:

a) Cost-effectiveness – no additional facilities construction required;
b) Easier transportation – the cut hull sections are on the ground (maintenance deck level) and their transportation to the dismantling installations is simpler; and
c) Dry dock free – CNI dry docks are not required and may be used to support other NS.

The Shiplift is an equipment designed to raise or lower ships up to 8.000 tons of displacement. It has a movable platform that launches at sea the submarines built at CNI facilities. It also raises conventional submarines from the sea to the CNI maintenance deck for overhaul and other maintenance periods.

The Main Hall is the shipyard main construction facility. It integrates most of the construction workshops and is responsible for join the submarine sections during the construction process. In front of it, there is a submarine maintenance deck where conventional submarine maintenance periods will be performed. The CNI shipyard Main Hall facilities and the Shiplift can be seen in Figure 16.

Source: Poder Naval, 2014

Figure 16 - CNI shipyard Main Hall facilities and the Shiplift.

In this phase the proposed sequence of steps to be accomplished are:

21. Receive the regulatory body authorization to decommission the SN-BR (SN-BR Decommissioning Authorization);

22. Prepare the SN-BR for the RC removal, cut the internal structures connected to the rest of the submarine and cut all the piping and the cables crossing the reactor sections bulkheads;

23. Decontaminate the RC and drain all the fluids inside the primary circuit equipment and piping;

24. Raise the SN-BR with the Shiplift and move it to the EBN Main Hall;

25. Cut the hull and remove the RC in the EBN Main Hall (separate the RC from the rest of the submarine);

26. Install containment bulkheads at both ends of the removed RC to ensure the confinement of the existing radioisotopes and prepare the removed RC for interim storage (RC encapsulation);

27. Install a ventilation system in the encapsulated RC to allow periodic inspection (radioisotopes decay and overall storage conditions follow up);

28. Transport the encapsulated RC to its interim storage facility;

29. Follow up the activity in the encapsulated RC;

30. Store the encapsulated RC in its interim storage until its dismantling;

31. Remove the encapsulated RC from the interim storage and transport to its dismantling facility;

32. Dismantle the RC and recycle the activated materials whose activity is within regulatory body authorized limits;

33. Prepare the remaining activated materials for deposition at the final repository (activated materials whose activity exceed authorized limits); and

34. Transport and dispose of the remaining activated materials in the final repository.

The RC encapsulation aims to enforce its radiologic safety. The proposed encapsulation process consists of:

1 – Construction of a resistant metallic container capable of housing the cut reactor compartment;

2 – Application of a resin protective layer on the RC; and

3 – Injection of expansive resin inside the primary circuit piping to ensure that no leak will take place in the event of a pipe break.

The proposed storage time of the SN-BR encapsulated RC is of 60 years (conservative approach).

5 HULL DISMANTLING PHASE

The Hull Dismantling Phase main objectives are: to reduce the risk of environmental contamination arising from the toxic and hazardous materials contained in the submarine fore and aft sections; and to reuse or recycle the equipment and materials existing therein, that could not have been previously removed through the SN-BR hatches (0.80 m of diameter). All the equipment and the materials are classified, processed, recycled or disposed in compliance with environmental regulations. This phase starts after the RC removal and it finishes when all the equipment and the materials are properly recycled or disposed. Alternatively, the SN-BR may be transformed into a museum ship, interrupting the Hull Dismantling Phase.

The hull dismantling is normally performed with MAPP[46] cut. Sows, hydraulic cutters and scissors are also used. These and other cutting options are discussed in (SARKISOV and Du CLOS, 1999). Environmental regulations may limit cutting options. Security precautions shall be taken during the dismantling process to prevent sensitive information disclosure.

In this phase the proposed sequence of steps to be accomplished are:

35. Transform the SN-BR into a museum ship[47]; or
36. Transport the submarine fore and aft sections to a dismantling facility;
37. Cut the submarine remaining sections into subsections, beginning the SN-BR dismantling;
38. Remove all reusable equipment whose removal could only be performed after the hull cut (did not pass through SN-BR hatches);
39. Classify and segregate the remaining materials within the subsections. The reusable materials are recycled and the toxic and hazardous ones are disposed in compliance with environmental regulations; and
40. Dismantle the subsections of the hull.

After the cut of the hull in subsections, the reusable equipment are registered and removed. The removed scrap is segregated into recyclable material and waste. The waste is further segregated into hazardous and non-hazardous. The toxic and hazardous wastes are segregated into types and disposed of in compliance with environmental regulation.

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[46] MAPP - methyl acetylene propadiene, it is an oxygen-gas mixture that can achieve high cutting rates.

[47] USN, RFN and FN transformed their first NS into a museum ship instead of dismantling its hull. The museum ship preserves the national technology history and is a cheaper achievement. The transformation of a decommissioned NS into a museum ship requires the building of a dummy RC to replace the removed one.

APPENDIX B - BRAZILIAN LEGAL FRAMEWORK AND REGULATIONS

Appendix B presents the Brazilian legal framework and regulations adopted in this thesis. Additionally, it presents the relevant IAEA Regulations that are complementary to the mentioned CNEN Regulations.

Table 31 Relevant National Legal Framework

Decree nº 40.110/56 of 10 Oct. 1956	Creates the Brazilian National Commission for Nuclear Energy (CNEN).
Law nº 4.118/62 of 27 Jul. 1962	Establishes the Nuclear Energy National Policy and reorganizes CNEN.
Law nº 6.453/77 of 17 Oct. 1977	Establishes the civil liability for nuclear damages and criminal responsibilities for actions related to nuclear activities.
Law nº 6.938/81 of 31 Aug. 1981	Establishes the National Policy for the Environment (PNMA) and creates: 1 - the National System for the Environment (SISNAMA); 2 - the Council for the Environment (CONAMA); and 3 - Brazilian Institute for the Environment (IBAMA).
Decree nº 88.821 of 06 Oct. 1983	Regulates the road transport service for dangerous goods or cargo.
Decree nº 99.274/90 of 06 Jun. 1990	Regulates the application of Law nº 6.938/81, establishing the environmental licensing process in 3 steps: pre-license, installation license and operation license.
Decree nº 2.210/97 of 22 Apr. 1997	Regulates the SIPRON, defines the Secretary for Strategic Affairs (SAE) as the central organization of SIPRON and creates the Coordination of the Protection of the Brazilian Nuclear Program (COPRON).
Law nº 9.605/98 of 12 Feb. 1998	Defines environmental crimes and establishes a system of enforcement and punishment.
Law nº 9.765/98 of 17 Dec. 1998	Establishes tax and fees for licensing, control and regulatory inspection of nuclear and radioactive materials and installations.
Decree nº 3.719/99 of 21 Sep. 1999	Regulates Law nº 9.605/98 and establishes penalties for environmental crimes.
Decree nº 3.833/01 of 05 Jun. 2001	Establishes the new structure and staff of the Brazilian Institute for the Environment (IBAMA).

Law nº 10.308/01 of 20 Nov. 2001	Regulates site selection, construction, operation, licensing and the control of: financing; civil liability; and guaranties related to the storage of radioactive wastes.
Decree nº 1.019/05 of 14 Nov. 2005	Promulgates the Joint Convention on: 1 - the Safety of Spent Fuel Management; and 2 - the Safety of Radioactive Waste Management.
Supplementary Law nº 140/11 of 08 Dec. 2011	Regulates the cooperation between the Union, the States, the Federal District and the Municipalities regarding administrative proceedings for the protection of the environment, the control of pollution in any of its forms, and the preservation of forests, fauna and flora.
Law nº 12.731/12 of 21 Nov. 2012	Reorganize the Brazilian Nuclear Protection System (SIPRON).
Law nº 14.222/21 of 15 Oct. 2021	Regulates the National Nuclear Safety Authority(ANSN)

Table 32 Relevant National Nuclear Regulations (CNEN Regulations)

CNEN-NE-1.04	Licensing of Nuclear Installations
CNEN-NN-3.01	Basic Guidelines for Radiologic Protection
CNEN-NN-5.01	Transport of Radioactive Materials
CNEN-NE 6.06	Selection and Choice of Sites for Radioactive Waste Disposal Facilities
CNEN-NN 6.09	Acceptance Criteria for Disposal of Radioactive Waste of Low and Medium Levels of Radiation
CNEN-NN-8.01	Management of Low and Intermediate Level Radioactive Waste
CNEN-NN-8.02	Licensing of Low and Intermediate Level Radioactive Waste Deposits
CNEN-NE-9.01	Regulation on Decommissioning of Nuclear Power Plants

Table 33 Relevant Naval Nuclear Regulations (ANSNQ)

ANSNQ-100	Fundamental Safety Principles for Nuclear-powered vessels
ANSNQ-101	Licensing of Nuclear-powered vessels
ANSNQ-102	Radioprotection Basic Guidelines
ANSNQ-112	Radioactive Waste Management and Decommissioning Requirements
ANSNQ-113	Radioprotection Criteria for Nuclear Propelled Submarines

Table 34 Relevant CONAMA and IBAMA Regulations (ANSNQ)

CONAMA – 01/86 of 23 Jan. 1986	Establishes requirements for conducting the environmental impact assessment (EIA) and the preparation of the report on environmental assessment impact (RIMA).
CONAMA-09/86 of 03 Dec. 1987	Regulates the matters related to public hearings
CONAMA-06/86 of 24 Jan. 1986	Establishes models for licensing application
CONAMA-06/87 of 16 Sep. 1987	Regulates the environmental licensing of large enterprises, especially in the area of electric energy generation
CONAMA-237/97 of 19 Dec. 1997	Establishes procedures for environmental licensing of several types of enterprises
IBAMA Normative Instruction n º 184/08 of 17 Jul. 2008	Establishes within this Agency, the procedures for federal environmental permits
NBR 10.004	Classification of solid wastes (ABNT standards)

Table 35 Relevant IAEA Regulations (complementary to CNEN Regulations)

IAEA-GSG-1	Classification of Radioactive Waste, 2009
IAEA-SS-63	Design, construction, operation, shutdown and surveillance of repositories for solid radioactive wastes in shallow ground, 1984
IAEA-SSG-29	Near-Surface Disposal Facilities for Radioactive Waste, 2014
IAEA-TRS-390	Interim Storage of Radioactive Waste Packages, 1998
IAEA-SSG-14	Geological Disposal Facilities for Radioactive Waste, 2011
IAEA-SS-53	Shallow Ground Disposal of Radioactive Wastes: A Guidebook, 1981
WS-G-1.1	Safety Assessment for Near-Surface Disposal of Radioactive Waste, 1999
IAEA-SS-62	Site Investigations, Design, Construction, Operation, Shutdown and Surveillance of Repositories for Low and Intermediate-Level Radioactive Wastes in Rock Cavities, 1984
IAEA-SS-63	Design, Construction, Operation, Shutdown and Surveillance of Repositories for Solid Radioactive Wastes in Shallow Ground, 1984
IAEA-SS-64	Safety Analysis Methodologies for Radioactive Waste Repositories in Shallow Ground, 1984
IAEA-SS-71	Acceptance Criteria for Disposal of Radioactive Wastes in Shallow Ground and Rock Cavities, 1985

IAEA-SSG-35	Site Survey and Site Selection for Nuclear Installations, 2015
IAEA-SSR-5	Disposal of Radioactive Waste, 2011