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GUIDELINE FOR THE DEVELOPMENT OF PRELIMINARY DECOMMISSIONING PLAN FOR THE REACTOR IPEN/MB-01

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Abstract
The Brazilian Nuclear and Energy Research Institute (IPEN - Instituto de Pesquisas Energéticas e Nucleares) has two research reactors, one of them is the IPEN/MB-01 Reactor. None of these reactors, as well as other Brazilian nuclear facilities, have a plan for decommissioning, even in a preliminary level. In Brazil, there is only one regulation that specifically addresses the decommissioning of nuclear power plants. The aim of this work is to present the current stage of the study as a guideline for the development of a preliminary decommissioning plan of IPEN/MB-01 reactor, highlighting the main proposed procedures. The preparation of these guideline, as a whole, are based on the technical documentation (SAR – Safety Analysis Report), on National Nuclear Energy Commission (CNEN) existing standards and on recommendations of IAEA publications. The preliminary decommissioning plan presents the actions and steps required, as well as the strategies to be adopted for the shutdown of the facility, in order to meet the workers and the general public safety and health, besides minimizing environmental impacts. The contribution of this paper intends, also, to meet a regulatory requirement of CNEN (Brazilian Nuclear Energy Commission) for the facility final shutdown, besides being a reference in the developing of other decommissioning plans for other national facilities..

Keywords
decommissioning plan; decommissioning strategies; waste management

1. Introduction

The Brazilian Nuclear Program has progressed in the past 60 years, resulting in six existing reactors; there is another under construction the ANGRA-III. Table 1, in the sequence, shows the general characteristics of the existing nuclear installations in Brazil.

Table 1. Brazilian Nuclear Facilities [1].

Reactor	Sorting	Type	Power	Operation age (years)
IPEN/MB-01	Research Reactor	Zero Power	100W	26
IEA-R1	Research Reactor	Pool	5MW	57
ARGONA-UTA	Research Reactor	Argonaut	500W	50
IPR-R1	Research Reactor	Triga Mark I	100kW	54
ANGRA I	Nuclear Power Plant	PWR	640MW	29
ANGRA II	Nuclear Power Plant	PWR	1350MW	13
ANGRA III*	Nuclear Power Plant	PWR	1405MW	---------------------

*under construction

With the establishment of CNEN, in 1962, it was possible to standardize the use of nuclear energy for peaceful purposes, regulating the activities and practices that use radiation or radioactive material. Regarding nuclear facilities, CNEN has specific legislation with various standards covering the licensing of nuclear installations, as CNEN-NE-1:04 [2], and all necessary safety procedures for the operation of nuclear facilities. The first Brazilian regulation in terms of decommissioning was published on November 2012, to comply with the intrinsic requirements of a nuclear power plant final shut down procedures [3]. However, the decommissioning has not been addressed, as a whole, by the current legislation, recommendations applied for nuclear research reactor.

Decommissioning refers to actions implemented to shut down a nuclear facility, technically and administratively, aiming at complete or partial removal of its regulatory controls focusing on the plant safety, workers and public health, plus the minimization of environmental impacts [4]. These actions require planning and organization to guarantee the safety during the activities which are synthesized in the decommissioning plan.

The United States, Canada, and several countries in Europe which have an advanced nuclear program, have established the practice, the legislation and the guidelines for decommissioning. However, for other countries the issue of decommissioning has been gaining relevance in recent years. In several cases, there is no standard or specific guideline for it. Thus, the IAEA (International Atomic Energy Agency) seeks to guide decommissioning activities to reinforce safety in all the steps to be performed during the preparation, implementation and conclusion of a nuclear plant decommissioning.

The IAEA recommends that all nuclear facilities, during the planning step, should already have a decommissioning plan. This plan is defined as the set of all initial, intermediate and final actions to be accomplished for a nuclear plant decommissioning with maximum safety. In some IAEA State members, for instance Hungary, the preliminary decommissioning plan is required for a nuclear plant licensing [5]. A preliminary and a final decommissioning plan for nuclear power plants has been asked to be an integral part of the licensing process in Brazil, since 2012 [3].

The SAFETY REPORT SERIES No.45 [6] is one of the main documents published by the IAEA referring to nuclear plants decommissioning. It contains all the items which should be covered by a decommissioning plan and it has been an important reference for this work.

In this current global context of nuclear energy, none of Brazil's nuclear facilities has a decommissioning plan, even on a preliminary way. All these works are ongoing. Therefore, a decommissioning plan is needed to adapt the country to the international and national guidelines and patterns, reinforcing credibility, quality and safety of its nuclear program.

Worldwide, several practices in decommissioning involving application of decontamination and dismantling techniques, project management and radioactive waste management have been developed over the past 20 years, with satisfactory results. Such experiences are found and listed in [7] and served as a reference for the development of this project.

The preliminary decommissioning plan is intended to guide the development in all procedures related to the preparation and implementation of decommissioning activities, in the specific case of IPEN / MB-01 Nuclear Research Reactor. This step is important in order to assist the regulatory body to make decisions related to project the decommissioning, when the shutdown date of the installation is announced and, also, to meet a regulatory requirement related to CNEN licensing [3].

With the adoption of procedures for decommissioning in the critical assembly (IPEN/MB-01Reactor), it is expected that the site may have doses compatible with the levels of public exposure established by CNEN 3.01 standard [8].

2. IPEN/MB-01 reactor

It is a nuclear research reactor, zero power type and with maximum nominal power 100 W. The reactor was concluded in 1988 from a partnership between IPEN (Nuclear and Energy Research Institute) and CTM-SP (São Paulo's Navy Technological Center). The IPEN/MB-01 Reactor is located at the University of São Paulo, in the city of São Paulo. The main characteristic is its versatility, allowing different core critical arrangements, obtaining different settings and performing naval propulsion core tests for the nuclear submarine [9].

Figure 1. IPEN/MB-01 Reactor [8].

The reactor core is inserted into a moderator tank in which neutrons are moderated with light water and placed on a metallic structure composed by three stainless steel spacers plates, called lower supporting plate, an intermediate spacer plate and a top spacer plate. The start neutrons source is a Am-Be, with 1 Ci activity [10].

The default configuration of the IPEN / MB-01 reactor core, is rectangular, and has a total of 680 rods, with an array of 28×26 and 48 control rods / safety with function to control the nuclear chain reaction and the reactor shutdown. The active dimensions of this type of configuration are 39×42×54.6 cm, with 2415 pcm excess reactivity [9]. The rods are coated with stainless steel, containing 52 pellets of uranium dioxide, enriched to 4.3%. The control rods are also coated with stainless steel and have inside neutron absorbing materials, Ag-In-Cd alloys. The safety elements have Boron Carbide (B4C) powder [10]. The neutron flux of the reactor is around $1\times10^{8}n\cdot cm^{-2} s^{-1}$. The Figure 2 shows the sectors of the IPEN/MB-01 reactor.

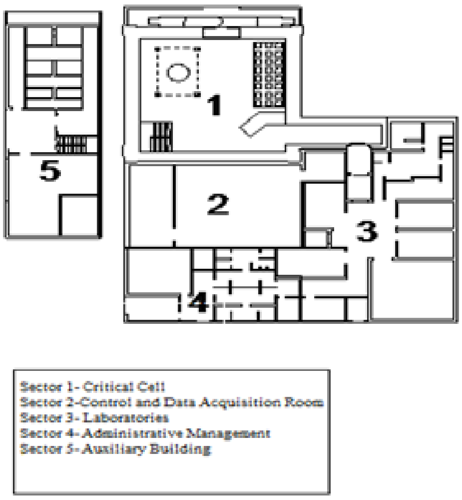

Figure 2. IPEN/MB-01 Reactor sectors [10].

The facility has been divided into five sectors to meet the safety criteria [2] according to the type of the developed activity [10]:
Sector 1-Critical Cell: The building where is the critical assembly. The core is moderated by light water, providing a flexibility in its conception to test different core settings;
Sector 2-Control: It is located the control room and data acquisition;
Sector 3-Laboratories: The area used as counting rooms for irradiated targets, for chemical activities, as decontamination rooms, warehouses for radioactive materials of low activity and radiological protection activities;
Sector 4-Administration: The conventional area where the gatehouse, the management and restroom;
Sector 5-Auxiliary building: It is used to shelter the water supply treatment, the air-conditioning and ventilation, compressed air for instruments and fire-fighting systems.

The focus of this work is on a component of the sector 1, to illustrate an example of the procedures to be implemented on the preliminary decommissioning plan. The choice of this component for the application is the fact that it appears as a potential source of radioactive waste, due its constituents are more susceptible to the neutron flux. The critical assembly involves radioactive and non-radioactive materials. The procedures adopted in the critical assembly could be as reference for the other sectors.

In short term, there is no forecast for the final shutdown of the facility, justifying the development of the guidelines to be used in the near future on development of the preliminary decommissioning plan.

3. Critical Assembly

The Figures 3 and 4 show the main components, and an overview of the critical assembly, respectively

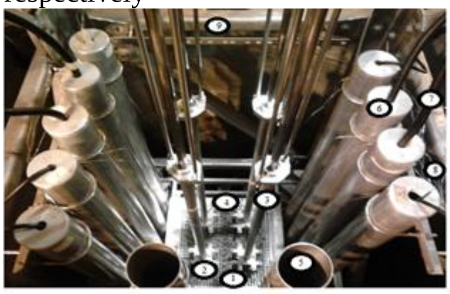

Figure 3. Critical assembly main components: 1-fuel rods; 2-device with absorber rods; 3-activation mechanism; 4-top spacer plate; 5-experiment detector tubes; 6-detector tubes; 7-cables; 8-data acquisition wiring; 9-moderator tank.

Figure 4: General view of critical assembly.

4. Methodology

This work is based on the international IAEA recommendations, which Brazil is a signatory. The IAEA has several documents and guidelines published, giving guidance to decommissioning activities and the preparation of items, which are present in a general plan. The main references are on [4, 11, 12]. The specific base references for decommissioning of research reactors are present on [13-16], among others. All these references bring information, assistance and experience to decommissioning activities, taking into account safety and ALARA principle ("As low as reasonably achievable"). Besides, there is an IAEA document, which guides and highlights the mandatory items that should be included in a decommissioning plan: Safety Report Series 45 [6]. It is an important guide, mainly for countries which do not have specific legislation regarding nuclear reactor decommissioning. With respect to national legislation, the main regulations used in this work are present in [8, 17, 18] and the standard for the decommissioning of nuclear power plant [3].

The Brazilian Nuclear Resolution (CNEN-NN-9.01) published in 2012, determines the need of a preliminary decommissioning plan for all nuclear facilities. The Regulation allows a period of two years from its publication for the Brazilian nuclear plants to meet its requirements [3].

Moreover, plans and programs already established at IPEN/CNEN-SP have been consulted, proposing an adaptation for the decommissioning process. These plans are: Radioprotection [19], Physical Protection [20], Radiological Emergency [21], Fire Protection [22] and the existing Radioactive Waste Management programs [23], Non-radioactive waste Management [24], Quality Guarantee [25], Environmental Radiological Monitoring [26], Chemical and Environmental Monitoring [27] and Personnel Training [28].

The IPEN/MB-01 reactor has a document required by standard [2] as part of its licensing, called SAR (Safety Analysis Report) [10], which describes the plant as a whole and all the programs and actions promoted to ensure the safety operation, the workers, the public in general and the environment. SAR has important information, items and programs for the operational phase of the facility and it has been useful to develop the guideline for the preliminary decommissioning plan.

5. Decommissioning Strategies

Several aspects have been considered to define the initial decommissioning strategy of the IPEN/MB-01 reactor, taking into account the Critical Assembly as a pilot example: the critical cell inventories, dose rate present in [10], the general analysis of the main factors affecting the decommissioning strategy selection (human resources, required technology, waste management in plants and health, safety and environmental impacts) [6, 16, 29]; the international experience and strategies in research reactors decommissioning presented in [11, 14].

It is important to mention other factors helping the selection of the decommissioning strategies, such as the existing legislation regarding the decommissioning, the involvement of stakeholders and social impacts associated with the project and costs. Referring to the first factor, the national legislation which provides, directly or indirectly support to the decommissioning procedures proposed in this work has already been mentioned on item 4. The second and third factors, a discussion and analysis about the social impacts, the involvement of stakeholders and the cost are relevant, in order to develop a final decommissioning plan, are not contemplated at this moment due do not exist a forecast for the final shutdown in short term.

The main considerations which justify the preliminary decommissioning strategy selection are briefly discussed as follow.

5.1. Critical cell - inventory doses

The presented estimated doses are based on the Safety Analysis Report. In order to justify the decommissioning strategies, an inventory of estimates doses was used near the critical assembly, in specific operation condition. The goal was to assess the radiological safety to access and perform decommissioning procedures. The obtained results can be found in Table 2 and Figure 5.

Analysis of data on Table 2 shows that doses decrease significantly in few days. According to the table, when the reactor operates 1 hour long, which is the average time period for the reactor's daily operation, the critical cell dose within the first 12 hours after shutdown is 40×10^{-5} Sv/h and, 12 hours later, this value can reach 16.5×10^{-5} Sv/h. These values are below the limit access for authorized persons in the building of critical cell set that is 100×10^{-5} Sv/h [10]. The graphic in Figure 5 shows that, in a few hours, the doses in the region close to the moderator tank decrease significantly and, 6 hours after shutdown, the dose is close to 0.

Table 2. Dose rate versus cooling operation time span, with the reactor operating on 100 W to 1 meter distance from the moderator tank [7].

Radiation time span (hours)	Cooling Time Span(days)								
	½	1	1 ½	2	2 ½	3	4	5	6
	Dosage (10^{-5}Sv/h)								
½	20,5	8,5	5,0	3,5	2,5	2,0	1,5	1,0	<1,0
1	40,0	16,5	10,0	7,0	5,0	4,0	3,0	2,5	<2,5
2	75,5	32,0	19,0	13,0	10,0	8,0	6,0	5,0	4,0
3	108,0	46,5	28,0	20,0	15,0	12,5	9,0	7,5	6,0
4	132,0	60,5	36,5	25,5	19,5	16,0	12,0	10,0	7,5
6	191,0	86,5	53,0	37,5	29,0	24,0	18,0	15,0	11,5
8	236,0	110,5	68,0	48,5	38,0	23,5	19,5	19,5	14,5
24	464,0	248,5	165,5	124,0	100,0	84,5	66,0	55,0	42,5

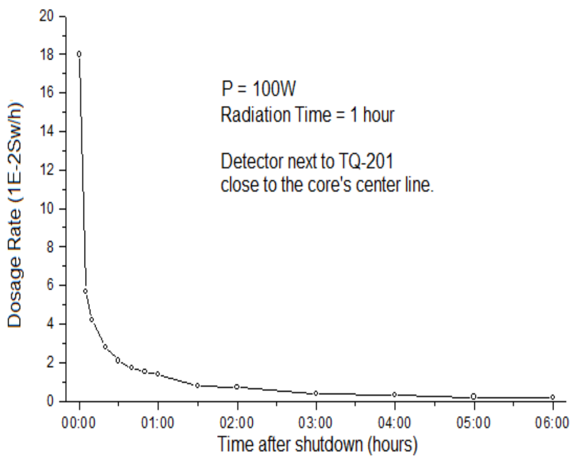

Figure 4. Dose rate versus decay time – detector next to moderator tank [7].

In order to decommissioning the critical assembly, these doses can be managed in such a way that a worker can receive a much lower dose than the constant in the annual limits in [8], until all tasks have been completed.

Thus, it is possible to secure access in the vicinity of the critical assembly, within a schedule, planning and supervision of doses established by radiological protection [10]. Therefore, the risks associated with radiation exposure are minimal during decommissioning activities (considering the fast decrease of dose rates, as seen on Table 2), allowing tasks to be safely performed by professionals and technicians in the area around the critical assembly.

5.2. Other factors

The information regarding to other factors that affect decommissioning strategies (human resources, required technology, radioactive waste management in the plants, and effects on health, safety, and the environment) are shown, respectively, as follow:

Human Resources: The IPEN/CNEN-SP has the necessary infrastructure to train personal for decommissioning tasks [29];

Required Technology: Decommissioning and industrial dismantling sophisticated technologies will not be required, as well as remote operations are not expected to be used. Following the radiological protection procedures, dismantling of the critical assembly will be classified as industrial dismantling;

Radioactive waste management: There are two plants which will be able to receive wastes from the dismantling of the critical assembly, except for the fuel elements. The first one is the Radioactive Waste Management Plant of the IPEN/CNEN-SP (GRR), is already in operation and Low and Medium-Level Radiation Waste Repository, expected to be in operation on 2018 [30];

Effects on health, safety, and the environment: Due to the low radiological risks shown in Table 2, a low amount of radioactive wastes and the low activity concentrations of radioisotopic inventory (alongside) [31] it is expected, no significant effects on health, and environment safety during decommissioning activities.

5.3. Strategy Selection

The general strategy recommended for decommissioning of the critical assembly is the immediate dismantling [16]. This action has to be carried out in agreement with the dose inventory's estimation results, the plant's characteristics, and the general analysis of the factors which affect the strategy as seen in [6, 16, 29]. The strategies recommendations related to research reactor are based on [11, 14], as follow:

- removal and temporary storage of fuel from reactor in pits;

- removal, packaging, storing, and definition of an appropriate place to send low-activity materials and clearance of materials, in accordance with the limits for disposal, as established in [17];
- dismantling of the critical assembly's components;
- managing to send radioactive waste;
- final radiological survey and supervision.

It is important pointing out that the immediate dismantling strategy does not need to be applied shortly after the plant shutdown. Since decommissioning requires a preparation period, it is still possible to keep the plant inactive for some specific time in order to promote the decrease of existing doses, as these doses decrease fast as shown in Figure 5. The amount of time required for the reactor to remain inactive will depend on radiological protection department.

6. Project Management

Project management has been based on specific characteristics of the plant and on recommendations shown in [32, 33]. The decommissioning project management proposal was planned and targeted at the activities described in the present study. This proposal can be applied to the entire plant.

The resources used to implement, coordinate and plan the decommissioning phases can be described, in general way, as material resources and technical/scientific to accomplish a specific task. The specific roles and proper organization of the managed project should be defined [6]. The resources necessary to implement decommissioning activities include:

- human resources (IPEN technicians and contractors);
- physical space and equipment necessary for administrative functions;
- safety system;
- tools required for certain tasks;
- radiation monitoring and detection equipment;
- packaging and barrels used to transport radioactive materials;
- personal protection equipment;
- radioactive and non-radioactive material transport vehicles.

The responsibility and organization in the project management is associated with the definition of specific functions to accomplish certain tasks, requiring specialized technical, administrative and field support, establishing how these functions are related [6], as showed on Figures 6 and 7 [33].

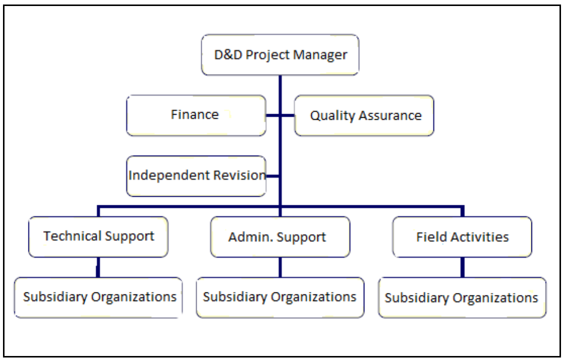

Figure 6. Overall hierarchy for decommissioning activities [33].

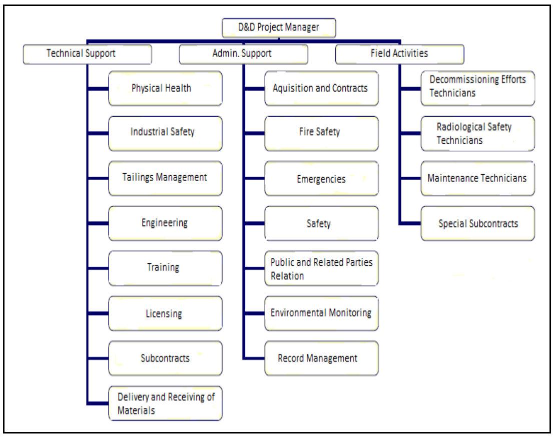

Figure 7. Support, administration, and field sectors' organizational hierarchy structure [33].

7. Decommissioning activities

The IAEA publications, as seen in [32] and [34], describe the distribution of decommissioning activities in work packages in detail. The activities have been divided in 4 work packages, as follow:

Package 1 – Before Decommissioning Activities:

- planning of quality, health and safety assurance, radioactive waste management, safety assessment, environmental assessment, safeguarding, surveillance and maintenance, training, and emergency plans;
- acquisition of barrels or containers to store and dispose of radioactive and non-radioactive wastes;
- development of documents related to the licensing of radioactive wastes barrels and containers;
- training;

− conclusion of the decommissioning plan, which will be sent to CNEN for further assessment.

Package 2 – Field Activities: Critical Assembly Dismantling:

- removal and storing of the fuel elements within the critical cell pits;
- removal of all equipment, wires, detectors and tubes of critical assembly;
- dismantling of control devices;
- removal of control/safety rods;
- dismantling of the core spacer plates;
- dismantling of the critical assembly upper platform;
- removal of the moderator tank;
- dismantling of the core support structure.

Package 3 – Radioactive Waste Management:

- storage and transportation of critical assembly wastes;
- storage of non-radioactive materials and final disposal.

Package 4 – Conclusion Activities:

- survey and final radiation monitoring around the critical assembly;
- conclusion of records and reports.

Activities related to Package 1 will be carried out by IPEN/CNEN-SP professionals and facility workers. Regarding Package 2, service will be carried out by a third-party company experienced in industrial dismantling, supervised by the project manager, in accordance with the established hierarchy seen in figures 6 and 7. Third party and IPEN/CNEN-SP workers are advised to perform Package 3. The Package 4, responsibility for activities may be performed by IPEN/CNEN-SP and reactor´ professionals. The activities mentioned in Packages 2, 3, and 4 will be supervised by radiological safety workers, who will plan a specific schedule maintaining the doses as low as reasonably achievable (ALARA Principle).

8. Waste Management

The proposed waste management procedures were based on [17], [23], [35], and [36]. Specific strategies were planned covering radioactive and non-radioactive waste in order to perform the actions related to the management of wastes, originated from the critical assembly decommissioning. The Figures 8 and 9, show the strategies.

In the sequence, the radioisotopic inventory of the main components of the critical assembly will be applied for proposals of waste management taking account the flowcharts showed in Figures 8 and 9.

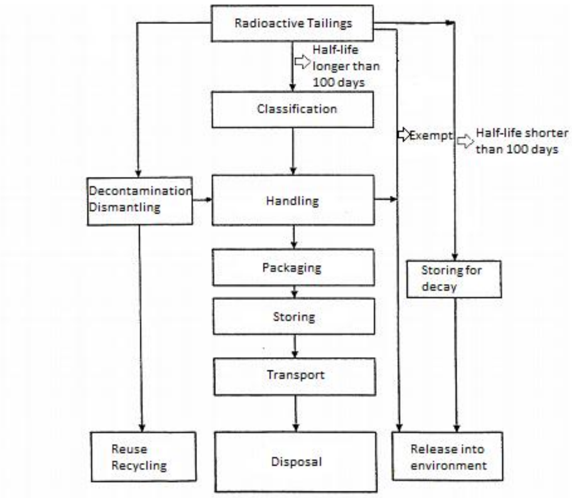

Figure 8. Radioactive materials strategy flowchart [35].

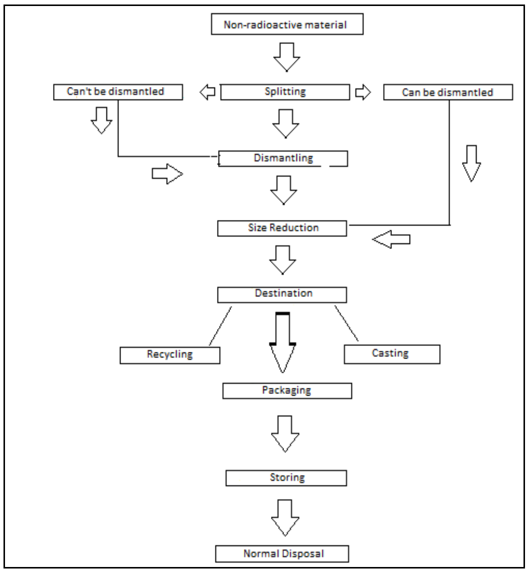

Figure 9. Non-radioactive materials strategy flowchart.

8.1 Radioisotopic Inventory of Critical Assembly Components

The radioisotopic inventory estimates are shown in Tables 3 and 4 [10]. The data refer to metallic components subjected, to the neutron flux and to fuel rods. The radioisotopic inventories of the main metallic components and of the fuel rod were estimated for the 24 hours operation on 100 W power. The results are presents in Tables 3 and 4.

The data on the Tables 3 and 4 reveal that the activities are considered low and most of the present radionuclides. The half-life is shorter than 100 days, with fast increasing decay. The radionuclides whose half-life is longer than

100 days, namely, 14C, 59Ni, 60Co, 63Ni and ^{182}Ta, among them, the ^{60}Co is that contributes more significantly to the components activities. The guide tube and the fuel rod coating activities are bigger than the other components, due they are closer to the core active region. The intermediate spacer plate is also located in this region, and should have a similar radioisotopic inventory. To facilitate the classification of radioactive waste in accordance with the determinations found in [17] and its management, the Table 5 shows the mass and volume of main components of the critical assembly.

Table 3. Steel AISI-340's activity (core structure).

Isotope	Activity (*Bq\kg*)		
	lower spacer plate	guide tube	fuel rod cladding
^{14}C	6,29E-06	4,15E+01	2,84E-05
^{59}Fe	1,86E+05	5,28E+11	3,99E+05
^{56}Mn	1,70E+08	3,74E+15	2,85E+09
^{31}Si	7,40E+04	4,36E+11	3,31E+05
^{32}P	9,58E+03	5,74E+04	4,34E+04
^{35}S	4,71E+01	2,80E+02	2,13E+02
^{61}Cr	8,10E+06	4,86E-03	3,68E+07
^{59}Ni	1,76E+01	8,05E+01	8,00E+01
^{60}Co	2,90E+04	1,70E+05	1,31E+05
^{63}Ni	2,76E+03	1,65E+04	1,25E+04

Table 4. Moderator tank activity [10].

Isotope	Activity *Bq/kg*
^{59}Fe	3,66E+04
^{14}C	4,95E-05
^{56}Mn	6,66E+07
^{31}Si	1,63E+04
^{32}P	6,94E+03
^{35}S	4,10E+01
^{51}Cr	8,38E+07
^{59}Ni	6,94E+00
^{182}Ta	4,06E+04
^{60}Co	1,38E+04

Table 5. Mass and volume of the main components of the critical assembly [10].

Materials	Mass (*kg*)	Volume (m^3)
moderator tank	1003	1.25E-1
guide tube	0/12	1.45E-5
lower support plate	41	5.24E-3
intermediate spacer plate	41	5.24E-3
top spacer plate	41	5.24E-3

According to the strategy of the radioactive waste management presented in Figure 8 and considering the information of the estimates presented in tables 3 and 4, the moderator tank is classified as class 2.1[17] waste, due to the presence of 60Co. Due the low activity compared to the other components shown in Table 4 and also the mass has a value less than 1000kg, the moderator tank can be stored until the radionuclides reaching the clearance limits established in [17] with the estimated time of 2.5 years. Satisfied this condition, the procedures described in Figure 9 can be applied.

The lower support plate (table 3) is also classified as class 2.1 waste [17] and has activity concentrations slightly higher than the moderator tank. Thus, this component can be stored according to the flowchart path presented in Figure 8, until the activity concentrations meet the clearance levels established in [17]. For this case the estimate times for exemption is approximately 8 years.

The guide tube and probably the intermediary spacer plate can follow the path for radionuclides with half-life longer than 100 days, as presented on the flowchart of Figure 8. These materials have activity concentrations compatible with Class 2.1 waste [17]. As the guide tube and, probably, the intermediate spacer plate have higher activity concentrations than the presents on moderator tank and lower spacer plate, is recommended that this component follows the path outlined above. If after performing treatment procedures, these materials reach the same clearance levels established in [17], it can be released, recycled or reused.

For all management waste procedures proposed, is recommended to analyse the feasibility in economic terms and other resources available.

In case of component to need be cut off, the most adequate techniques to be used are: thermal cutting techniques using a plasma arc; the contact arc metal cutting (CAMC); a mechanical technique using arc saw. All these techniques take into consideration the fact that the above mentioned components are composed of stainless steel [36]. Fuel rods are classified as nuclear material according to [23], thus the CNEN should establish the final disposal [37].

The instrumentation and other critical assembly components, after being monitored and inventored, will have the waste management submitted to the strategies defined in the flowcharts of figures 8 and 9, according to the radionuclides concentration and activity. All of these components are classified as solid wastes and are incompressible, according to [23].

8.2 Waste Destination

The adequate location for disposal of metallic wastes is the Low and Medium-Level Radiation Waste Repository, due these wastes comply the acceptance criteria established by the GRR, regarding materials activities. The Repository is designed to receive wastes with very short half-life (approximately, 100 days) and short half-life (30 years), from decommissioning activities of nuclear facilities.

The fuel rods will remain in dry cast storage within the pits in the critical cell building until the Brazilian government establishes a policy for the used fuel elements final disposal.

9. Conclusion

This work presents a series of recommendations as a guideline including the main procedures and actions that should be used to develop the preliminary de-commissioning plan of the IPEN/MB-01 reactor on near future.

The guideline presented shows all phases of a typical decommissioning project taking account recent experience and good practice reflecting the new safety requirements.

The strategy selected for the reactor is the immediate dismantling considering the analysis of the radioisotopic inventory estimates.

The main contribution is that, Brazil so far, does not have a policy decommissioning regarding to nuclear research reactors, therefore, this study can contribute as a reference on the development of decommissioning plan of others Brazilian research reactors.

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