BJRS

BRAZILIAN JOURNAL
OF
RADIATION SCIENCES
10-04 (2022) 01-24

SBPR
Sociedade Brasileira de Proteção Radiológica

Risks to be considered in Nuclear Reactor Decommissioning Projects in Brazil

Neto A. B.C.

Instituto de Pesquisas Energéticas e Nucleares (IPEN/ CNEN-SP)
Av. Professor Lineu Prestes, 2242, 05508-000, São Paulo, SP, Brasil
alvaron@usp.br / alvaro.caldas@marinha.mil.br

ABSTRACT

In recent years, Brazil has intensified investments in nuclear innovation for peaceful purposes. Currently, in the country, there are six reactors in operation and three under construction. These reactors, at the end of their useful life, must be decommissioned, in a process that includes technical and administrative actions aimed at the partial or total removal of regulatory control, with a view of to the safety of the installation site, the health of employees, the public, and the protection of the environment. Thus, these activities involve risks that must be managed systematically, following the rules and guidelines established by responsible bodies. The International Atomic Energy Agency (IAEA) recently identified the need for practical guidelines for risk management in decommissioning projects and elaborated the publication "Management of Project Risks in Decommissioning" of the Safety Reports Series Nº 97. In Brazil, there is no experience in execution the decommissioning of nuclear reactors, thus, this work will present and analyze the main risks of nuclear reactor decommissioning projects in Brazil, using techniques from the risk assessment process of the ISO/IEC 31010 Standard, considering the wide international experience portrayed on the subject.

Keywords: **Decommissioning, Nuclear Reactors, Risk Management, Radioactive Waste.**

ISSN: 2319-0612
DOI: https://doi.org/10.15392/2319-0612.2022.2111
Submitted: 2022-09-28
Accepted: 2022-11-21

1. INTRODUCTION

Since the development of nuclear reactors in the 1940s, humanity has experimented with the most varied forms of application of nuclear technology for peaceful purposes. The growth of this type of installation for the generation of electricity, research in the areas of health, industry and agriculture fill an important role in the development of a nation and increasingly expand the horizons for progress.

Brazil, through its state policies (nuclear, energy, defense, science, and technology), has been investing heavily in innovation, with the objective of positioning Brazil among the most developed countries in the world. In this respect, the safe exploitation of nuclear technology is one of the priorities, whether in energy generation, industry, health, and agriculture. Currently, Brazil has 6 reactors in operation (2 for power and 4 for research) and 3 reactors under construction (1 for power and 2 for research).

Due to the criticality associated with possible nuclear or radioactive accidents and disasters that can happen in a nuclear installation, strict safety control is necessary throughout its life cycle, which must be monitored by the country's regulatory body. The regulatory body is responsible for licensing the facility during the construction, assembly, and commissioning phases, to verify its compliance with the design and performance criteria. This regulatory body will maintain control activities throughout the installation's life cycle, that is, until decommissioning [1].

In this sense, after using the benefits of nuclear technology, these facilities, either at the end of their useful life, or in the case of early withdrawal from operation by accident or by decision of the organization operating the facility, must be decommissioned, in a process which comprises "administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility" with a view to the safety of the installation site, the health of employees, the general public and the protection of the environment [1].

Technical decommissioning actions include decontamination, dismantling, and removal of structures, systems, and components, including radioactive waste management and radiation protection of workers performing decommissioning, as well as conducting characterization surveys to support decommissioning [1].

On the other hand, administrative decommissioning actions involve the management of financial resources intended for technical and administrative activities performed for the partial or total withdrawal of regulatory control, ensuring the proper management of the funds necessary to guarantee safe decommissioning and waste management of radioactive substances generated during decommissioning [2]. Decommissioning of a nuclear facility is completed when all radioactive material has been removed from the site, and the site is released from regulatory control for unrestricted use [1].

Thus, the decommissioning process of nuclear reactors is associated with numerous risks, in the areas of safety, human resources, regulatory, financial, and technological aspects, etc., which must be managed systematically. In this way, the IAEA recently (2019) identified the need for practical guidelines for risk management in decommissioning projects and prepared the publication "Management of Project Risks in Decommissioning" from the Safety Reports Series No. 97, which was used as a guide. for this work [3].

It is never too much to remember that, in Brazil, there is no experience in executing the decommissioning of nuclear reactors, and, therefore, there may be gaps to be observed. Examples will be analyzed in the course of the work. The planning and execution of a decommissioning of this size are associated with different risks, which, with the extensive international experience portrayed on the subject, will serve as a basis for the preparation of this work.

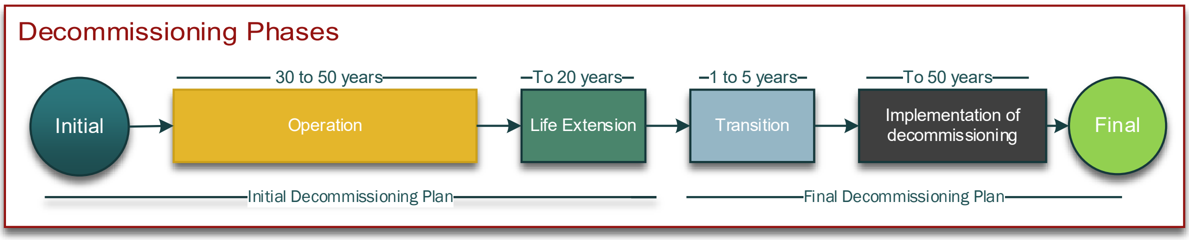
In view of the above, this work aims to analyze the main risks associated with nuclear reactor decommissioning projects using information, tools and methodologies already used internationally, but considering the Brazilian reality regarding legislation and the characteristics of the reactors to be decommissioned. Due to the limitation and scope of the work and to elucidate the analysis and risk assessment in accordance with the IAEA Publications, four main associated risks will be analyzed in more depth: financial, radioactive waste management, human resources (management of knowledge and training), and technology.

To achieve the objectives, this work will be based on the regulations of the National Nuclear Energy Commission (CNEN), the guidelines and documents of the IAEA, the articles published in the area, and the lessons learned by countries that carried out decommissioning of nuclear reactors. To analyze some of the risks, some techniques will be used for the risk management process of the ABNT NBR ISO/IEC 31010 standard.

2. RISK MANAGEMENT IN DECOMMISSIONING

Decommissioning a nuclear facility is a process that can take decades to plan and execute. It usually starts with the elaboration of an Initial Decommissioning Plan (IDP) still in the design phase, follows the entire construction and operation phases, and at the end of its useful life, a Final Decommissioning Plan (FDP) is prepared, which must be approved by the regulatory body, which will issue an authorization for decommissioning. Then, the execution phase of the decommissioning begins. Actions end when decommissioning, decontamination and cleaning are completed, and the license can be terminated [3]. In figure 1, the phases of decommissioning are illustrated.

Figure 1: *Decommissioning Phases*



Source: [4]

To support countries in developing capacities and plans to carry out safe decommissioning activities, the IAEA created an International Decommissioning Network that recognized risk management in projects as an important factor for decommissioning. Thus, the "Project Decommissioning Risk Management" (DRiMA) was created with the objective of providing practical recommendations and methodology on the existing risk management approach during the planning and execution of decommissioning.

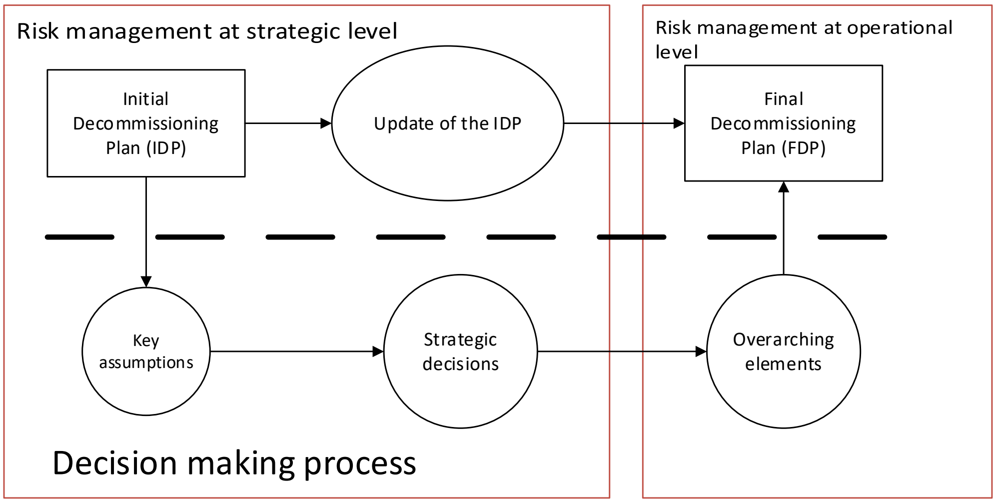
Thus, this work will adopt the recommendations of DRiMA, suggesting examining the risks of decommissioning projects in two topics: for planning purposes, Risk Management at the Strategic Level (RMSL), and for execution, Risk Management at the Operational Level (RMOL) [5].

In this sense, the RMSL approach is related to IDP and the strategic decisions that will be associated with the FDP. The IDP is usually developed with a large amount of uncertainty, as little or no details may be available, such as dismantling and decontamination technologies, waste acceptance criteria, availability of radioactive repositories, regulatory framework, financial availability, human resources, etc. Thus, the assumptions associated with this phase must be well examined and adjusted during the life cycle of the nuclear installation. The importance of initially carrying out "assumptions management" is highlighted to mitigate the uncertainties that will later be transformed into risks [3].

The second approach is RMOL, which is the management of risks associated with the execution of decommissioning activities and is related to the preparation of the FDP and the detailing of the execution of the decommissioning and decontamination activities. At this stage, the FDP cannot tolerate uncertainty, as it will be used to dictate the actual execution of the decommissioning works [3].

Thus, the RMSL is linked to the IDP, which after many years, will be transformed into an FDP, which will be related to the RMOL. In this way, RMSL will accompany the transformation process up to RMOL. Figure 2 illustrates the evolution of the decommissioning plan and the relevant aspects for risk management.

Figure 2: *Evolution of the Decommissioning Plan*



Source: [5]

Overall, the RMSL serves to ensure that decisions and strategic plans in the FDP are based on the best available information. And RMOL serves to ensure that these decisions are carried out later with as little risk as possible.

3. RISKS TO BE CONSIDERED IN DECOMMISSIONING

The decommissioning of nuclear reactors is associated with a huge number of risks to be considered, so risk management in decommissioning projects allows identifying, analyzing, evaluating, and taking measures to avoid, mitigate or exploit, in case of opportunity, these scratches. As previously discussed, the risks in decommissioning result from uncertainties inherent to planning (RMSL) and execution (RMOL). This item will illustrate the dynamic nature of some of the main risks in decommissioning and how you can use the techniques of the risk assessment process to analyze it.

For the establishment of assumptions, those that could cause a major change in the decommissioning strategy, a financial impact, or an impact on the schedule were considered. From the documents and articles researched, the following premises were established:

a) the facility will operate during its lifetime without major incidents of a type that would prevent a change in decommissioning strategy [3];

b) the facility will operate long enough to collect adequate funding for decommissioning [3];

c) the National Repository of Radioactive Waste of Low and Medium Levels of Radiation (RBMN) or intermediate or final deposits will be in operation and will have sufficient capacity for all types of radioactive waste produced during decommissioning;

d) there will be no regulatory changes in the Brazilian nuclear sector that will impact decommissioning;

e) experienced and trained human resources will be maintained at the facility and new employees will always be hired and trained to replace them;

f) the proposed decommissioning technologies will be sufficient for safe dismantling and decontamination actions; and

g) the installation will act with transparency of information and involvement of interested parties.

In this way, the risk assessment process technique “Cause and Consequence Analysis” will be used. This technique was chosen because it is a combination of Fault Tree Analysis and Event Tree [6]. Due to the scope and limitation of this work, the risks derived from the assumptions that have a higher level of uncertainties selected by the author will be analyzed, which are risks: financial, associated with the management of radioactive waste, associated with human resources (which include the management knowledge and training) and technology.

Thus, to assess the probability and impact of these risks, this work used the examples provided by the IAEA [3]. For the probability assessment, a linear scale was used, as shown in Table 1. This scale includes a score, the probability of occurrence and the criteria.

Table 1- Scale of Probability for risk analysis

Score	Probability	Criteria
1	0-20%	Very unlikely to occur; not known to have taken place with similar types of decommissioning projects
2	21-40%	Unlikely to occur; known to have occasionally taken place with similar types of decommissioning projects
3	41-60%	Known to have taken place with reasonable regularity on similar types of decommissioning projects
4	61-80%	Typically takes place with similar types of decommissioning projects
5	81-100%	Almost certain to take place

Source: [3]

To score the financial and schedule impact assessment, a linear scale was also used, as shown in Table 2.

Table 2 – Scale of impact in risk analysis

Score	Financial impact criteria	Schedule impact criteria
1	<1% of the remaining budge	<1% of the remaining duration
2	1 a 5% of the remaining budget	1 a 5% of the remaining duration
3	6 a 10% of the remaining budget	1 a 5% of the remaining duration
4	11 a 20% of the remaining budget	11 a 20% of the remaining duration
5	>20% of the remaining budget	> 20% of the remaining duration

Source: [3]

The Risk Score (RS) is determined through the product of the highest value probability and impact scores (probability x impact). For example, a nuclear accident risk is very unlikely to happen, less than 20% (score = 1), but the financial impact, if it does occur, is high, above 20% of the budget (score = 5) and suppose that the schedule is affected by between 11 and 20% of the remaining duration (score = 4). The RS for this example will be 5 (1 X 5), as the choice of impact, following practice, will always be based on the highest value [3].

To allow a better understanding of the diagrams analyzed below, a risk matrix was used, according to Table 3, in accordance with the recommendation of the IAEA publication [3], allowing to compare the RS between them, to determine the strategy of risk treatment.

Table 3-Risk matrix

Probability of Occurence		Risk Score = Probability Scale X Impact Scale (PXI)				
> 80%	5	5	10	15	20	25
60%-80%	4	4	8	12	16	20
40%-60%	3	3	6	9	12	12
20%-40%	2	2	4	6	8	10
0%-20%	1	1	2	3	4	5
		1	2	3	4	5
	Impact of Occurence	Insignificant	Minor	Moderate	Major	Severe

Source: [3]

To propose the appropriate risk treatment strategy in relation to the RS, the IAEA's suggestions were adopted, as shown in Table 4, which contains the strategy to be adopted, the RS and the definition [3].

Table 4-Risk treatment selection guide

Strategy	Risk score	Definition
Avoid	20 -25 (red)	Change the project plan/activity so that threat does not or cannot occur
Mitigate	6-16(mustard yellow)	Take action to reduce the probability and/or impact of the threat such that the risk is lowered to an acceptable level
Transfer	6 – 16 (yellow)	Transfer the risk to another party (e.g. a contractor) better positioned to address the threat and thereby lower the risk to acceptable levels
Accept	1-5 (green)	Accept the risk and take no further action; monitor the risk to ensure it remains acceptable

Source: [3]

The Cause and Consequence Analysis diagrams of the risks related to the assumptions made in this work will adopt these mechanisms.

3.1 Financial Risk

Decommissioning nuclear reactor is a process expensive and time-consuming, current estimates range between US$400 million and US$1 billion [7]. The costs of decommissioning cannot be underestimated, regardless of when it will be carried out. In Brazil, there is the CNEN Regulation NN 9.02, which regulates the Management of Financial Resources of Nuclear Power Plants for decommissioning, which, due to lack of regulation, can be used, for the time being, for other types of reactors. It determines that the installation ensures the management of financial resources, for the necessary period, in order to cover the costs associated with the implementation of the FDP previously approved by the regulatory body. The Regulation establishes that the operating organization, or the officially established management organization, is responsible for the proper management of the funds necessary to ensure the safe decommissioning and management of radioactive waste generated during decommissioning [2].

As there was no decommissioning of nuclear reactors in Brazil, there is no historical cost data to be consulted. This is compounded by also not knowing how to estimate the costs associated with the use of certain technologies and the management of radioactive waste. The basic answer to this type of uncertainty is to add contingency allowances calculated on top of the basic cost estimates. The US, for example, added 25% and 50% contingencies above the estimate. The UK used values between 50% and 75% for more uncertain scenarios. Even with these contingencies, in some cases, it ends up being insufficient [8].

There are some risks that could lead to the nuclear installation not securing the financial resources for decommissioning. One is that, despite nuclear reactors having an excellent operational record, accidents during operation are not unlikely. To illustrate, there is, for example, the Fukushima accident, which had an estimated cost of US$7.4 billion to repair the damage caused. As the estimate for decommissioning is between $400 million and $1 billion. It can be said, even with the very low probability of happening, that an accident could lead to the bankruptcy of the operating organization [7].

The second risk is that, possibly, the operating organizations could go bankrupt due to radical changes in energy market conditions or due to losses from other commercial activities, such as the production of radioisotopes, putting companies in financial difficulties. One example was the company First Energy Solutions which, in 2018, filed for bankruptcy in the US to escape a series of debts linked to the closure of several nuclear units that were not profitable [7].

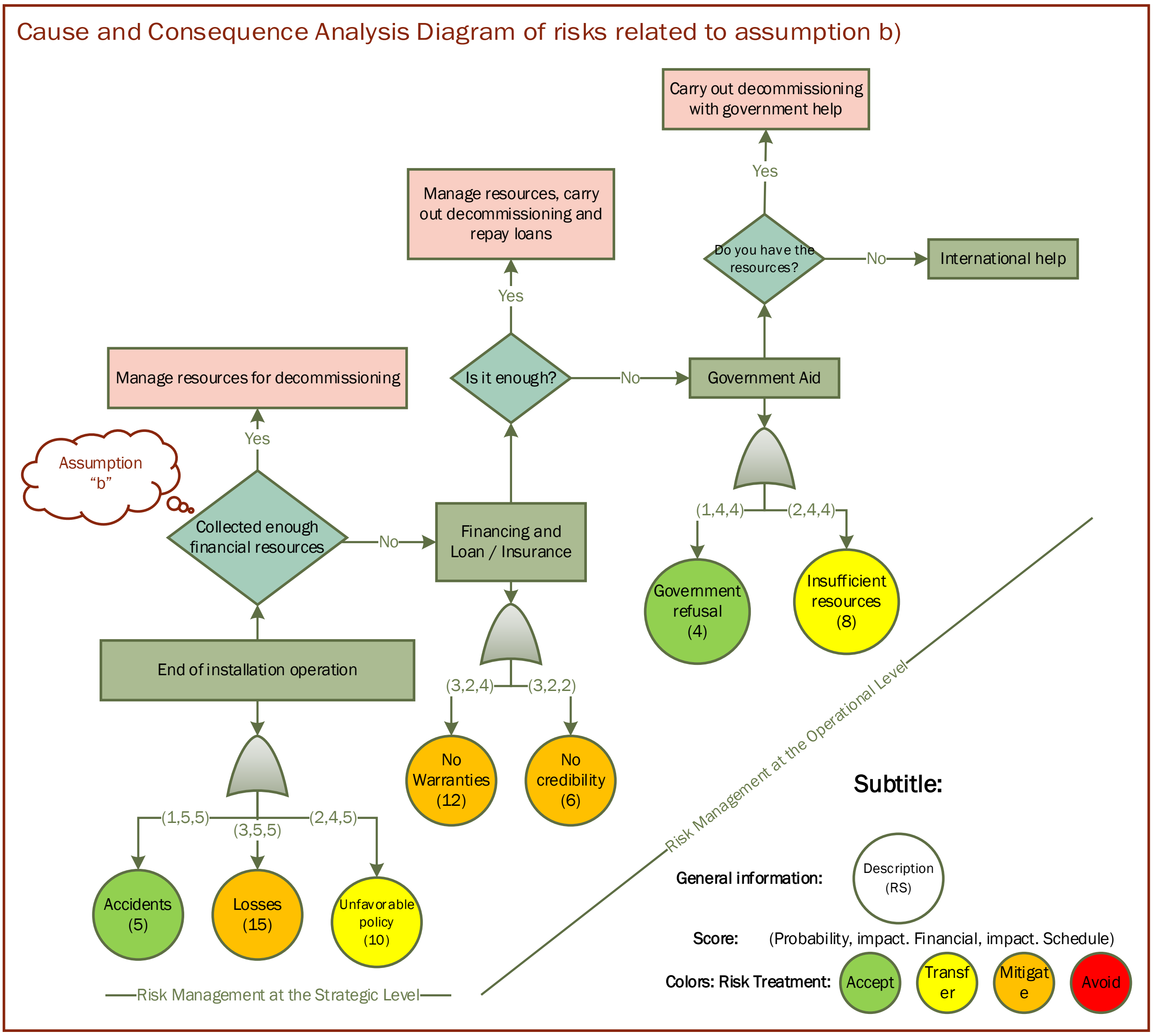
Another risk identified is political decisions before the decommissioning process. An example was the case of the Yankee NPP (Nuclear Power Plant), where the local population, in Haddam Neck, forced the government to add more stringent standards in the decommissioning procedures of the facility, exceeding the balance of the decommissioning fund initially foreseen [7].

The risks mentioned above are some examples that deal with assumptions that must be analyzed and adjusted during the operation phase so that the operating organizations ensure the necessary resources until the end of decommissioning to meet the assumption that the facility will operate long enough to collect adequate funding for decommissioning (assumption 'b' cited in chapter 3). These risks are described in the analysis presented in Figure 3.

In cases where the facility is unable to provide the necessary financial resources for decommissioning and it is no longer in operation. It is possible that the cost of decommissioning exceeds tens of millions of dollars due to project problems, cost, or external factors, as has already occurred in the USA at times [7]. It is important to point out that, from that point on, risk management becomes RMOL, as the installation will no longer be profitable and will no longer be able to obtain resources through the activity for which it was designed.

At this point, the company will be able to request financial loans from creditors (Banks, Funds, etc.), and place the company's assets as collateral to obtain the additional resources necessary to complete the decommissioning. Although, they can also obtain funds from governmental financial institutions, these may not yet be sufficient to carry out the decommissioning. In Brazil, nuclear facilities may not have sufficient guarantees for creditors to provide the necessary resources, as the Brazilian nuclear area is still maturing. In this sense, the Government, which has the monopoly of nuclear activities in Brazil, must provide the guidelines and provide means to supply the decommissioning funds, as well as protect the activities in case of bankruptcy or lack of resources. An alternative is for the Brazilian Congress to legislate to encourage the creation of insurance to cover eventual decommissioning needs. In the USA, for example, a Law (Price-Anderson) was created that guarantees coverage for possible losses for personal and material damages caused by NPP accidents in the American territory, and which also allowed the creation of insurance for decommissioning [7]. In view of the information mentioned above and to simulate the probabilities and consequences, Figure 3 shows the cause and consequence analysis diagram of the risks. Indicating the risk level (defined by the author), using the criteria described in reference 3.

Figure 3: *Cause and Consequence Analysis Diagram of risks related to the assumption that the facility will operate long enough to collect adequate financial resources for decommissioning (assumption 'b').*



Source: [Author]

3.2 Risks associated with the Management of Radioactive Waste

It is certain that the process of decommissioning nuclear reactors will produce a large amount of radioactive waste, in these days, there is no technology to solve this problem. Most of these wastes pose a danger to human health and the environment for periods much longer than the lifetime of the institutions of human society. Thus, radioactive waste management aims to minimize the amount of waste generated, maintain control at all stages and minimize the doses and costs of keeping these wastes under control [9].

In Brazil, there are Regulatory Norms (RN) that establish procedures for the management of Class 1 and 2 radioactive waste and for the licensing of initial, intermediate, and final deposits. These RN determine that every nuclear facility has a radioactive waste management plan, which segregates it into conditioned packaging, which meets the basic safety requirements and meets the minimization of the volume of waste generated during the operation of the nuclear facility, as well as establishes the basic safety and radiological protection criteria related to the licensing of initial, intermediate, and final deposits of radioactive waste [10][11].

However, one of the main concerns in the management of radioactive waste derived from the decommissioning of nuclear reactors is how to store the irradiated fuel (Class 3), as it contains radioactive waste of high activity and has a high risk associated with leaks to the environment, which may lead to air, water, and soil contamination. It is important to mention that the RBMN will be a national repository of low and medium levels of radiation (Class 1 and 2) waste and is not designed to store this type of waste. It is up to the installation itself, together with the regulatory body, to build its final high-activity waste deposit.

Another way to recycle irradiated fuels is to use the process known as "Reprocessing", however, Brazil, due to political decisions and international agreements, does not have plans for projects to develop a plant for reprocessing. Generally, irradiated fuels are stored in the reactor pool itself.

The Federal Audit Court (TCU in Brazil) gathered information to identify possible risks and subsidize future control actions for the management of radioactive waste in Brazil and found that there is no law or regulatory standard that establishes the procedures for the management of irradiated fuel and there is no positioning of the country on what the solution to be adopted will be [12].

Although there may be a series of risks associated with the management of radioactive waste, in this work, as a way of exemplifying the use of risk assessment process techniques, the risks associated with assumption that the RBMN or intermediate or final deposits will be operational and will have sufficient capacity for all types of radioactive waste produced during decommissioning (assumption 'c' cited in chapter 3) will be analyzed. These risks are described in the analysis presented in Figure 4.

In this sense, at the end of the installation's life cycle, and after authorization of the FDP by the regulatory body, the decontamination and dismantling process begins. There are several techniques to carry out each process, but strategies based on technical, safety, regulatory and cost considerations should always be considered, each of which will produce a certain amount of radioactive waste. As a result, the techniques to be selected for decommissioning will have a major impact on minimizing waste [13].

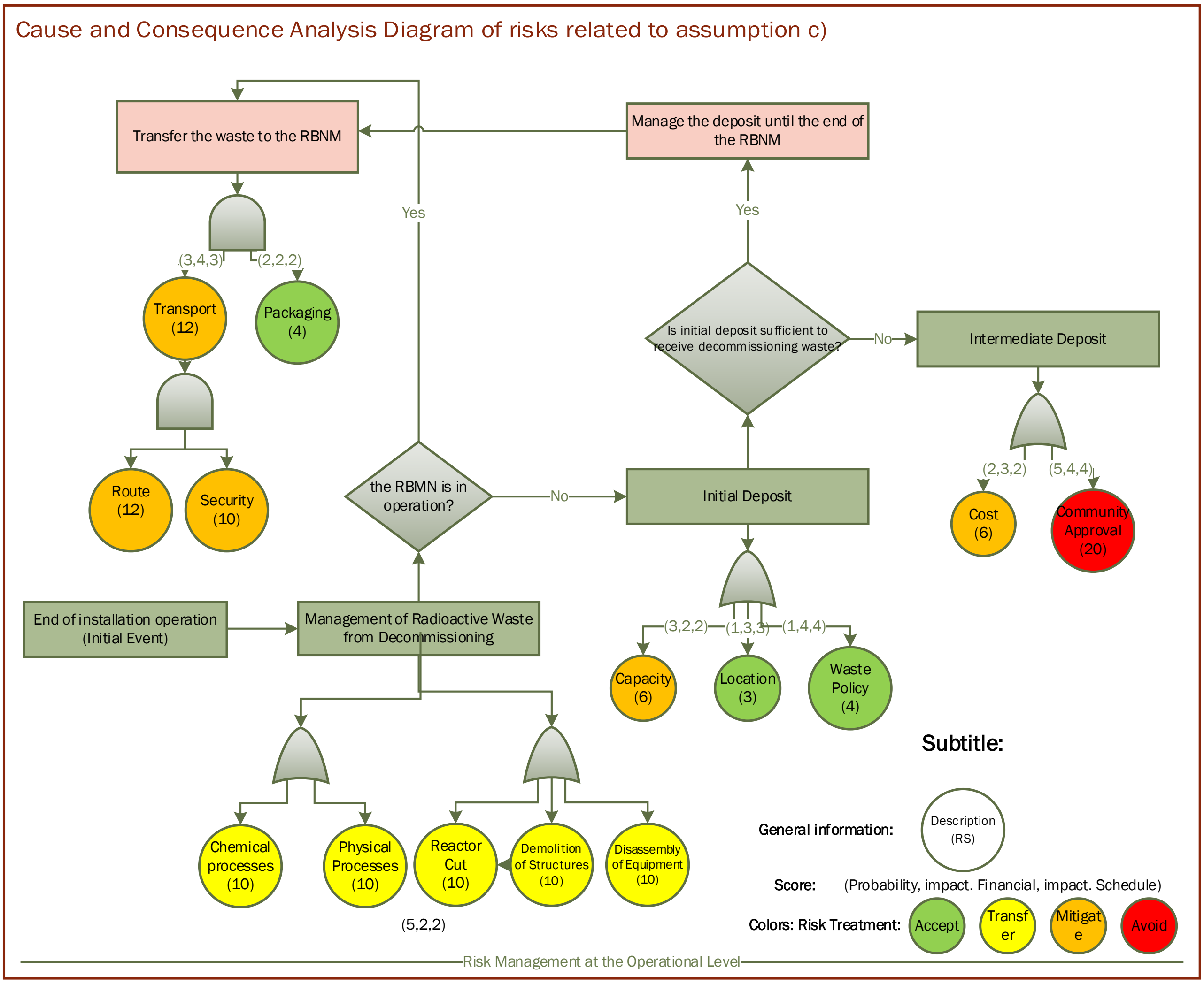
These wastes will initially be stored in the initial deposit of the facility, to be later transferred to the RBMN or intermediate deposits. However, the RBMN is still in the project phase, with no forecast of when it will be in activity. Thus, during the installation's operating life cycle, it is important to follow the evolution of the RBMN construction for strategic decision making and verification of possible associated risks.

Considering the assumption that the RBMN is in operation, before starting the decommissioning phase, the risks of packaging and transporting radioactive waste from the installation to the RBMN site must be analyzed. At this point, attention should be given to the risks associated with the transport route and to the physical security criteria (Security) of the transport of radioactive material. The rate of vehicle accidents on Brazilian roads is high, especially on some routes located close to the reactors installed in Brazil, for example, the road that connects the city of Angra dos Reis-RJ, where the "Central Nuclear Almirante Alvaro Alberto" is located, between March/21 and March/22, there were 10,757 traffic accidents, around 30 accidents per day on average [14].

If the RBMN is not in operation, it will be necessary to manage the radioactive waste in the initial deposit. As decommissioning will generate a lot of waste, the storage capacity, and the possibility of expanding the infrastructure at the site must be calculated, in addition to adopting policies to minimize and segregate the waste generated, even if it is necessary to acquire new equipment. Another condition to be analyzed is, if the RBMN is ready, but the transport routes do not offer sufficient security for transport. In this case, the analysis can confirm that it is more feasible to request the construction of a final deposit close to the installation than to transport it to the RBMN.

In view of the information mentioned above and to simulate the probabilities and consequences, Figure 4 shows the cause and consequence analysis diagram of the risks. Indicating the risk level (defined by the author), using the criteria described in reference 3.

Figure 4: *Cause and Consequence Analysis Diagram of risks related to the assumption that the RBMN or intermediate or final deposits will be operational and have sufficient capacity for all types of radioactive waste produced during decommissioning (assumption 'c')*



Source: [Author]

3.3 Risks associated with Human Resources

Human resources (HR), knowledge management and training are essential for successful decommissioning. As highlighted in the publication “Training and Human Resource Considerations for Nuclear Facility Decommissioning” [15], enough personnel must be available at all stages of the facility's lifecycle, including decommissioning. The operating organization must “ensure that suitably trained, qualified and competent personnel are available for decommissioning”. This document also highlights the importance of requiring actions to be taken by the operating organization to “ensure that institutional knowledge about the facility is recorded and made accessible, and to the extent possible, that key personnel are retained” [15].

However, it is worth noting that there is a big difference in the activities that are carried out by employees during the operation phase and the decommissioning phase. During the operational phase, employees perform routine procedures, with a stable risk profile based on nuclear and radiological risks. On the other hand, in the decommissioning phase, changes are constant, activities are varied, there is a decrease in nuclear risk and industrial risks arise, with the participation of workers from different companies. Thus, the transition from operation to decommissioning requires a transformation in the operator's organizational structure [15].

Regarding human resources, the IAEA publication adopts 4 approaches for operating organizations to carry out decommissioning. The first is that the operating organization itself will carry out the decommissioning activities with the existing staff, thus, a significant reorganization and retraining of the organizational staff would be required [15]. A study carried out by BORMAN F. [16] raised some aspects of HR management in decommissioning in this approach. The study shows that facility employees felt unmotivated because decommissioning is a phase of “elimination” of the facility, and thus, leads to a sense of destruction of their jobs [16].

The second approach is for the operating organization to retain control of the project but outsource decommissioning activities. The third is for the operating organization to hire a specialized outsourced company and work in partnership. And the fourth is when the operating organization transfers the responsibility for decommissioning to a specialized company, in which case the specialized knowledge in decommissioning would need to be complemented by the specific knowledge of the installation. At this point, the protection of intellectual property and knowledge should be considered [15].

The factors for choosing an approach will depend on the size of the decommissioning project and whether transfer of license or responsibility is allowed. Regardless of the approach chosen, the knowledge and history recorded during the operation phase must be available for the decommissioning phase [15]. The HR management approach to be chosen to carry out decommissioning is typically defined during the preparation of the IDP, which is maintained and updated throughout the life of the facility. At this point, regardless of the choice made, it is possible that changes may be necessary over time.

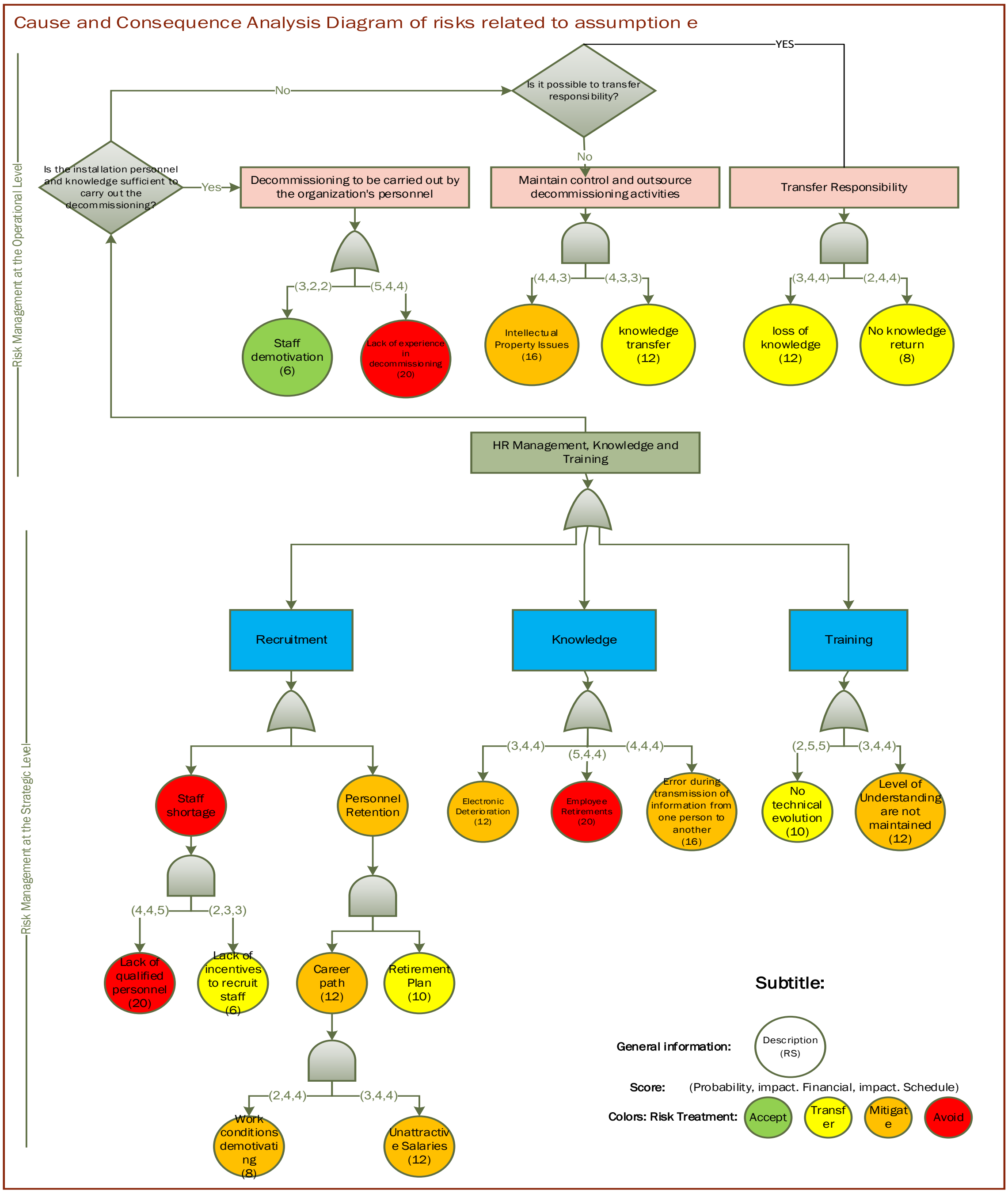
In Brazil, there is RN CNEN NN 9.01, which provides for the decommissioning of nuclear power plants. Item d) of Section II of this standard requires the operating organization to submit the FDP to CNEN, two years before the end of the operation, covering a series of requirements, including the preparation of a decommissioning management plan, containing an organizational structure, responsibilities, necessary human resources, and adequate training [17].

Another point to be analyzed in the Brazilian context is the lack of qualified personnel to work in the nuclear area. As most of the bodies that work in the nuclear area are state or government institutions (since the Government has a monopoly on nuclear activities in Brazil), to join the body of these institutions, it is necessary to carry out "public tenders". An example is the Nuclear Energy Research Institute (IPEN/CNEN), which has been losing highly trained and experienced employees, without replacement and transfer of this knowledge.

Human resource training is also essential for the completion of decommissioning. Employees who will carry out decontamination and decommissioning activities must have technical knowledge of the technology adopted, for example, skills for robotic remote handling of cutting, packing, and removal of highly radioactive components and removal of heavy components with cranes. In addition to knowledge in the areas of quality assurance, health, safety, and industrial safety (training of scaffolding and ladders, confined spaces, risks and hazards, fire protection, electrical safety, handling of hazardous materials, etc.) [15].

Although there are several risks associated with human factors, knowledge and training, this work will analyze the possible causes and consequences regarding assumption that experienced and trained human resources will be maintained at the facility and new employees will always be hired and trained to replace them (assumption 'e' cited in chapter 3). In this sense, Figure 5 illustrates the Cause and Consequence Analysis diagram of the risks associated with this assumption.

Figure 5: *Cause and Consequence Analysis Diagram of risks related to the premise that experienced and qualified human resources will be kept at the facility and new employees will always be hired and trained to replace them (assumption 'e')*



Source:[Author]

3.4 Technological Risks

The main components to be dismantled in a nuclear reactor are: the pressure vessel, steam generator, cooling pump, and pressurizer. The dismantling of these components is performed under a high dose of radiation, being very dangerous. Thus, the use of technological resources helps to carry out safe and economical decommissioning in order to remove all radioactive material from the reactor.

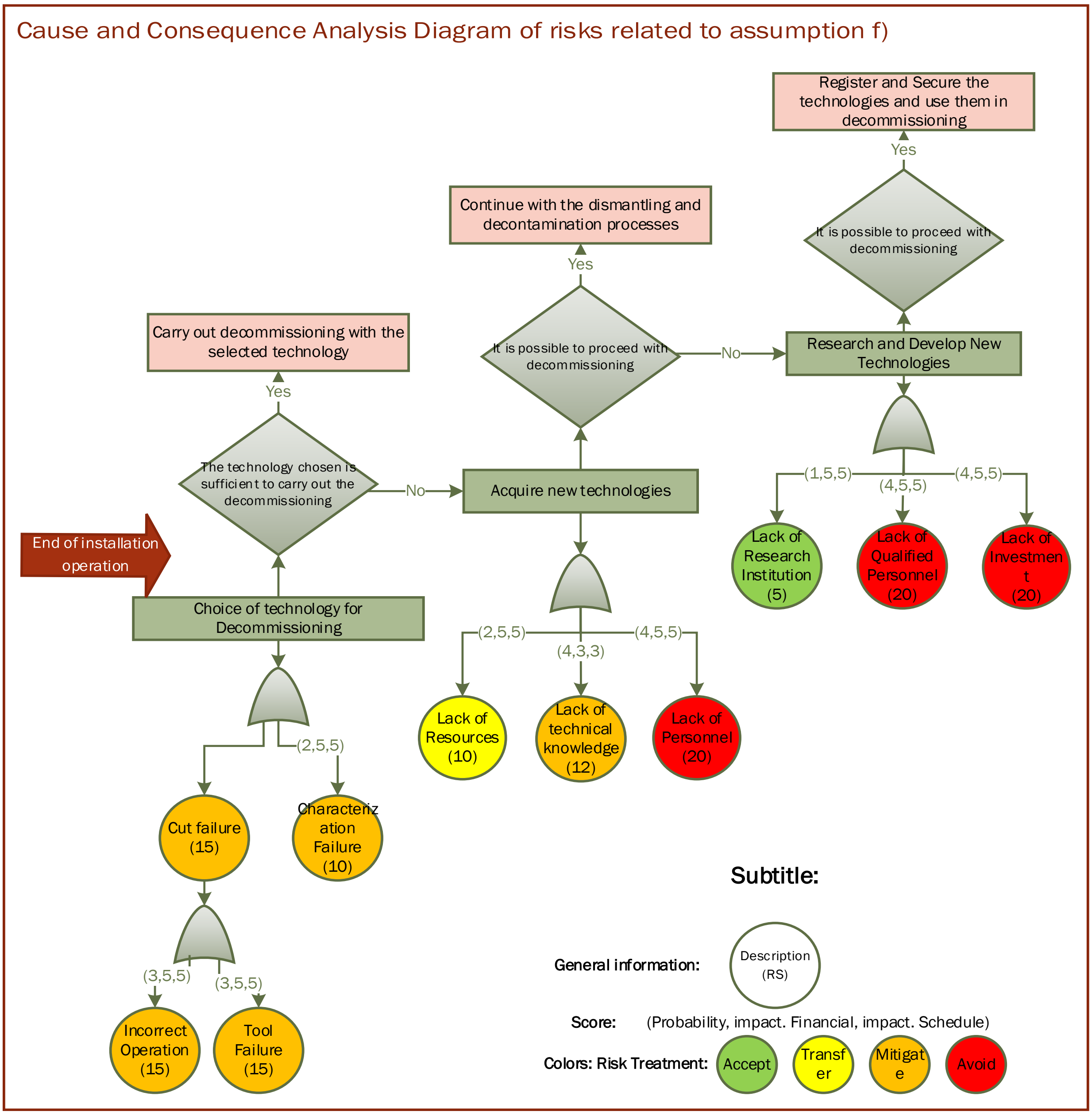
Between 1980 and 1990, several decommissioning technologies were based on experience gained in activities that were not related to the nuclear area. With the escalation of decommissioning after 1990, there were optimizations of these technologies and the emergence of new ones, resulting in a broad standardization of the technology applied to decommissioning. At this point, it has been demonstrated that there are technologies available to handle almost all types of decommissioning operations. Nevertheless, even considering that the technology is available, some technical problems may arise, and research and development activities may be necessary to solve them [18].

The select of technology depends on a number of factors, such as the decision on the decommissioning strategy, the physical condition of the facility, radiological status, operational history, accessibility of technologies, cost, safety, and regulation [19]. In general, these technologies are used to apply decontamination and dismantling techniques in decommissioning processes.

Decontamination is defined as the removal or reduction of radioactive materials, which may also contain hazardous materials (explosive, corrosive, toxic), from surfaces of equipment or structures through chemical, electrochemical, thermal, or other techniques. Dismantling is the process of dismantling and demolishing components and structures. Structures can be made of concrete or metal (e.g. stainless steel, cast iron, aluminum) and of varying shape, size, and thickness and therefore require specific technologies. Cutting techniques can be thermal (laser, flame cutting, plasma cutting) or mechanical (saws, diamond wire, high pressure water jet, etc.). Potentially dangerous tasks require remote operations or specialized processes. [20] [21].

In view of the above, it is possible to analyze several risks that may be associated with the technology, in order to exemplify one of the possible risks, the risk described in the assumption that the proposed decommissioning technologies will be sufficient for the actions of dismantling and decontamination safely (assumption 'f' cited in chapter 3). This risk is cited in Figure 6, that illustrates the analysis performed by the author.

Figure 6: *Cause and Consequence Analysis Diagram of risks related to the premise that the proposed decommissioning technologies will be sufficient for the safe dismantling and decontamination actions (assumption 'f')*



Source:[Author]

4. CONCLUSION

For nuclear reactors, decommissioning is the final phase of the life cycle after construction, commissioning, operation, transition, and shutdown. It is a process that involves a wide range of technical (decontamination, decommissioning, radioactive waste management) and administrative (financial resource management, human resources, and knowledge management) activities, always considering the protection of health, safety, and of the environment.

The decommissioning process could take decades to complete, in this sense, all efforts must be made by the generation that used the technology to leave everything “well done” for the solution of the problem after the installation is shutdown. The alternative of leaving the problem of decommissioning to future generations is not politically acceptable, as there are no reasonable guarantees that future generations will be able to manage them properly, and it is unethical to use the benefits of technology and not solve the problem, especially waste that was generated.

Another important point is the time that the waste will be stored and the regulatory adaptations that may be necessary during this time. Today, with current technologies, there are predictions of storage for millions of years. A time much longer than the existence of homo sapiens (200 thousand years) and the emergence of Nation-States. Nothing guarantees that 1,000 years from now everything will have changed.

The IAEA has been strongly active in this area and has identified the need to analyze practical guidance on risk management in decommissioning projects in order to obtain the benefits of applying risk management techniques and help ensure decommissioning plans (IDP and FDP) more realistic as well as support the completion of decommissioning objectives in a timely and cost-effective manner.

It is important to emphasize that risk management involves carrying out a thorough analysis of the context to identify threats and opportunities, this work analyzed only a few risks that must be considered considering the Brazilian scenario. The approach of a specialized team may have discrepancies, but this work serves as a reflection on the subject and may serve as a basis for carrying out more complete risk analyses on the subject.

This work also identified some gaps in the Brazilian scenario that need to be better analyzed for more robust development of nuclear reactor decommissioning projects, of which the following stand out:

a) develop a national policy for the management of radioactive waste, contemplating the strategy to be adopted, mainly on irradiated nuclear fuel;

b) regulation of the decommissioning of research reactors.

c) adoption of strategies to ensure that nuclear facilities ensure the collection of financial resources to be used in decommissioning and, at the end of their useful life, if this is not sufficient, provide a support mechanism so that decommissioning activities are not interrupted.

d) adoption of personnel management and knowledge management policies at nuclear facilities to encourage employees to continue at the facility and promote appropriate career paths.

e) adoption of mechanisms to encourage science, research, and innovation in decommissioning and to protect technological knowledge; and

f) develop a robust system of awareness and communication with the Brazilian population in order to clarify the benefits and limitations of nuclear technology.

In view of the above, the decommissioning action is an important process in the life cycle of a nuclear installation. Thus, being well executed and planned, it will show society that it is possible to make the most of the benefits of nuclear technology and return to the site without presenting any risk to the public and the environment. Lessons learned from the growing experience of decommissioning and applicability in many nuclear projects allow advances in the state of the art and promote development necessary to solve complex challenges existing in decommissioning. There is a horizon of information regarding the topic and a good opportunity to study strategies, good practices and lessons learned.

5. REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, **Decommissioning of Facilities**, General Safety Requirements Part 6, VIENNA. 2014.

[2] COMISSÃO NACIONAL DE ENERGIA NUCLEAR. **Gestão Dos Recursos Financeiros Destinados ao Descomissionamento De Usinas Nucleoelétricas**. CNEN-NN-9.02, Rio de Janeiro, Brasil, 2016.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, **Management of Project Risks in Decommissioning**, Safety Reports Series Nº 97. Vienna. 2019.

[4] INTERNATIONAL ATOMIC ENERGY AGENCY. **Safety Considerations in the Transition from Operation to Decommissioning of Nuclear Facilities**: IAEA Safety Report Series No. 50. IAEA. Viena, 2007.

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, **DRiMa Project, International Project on Decommissioning Risk Management,** Viena, (2017).

[6] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **Gestão de risco: técnicas para o processo de avaliação de risco**. Rio de Janeiro, 2012. (NBR ISO/IEC 31010).

[7] PERRET R., SLOAN R., ROSNER R., **Decommissioning the U.S. nuclear fleet: Financial assurance, corporate structures, and bankruptcy**. Energy Policy, USA, 2021.

[8] LAGUARDIA, T.S., MURPHY K.C. - **Financing and economics of nuclear facility decommissionin**. LaGuardia and associates LLC, USA, 2012.

[9] VICENTE R. – **Gestão de Rejeitos Radioativos na industria, medicina e pesquisa**. Material de Sala de aula, São Paulo-SP, 2022.

[10] COMISSÃO NACIONAL DE ENERGIA NUCLEAR. **Gerenciamento de Rejeitos Radioativos de Baixo e Médio Níveis de Radiação**. CNEN-NN-8.01, Rio de Janeiro, Brasil, 2014.

[11] COMISSÃO NACIONAL DE ENERGIA NUCLEAR. **Licenciamento de depósitos de rejeitos Radioativos de Baixo e Médio Níveis de Radiação**. CNEN-NN-8.02, Rio de Janeiro, Brasil, 2014.

[12] BRASIL. TRIBUNAL DE CONTAS DA UNIÃO. Levantamento: **Identificação de riscos acerca do gerenciamento seguro de rejeitos radioativos e de combustível nuclear usado. Determinações. Recomendações. Arquivamento**. Brasília: TCU, Entidades: Comissão Nacional de Energia Nuclear; Eletrobrás Termonuclear S.A, 2013.

[13] INTERNATIONAL ATOMIC ENERGY AGENCY. **Methods for the Minimization of Radioactive Waste from Decontamination and Decommissioning of Nuclear Facilities**: IAEA Technical Reports Series No. 401. IAEA. Viena, 2001.

[14] BRASIL, MINISTÉRIO DA INFRAESTRUTURA. **Registro Nacional de Acidentes e Estatísticas de Trânsito** Disponível em: < https://www.gov.br/infraestrutura/pt-br/assuntos/transito/arquivos-senatran/docs/renaest> Acesso em: 28 de julho de 2022.

[15] INTERNATIONAL ATOMIC ENERGY AGENCY. **Training and human resource considerations for nuclear facility decommissioning**: IAEA Nuclear Energy Series No. NG-T-2.3(Rev1). IAEA. Viena, 2022.

[16] BORMAN F., **Knowledge management toward, during, and after decommissioning**. iUS Institut für Umwelttechnologien und Strahlenschutz GmbH, Alemanha, 2017.

[17] COMISSÃO NACIONAL DE ENERGIA NUCLEAR. **Descomissionamento de usinas nucleoelétricas**. CNEN-NN-9.01, Rio de Janeiro, Brasil, 2012.

[18] LAIARA M., **Introduction to nuclear decommissioning: definitions and history**. AIEA, Austria, 2012.

[19] McINTYRE P. J., **Nuclear decommissioning policy, infrastructure, strategies and project planning**. Carnatic Solutions Ltd, UK, 2012.

[20] NOYNAERTE L, **Decontamination processes and technologies in nuclear decommissioning projects**. SCK•CEN, Bélgica, 2012.

[21] STEINER H., **Dismantling and demolition processes and technologies in nuclear decommissioning projects**. Kernkraftwerk Gundremmingen, Alemanha, 2012.