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Comparison of Estimates of Costs involved between two Decommissioning Strategies for PWR type Nuclear Power Plants

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ABSTRACT

This work compares the project costs of two possible decommissioning strategies for a hypothetical nuclear site with similar characteristics to the CNAAA reactors. The cost of the process is sensitive to the type of strategy adopted, as the type of strategy involves the duration of the process. Defining project strategy/duration and estimating cost are part of a coupled problem. Thus, decommissioning cost is a relevant step and needs to be rigorously defined before starting the decommissioning process, as demobilizing teams/equipment, and remobilizing entail extra costs. Cost estimates follow the Av-Descom model. Tool easily implemented by a spreadsheet-like code. Among the stages of the two strategies presented, the one with the greatest impact on the cost of the project is the stage referring to the transition period comprised by the decontamination tasks of the systems, equipment, and structure of the deactivated NPP. This step exposes workers to radiation doses and to the greatest occupational hazards. It was observed that the cost variation from one strategy to another is above 50% of the total cost of the project. It was concluded that defining the best decommissioning strategy is complex and important to be defined from the beginning of the decommissioning process. It was inferred that the strategy that best fits the Brazilian reality is the delayed decommissioning.

Keywords: **decommissioning, nuclear power plant, costs estimation, strategy decommissioning.**

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1. INTRODUCTION

Coal, gas, and nuclear power plants have finite activities beyond which it is not economically attractive to operate them. In theory, the first nuclear power plants were designed for a life of about 30 years, and, in some cases, many plants were able to operate for a period much longer than the initial design. Newer plants are designed for a lifespan of around 40 years, in some cases extended to another 20 years. At the end of the useful life of any plant, it needs to be decommissioned, cleaned and demolished so that the site can be made available for other purposes [1].

The term decommissioning, for nuclear power plants, includes all cleaning up of radioactivity and the progressive dismantling of the power plant. For practical purposes, it includes fuel removal and coolant removal, although the NRC (Nuclear Regulatory Commission) defines it as strictly starting only after the fuel and coolant are removed. The process is completed with the termination of the license after the decontamination is verified and the residues removed [2,3].

The operations of power reactors began in the 1950s, shortly after the Second World War, and, with the estimated useful life of these reactors around 40 years, in some cases being extended for another 20 years, several plants had their activities ended in the 1990s. Between 1970 and 2000, the USA carried out several studies in order to establish technology, safety and costs associated with the decommissioning process of different types of reactors [4].

There are three possible decommissioning strategies, namely: (1) immediate decommissioning (decom), (2) delayed decommissioning (safstor) and (3) containment (entomb). The first strategy (decom) envisages that all equipment, structures and parts of the plant containing radioactive contaminants are removed or decontaminated shortly after the closure of plant operations to levels that allow the site to be cleared for unrestricted or restricted use. In the second strategy (safstor), the process takes place after a Safe State Period (SSP) - defined as the maintenance of the NPP (Nuclear Power Plant) deactivated, equipment and facilities so that there is no spread of radionuclides in the environment, during which the NPP remains deactivated so that the radiological activity drops to levels that allow the dismantling at lower doses of radiation for the work teams. The last strategy (entomb) is only used in cases where the confinement time is practically indeterminate, for example, accidents such as CHERNOBYL and FUKUSHIMA I, in which radioactive systems, structures and components are confined in structures, or sarcophagi, of concrete. The three strategies exposed are defined in detail in CNEN resolution 133/2012.

For each type of strategy adopted by the operating organization there will be an associated cost. Resolution CNEN 133/2012 stipulates that the operating organization must present the Preliminary and Final Decommissioning Plans for the plant in accordance with the strategy used.

For this work, the steps related to the decommissioning process and the cost estimates associated with a hypothetical Nuclear Power Plant (NPP) with the same characteristics of the interdependent nuclear plants of the Central Nuclear Almirante Álvaro Alberto (CNAAA) will be presented, classified as: NPP1 – Angra 1, NPP2 – Angra 2 and NPP 3 – Angra 3 with PWR type reactors. As these factories share part of the resources necessary for their operation and support facilities (operational and management teams, laboratories, workshops, warehouses, as well systems/structures) they are therefore considered interdependent. Only Angra 1 and 2 share systems/structures, such as the discharge of hot water from condenser cooling. Consequently, the decommissioning of an interdependent plant directly interferes with the operations of the other plants (either in the commercial operation of Angra 2 or in the construction of Angra 3).

The costs presented in Tables 4 and 5 refer to the comparison of cost estimates between the main decommissioning strategies, DECON and SAFSTOR, for a hypothetical multi-reactor plant with characteristics similar to the Brazilian ones. The cost estimate is given by the Av-Descom model. This is the tool for calculating the costs associated with decommissioning strategies and was implemented by a spreadsheet-like code (Excel - 2016) [5,6,7,8].

Therefore, the results of Tables 4 and 5 are based on data provided by the reports of the operator of the Almirante Álvaro Alberto Nucleoelectric Center (CNAAA), taking into account the international experience of the regulatory guide 1.202, Standard Format and Content of Decommissioning Cost Estimates for Nuclear Power Reactors [2].

The relevance of this work is to compare possible impacts on the cost of projects based on the type of strategy that the operator will adopt for the decommissioning process. The cost of the process is directly affected by the decommissioning strategy adopted, as it affects its duration. Therefore, the definition of project strategy/duration and cost estimates are part of a coupled problem. Therefore, the cost of decommissioning is an important parameter that must be rigorously evaluated before the start of the process, since the financial contribution needs to be sufficient to cover the entire decommissioning process, and thus avoid the need to demobilize teams, equipment and remobilize after a period, as this will imply new costs.

2. MATERIALS AND METHOD

2.1 Decommissioning Strategies

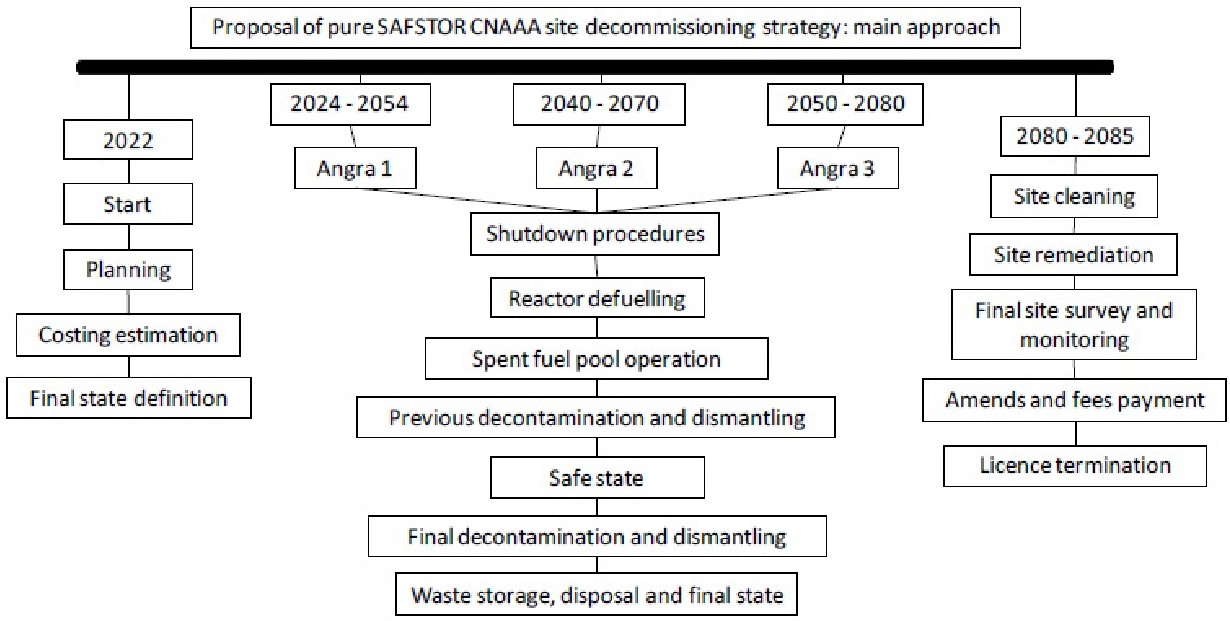
Since the beginning of the nuclear industry, there are 3 types of main strategies in the literature in the decommissioning phase and adopted worldwide in nuclear reactor projects. The difference from one process to the other is given by the need for time, radiological risks and costs. All of them must take into account the ALARA (As Low As Reasonable Achievable) principles [5-7]. The national normative base CNEN nº 133/2012 defines these strategies in the following acronyms: DECON, SAFSTOR and ENTOMB [3]. Even with different approaches, the strategies share common tasks, such as: planning, NPP shutdown sequence, site decontamination, disassembly, waste disposal, among others [9,10].

Taking into account the characteristic profile of Central Nuclear Almirante Álvaro Alberto (CNAAA) and the main requirements of the Brazilian CNEN bidding rules, the SAFSTOR strategy is the one that presents the best cost-benefit. In the SAFSTOR strategy, the NPP (Nuclear Power Plant) is placed in a safe state for a long enough period so that the activity of the radio nuclides (radioactivity) contained in the plant decreases to levels with lower doses of radiation in the work teams according to the CNEN Standard 3.01/2014 [11]. The estimated time variation is in the range of 10 years to decades, in general a time of 30 years is stipulated. Despite longer downtime than DECON, the lower activity level makes tasks easier, resulting in lower costs. On the other hand, the costs with security teams, activity monitoring and eventually maintenance increase [5]. Other restrictions are: NPP shutdown schedule and final state of the field.

The schematic representation of the dates referring to the CNAAA decommissioning schedule, following the SAFSTOR (main l and alternative approach) and mixed decommissioning DECON + SAFSTOR strategies, is represented by figures 1, 2 and 3 based on the work [5]. As shown below:

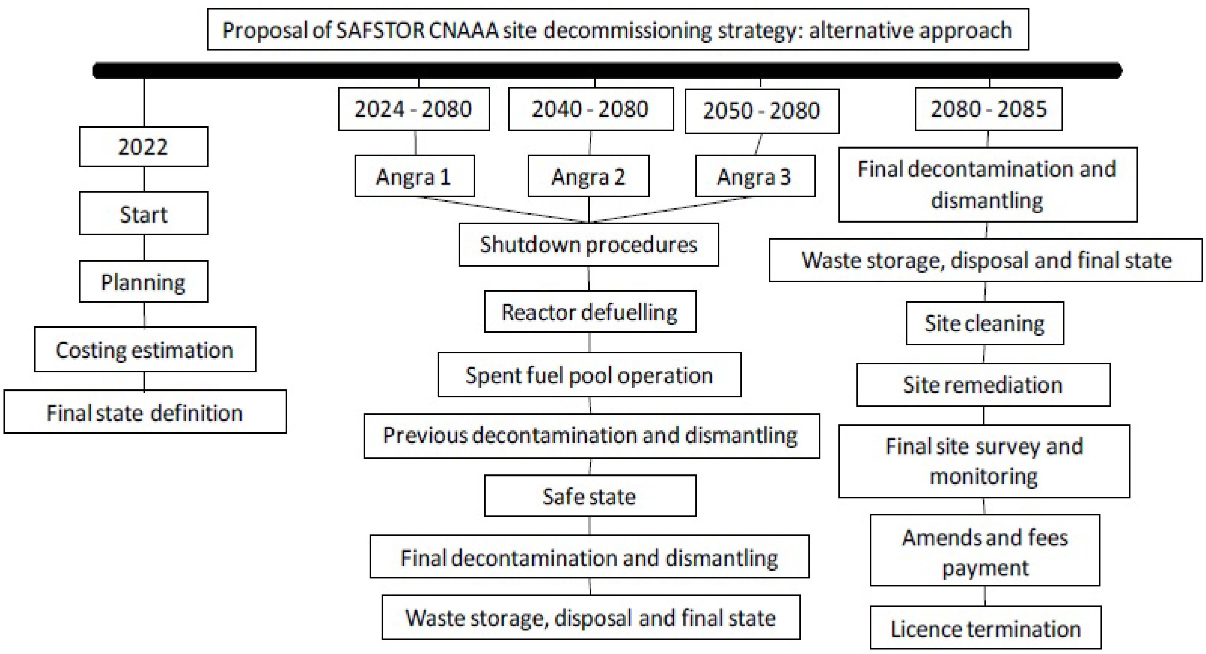
Source:

Figure 1 - *Main Program SAFSTOR CNAAA*



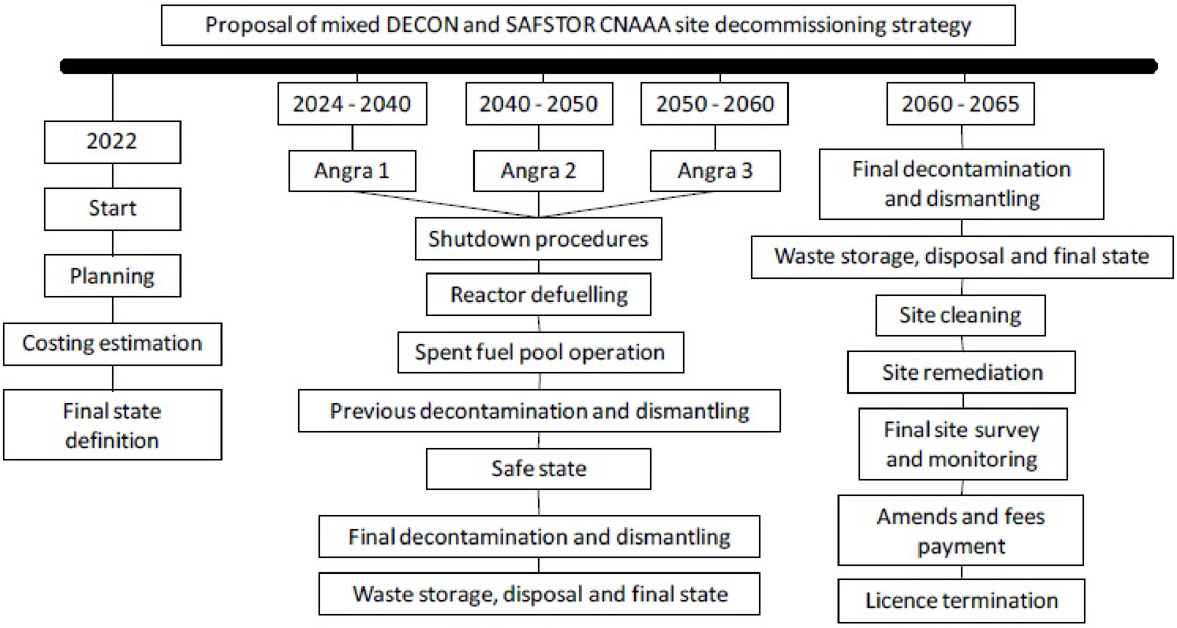
MONTEIRO, D.B.; MOREIRA, João M.L.; MAIORINO, José R. [5]

Figure 2- *Alternative Schedule SAFSTOR CNAAA*



Source: MONTEIRO, D.B.; MOREIRA, João M.L.; MAIORINO, José R. [5]

Figure 3 - *Timeline with mixed strategies DECON + SAFSTOR*

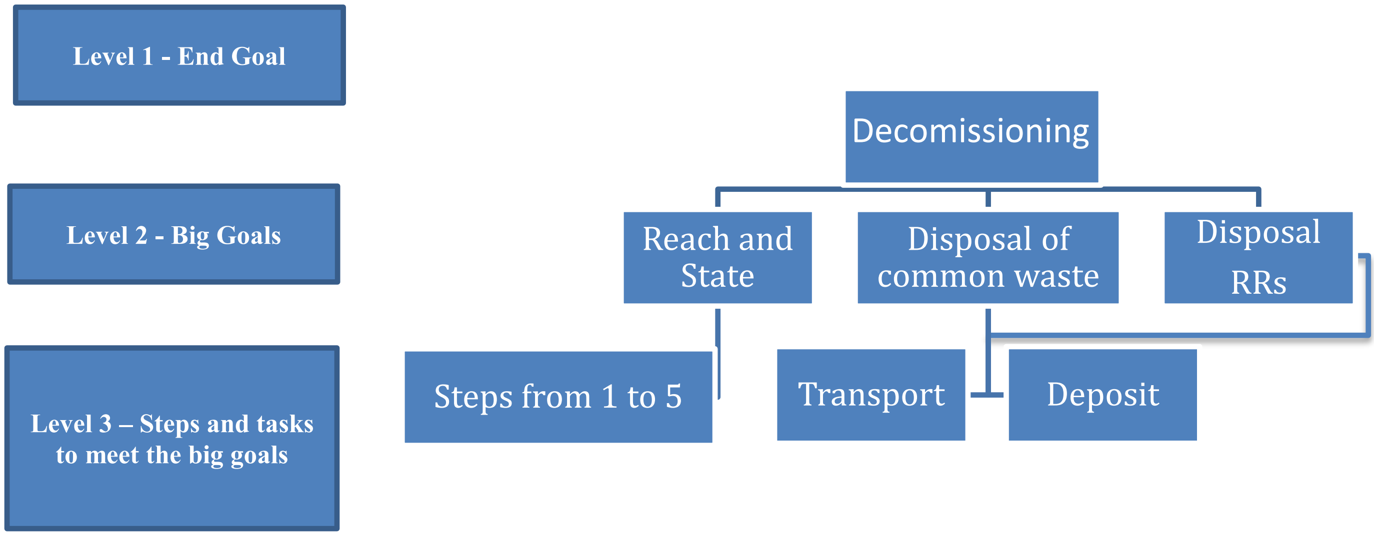


Source: MONTEIRO, D.B.; MOREIRA, João M.L.; MAIORINO, José R. [5]

2.2 Decommissioning Steps

The main steps of the decommissioning process are specified below, considering the main details of each strategy that must be adopted until the complete cleaning of the site. In figure 1, it represents the detail of the decommissioning process according to the level of the objectives related to each phase.

Figure 4 - *Detailing of the Decommissioning process*



Source: MONTEIRO, D.B[7]

Tables 1, 2 and 3 show, respectively, the variations from 1 to 5 of the Main Decommissioning Stages, the Correlation between Stages and Tasks in the decommissioning process and Tasks related to the removal of Radioactive and Common Waste.

Table 1 - Main Stages of the Decommissioning Process

Steps	**Main Stages of the Decommissioning Process**
	Process Steps
1	Decommissioning pre-planning
2	Transition period between commercial operation and decommissioning
3	Period of *Safe Storage*
4	Decontamination and dismantling of NPPs and support facilities, removal of radioactive waste
5	Demolition of conventional buildings, removal of common RRs and restoration of the site, according to the final state defined

Table 2 – Correlation between Decommissioning Steps and Tasks

STEPS	**TASKS**
Step 1 (Decommissioning pre-planning)	Planning
	Infrastructure
Step 2 (Transition period)	Permanent Termination of the NPP
Step 3 (Safe state period - *Safe Storage*)	Physical security of the site and plants
	Maintenance of structures and equipment
	Storage of RRs on site
Step 4 (Decontamination and Dismantling – D-D)	Decontamination
	Dismantling
	Treatment and storage RRs
	Purchase of materials and supplies
Step 5 (Site completion and restoration)	Termination of licenses, payments
	Demolition of buildings and site restoration

Table 3 – Tasks relating to the removal of radioactive and common waste.

Common Waste	**Packing and Transport**
	Off-site disposition
Radioactive Waste	**Packing and Transport**
	Off-site disposition

The phases and steps presented so far are important for planning the costs involved in the process of deactivating a nuclear site. The modeling of these costs will be detailed in the next item, which will present the main variables important for cost estimation according to the DECON and SAFSTOR strategies, presented in Tables 4 and 5, respectively.

2.3 **Equation**

The general total cost of decommissioning (CD) model will follow the model proposed by *Jeong et al.* [12]:

$$CD = \sum_{i=1}^{n} C_i \tag{1}$$

Where, C_i is a set of tasks, and the total cost is the sum of these groups that we can list below:

1) Project Preparation and Management;

2) Plant shutdown;

3) Decontamination and Dismantling;

4) Tailings handling and management;

5) Site restoration;

6) Other activities.

The global CD cost modeling proposed in detail by [6] takes the form:

$$CD_n = \sum_{i=1}^{5} C_{Ei} + C_{TRR} + C_{DRR} + C_{TRC} + C_{DRC} \quad (2)$$

C_{Ei}, $i = 1, \dots, 5$ represent the costs of the 5 steps of the entire decommissioning process. In accordance with Monteiro et al, the main steps of the decommissioning process are: Planning (Step 1), Transition (Step 2), Safe Storage Period - SAFSTOR (Step 3), Decontamination and Disassembly (Step 4), Process Finishing (Step 5) [6]. C_{TRR} is the cost of transporting radioactive waste. C_{DRR} is the cost of disposing of radioactive waste. C_{TRC} is the cost of transporting conventional waste. $C_{DRC}$is the cost of final disposal of conventional waste [7,6].

The cost estimate is given by the Av-Descom model. This model was developed by Monteiro et al. considering the decommissioning of a hypothetical site of a multiple reactor with n interdependent plants, that is, based on national experience $n = 3$ (Central Nuclear Almirante Álvaro Alberto - CNAAA).

We note that CD_n is the decommissioning cost of each plant belonging to the site. For each plant the cost can be obtained by the equation:

$$CD_{Sítio} = \sum_{n=1}^{3} CD_n \quad (3)$$

Considering that there will be no interruption in the project [7].

3 ANALYSIS AND DISCUSSION OF RESULTS

The cost estimates presented in Tables 4 and 5, below, are based on the Av-Descom model developed by Monteiro et al., considering the decommissioning of a hypothetical site for a multiple reactor with interdependent plants and with particularities close to the Nuclear Power Plant. Admiral Álvaro Alberto - CNAAA.

Table 4 – Cost table using Strategy DECON [7]

Decommissioning objectives / steps			NPP1	NPP2	NPP3	SITE
End	**Big Goals**	**Steps**	**Strategy DECON**			
			Costs are given in millions/US$x10^6			
DECOMMISSIONING	**Reach End State**	**Step 1**	134,6	121,0	126,7	382,4
		Step 2	16,1	15,8	16,6	48,5
		Step 3	-	-	102,7	102,7
		Step 4	400,5	403,7	424,9	1.229,1
		Step 5	6,0	5,7	3,5	15,2
	Common waste disposal	**Treatment**	-	-	-	-
		Transport	-	-	-	-
		Deposit	7,6	8,6	8,6	24,8
	RRs Disposition	**Treatment**	1,6	1,8	32,5	35,9
		Transport	15,8	18,1	18,2	52,1
		Deposit	24,4	27,9	27,9	80,2
Total			606,6	602,7	761,7	1.971,0

Table 5 – Cost table using Strategy SAFSTOR [8]

Decommissioning objectives / steps			NPP1	NPP2	NPP3	SITE
End	**Big Goals**	**Steps**	**Strategy SAFSTOR**			
			Costs are given in millions/US$x10⁶			
DECOMMISSIONING	**Reach End State**	**Step 1**	14,4	19,5	169,2	203,1
		Step 2	15,5	15,2	14,4	45,2
		Step 3	-	-	138,5	138,5
		Step 4	102,3	112,9	134,0	349,1
		Step 5	-	-	5,8	5,8
	Common waste disposal	**Treatment**	-	-	-	-
		Transport	-	-	-	-
		Deposit	7,6	8,6	8,6	24,8
	RRs Disposition	**Treatment**	1,6	1,8	22,2	25,6
		Transport	15,8	18,1	18,5	52,4
		Deposit	16,4	33,4	33,4	83,2
Total			173,5	209,5	544,6	927,6

In Table 2, it can be seen that Step 4 (step specified in Table 1) contributes to a higher cost of the decommissioning process for all NPPs. It is attributed to the fact that this stage in this type of strategy is the one that presents the greatest degree of difficulties in the execution of the tasks. Similarity is observed in the distribution of costs related to the plants, this similarity is attributed to the dismantling of each of the NPPs and their respective support facilities independently, requiring a greater number of teams and less sharing between tasks.

Another relevant point for the strategy adopted, DECON, in Table 2 is how to arrange the decommissioning schedule of the NPPs. As it is a site with 3 interdependent plants, it is proposed that the duration of the process follows the schedule of NPP3, in such a way that NPP1 is dismantled in stages due to the large number of interdependencies with NPP2. Only in this way will it be possible to independently decommission and release the site in a minimum amount of time.

Comparing the cost values presented between the strategies in Tables 4 and 5, it is observed that the costs related to the SITE decommissioning stages are significantly lower for the strategy in

Table 5. In the strategies presented, the stage with the greatest impact on the project costs is step 4. According to the distribution of the steps in Table 1, this is the step related to the transition period comprised by the decontamination tasks of the systems, equipment, and structure of the deactivated NPP, which is the step that exposes workers to doses radiation and the greatest occupational hazards. The degree of complexity of step 4 is the most aggravating, when compared to other steps, and depending on the type of strategy adopted, the related costs will also be higher. By the values presented in Tables 4 and 5, the cost variation from one strategy to another is above 50% of the total cost of the project. [7]

It is worth noting that the interdependencies between the plants significantly affect the total costs of the project. This is attributed to shared costs being mainly allocated in the NPP3 cost estimates. Thus, it can be concluded that the interdependence between the plants needs to be considered, as they significantly impact the cost schedule of the decommissioning process of each plant.

Another important cost estimate for the two strategies presented is related to phase 3 of the decommissioning process. This is the PES phase, Safe Storage Period, referring to physical security tasks, maintenance of structures and equipment and storage of Radioactive Waste (RRs) at the site. It is observed that there is no cost estimate associated with NPPs 1 and 2 in phase 3, in fact, the costs of physical security, maintenance and radiation protection teams are all allocated in the NPP3 cost estimate, mainly during the SAFSTOR period.

Brazil's biggest problems will face to decommission the CNAAA site is in relation to the interdependencies with the plants, mainly, Angra 1 and 2 that keep a greater number of interdependencies with each other and their physical proximity and sharing of systems.

Given the above, it is clear that defining the best strategy to be adopted by the operating company (Eletronuclear), considering the lowest cost-benefit, is complex and needs to be carefully evaluated before starting the process. According to Monteiro, the strategy that best fits the Brazilian SITE is SAFSTOR [7].

4 CONCLUSION

In the brief comparison between the two strategies presented, it was found that the Immediate Decommissioning strategy (DI/decon) does not present significant advantages in relation to the Delayed Decommissioning strategy (DP / safstore.). The first disadvantage is the high cost of the project, exceeding more than 50% of the total value of the site, as well as the release of the site cannot be anticipated since it is dependent on the NPP3 process.

The results between the costs show that the interdependencies plants can significantly change the processes. Another relevant point is considered as Decontamination and Decommissioning activities (Estage4) more important for the two strategies associated with this preliminary analysis.

Finally, this work is part of a brief analysis of what exists within the Brazilian literature based on international experiences related to costs and associated as hypothetical studies adopted in NPP projects.

In the future, it is intended to present other important factors for analysis, such as the impacts on project costs considering the influence of Radioactive Waste (RRs) classes and associated impacts on decommissioning costs from hybrid variations between strategies for sites with profile of the Almirante Álvaro Alberto Nuclear Power Plant (CNAAA) presented here preliminarily.

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