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Safety Assessment on the Decommissioning Stage of Indonesian TRIGA 2000 Research Reactor

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A B S T R A C T

Decommissioning is the final stage of a nuclear reactor. In preparing the decommissioning plan, one of the important elements that need to be considered is safety assessment. During decommissioning, there are many complex tasks to be done where the radiological and non-radiological hazards arise and can significantly affect not only the workers but also the general public and the environment. Indonesia has no experience with nuclear reactor decommissioning, so it is necessary to study various experiences of decommissioning activities in the world. This study proposes a framework to implement the safety assessment on the decommissioning of the TRIGA 2000 research reactor. The framework was developed on desk-based research and analysis. The proposed framework involves the facility and decommissioning activities, hazard identification, hazard analysis, hazard evaluation, hazard or risk control, and independent review.

1. INTRODUCTION[*]

Worldwide, more than 60% of Nuclear Power Plant (NPP) have been operating for 25 years. This condition raises an important question regarding the proper schedule for retirement. In 2025, about 50 of 129 European nuclear reactors in operation (39%) need to be shut down and by 2030 almost 90% of all European NPP are facing a stage of shut down if no revitalized actions are undertaken for prolongations of their operational life [1]. When the permanent shutdown has been accomplished, nuclear facilities need to be decommissioned. Since 2011, the decommissioning program of Japanese reactors has increased threefold and is even likely more to increase [2].

Decommissioning is an action to permanently stop the operation of a nuclear reactor, removing the facility and reducing the residual radioactivity to an allowable level[3]. It is also including the transfer of nuclear fuel from the nuclear reactor core, dismantling of reactor components, decontamination, and final security.

The main focuses in decommissioning process of NPP are safety, radioactive waste, and energy security. These lead to an increase in the strengthening of facility, replacement, or shutdown, scheduling the decommissioning, dismantling strategies, and radioactive waste management [4]. Aside from those, the increasing cost of strengthening the facility due to increased safety

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requirements is also confronted by the operators [1, 5].

Decommissioning has been conducted in KRR-2 (Korean Research Reactor-2) and KRR-1 (Korean Research Reactor-1). KRR-1 and KRR-2 are both TRIGA pool-type reactors. KRR-1 is TRIGA Mark II, while KRR-2 is a TRIGA Mark III. In carrying out decommissioning of KRR-2 and KRR-1, various methods related to risk assessment have been developed, both qualitative and quantitative.

The TRIGA 2000 Research Reactor in Bandung city is one of the three research reactors operating in Indonesia. The reactor is mainly used for radioisotope production, neutron activation analysis, radiation chemistry, neutron and gamma dosimetry, neutron spectrometry, and neutron radiography [6].

National Research and Innovation Agency (BRIN), revealed the plan to cease the operation of TRIGA 2000. BRIN stated that the reactor can be consideres as old, even though several of its components have been revitalized. Hence, it is necessary to pay serious attention to the preparation for decommissioning of the TRIGA 2000 research reactor.

To identify the potential hazards and risks, both radiological and non-radiological, the safety assessment of decommissioning is necessary to be applied. The decommissioning plan of nuclear facilities should be established based on their structural conditions and radiological characteristics, followed by a qualitative and quantitative safety assessment [7].

To get an overview of the safety assessment methodology in decommissioning nuclear reactors, this study proposed desk-based research and analysis using the Safety Assessment Process approach. Indonesia possesses no experience related to nuclear reactor decommissioning, so it is necessary to study the literature from various experiences of nuclear reactor decommissioning in several other countries that formulate the stages of decommissioning, especially related to safety assessment for decommissioning. The objective is to provide recommendations regarding the decommissioning plan of the TRIGA 2000 research reactor.

2. METHODOLOGY

Primary activities in decommissioning consist of Planning, Characterization, Decontamination, Dismantling, and Safe Storage. The decommissioning activities have many potential hazards since these activities take place in the main facilities, the reason why safety assessment needs to be carried out. A safety assessment is an integral part of the overall decommissioning plan used for facilitating the framework and provides the steps to reduce the hazard.

To get an overview of the safety assessment methodology in decommissioning nuclear reactors, this study is providing desk-based research and analysis from books, journals, and other references. The results of the study will be used for the recommendation of the decommissioning process of the TRIGA 2000 research reactor. The proposed safety assessment processs for the TRIGA 2000 research reactor is graphically depicted in Figure 1.

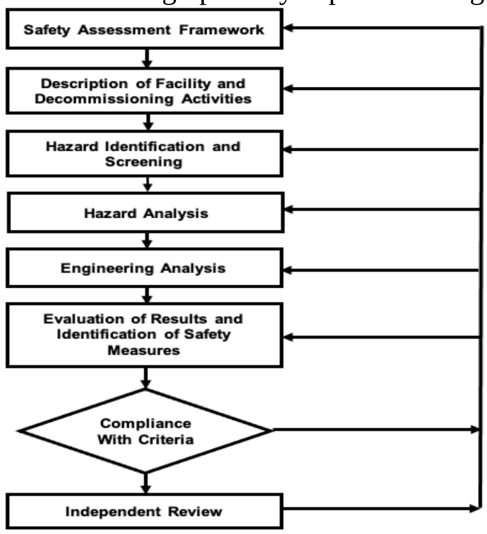

Fig. 1. Safety Assessment Process[8, 9]

The first step was to define the scope and objectives of the assessment, including a description of the facility and the activities of the decommissioning. The information was used to identify the hazards, both existing and potential. These hazards are inherent in the facility and will arise because of the activities in the decommissioning [10]. The hazards should be analyzed qualitatively and quantitatively, complemented by an engineering analysis of the Structure, System, and Components (SSCs).

An evaluation and control of the resulting doses and risk of the decommissioning should be done by safety measures to eliminate and reduce hazards. The dose must also be compared with the relevant safety requirement and criteria in the national regulatory to ensure the dose comply with them. The resulting doses and the risks from decommissioning activities should be evaluated and controlled with safety measures to eliminate hazards and reduce the risks, so it meets the safety requirements and criteria of national legislation. As a final step, to provide trust, all previous stages should be subjected to an independent review.

3. RESULTS AND DISCUSSION

3.1. Safety Assessment Framework

Before conducting the safety assessment, it is necessary to set the safety assessment framework. This framework describes the context of safety assessment, objectives of the assessment, time frames, the endpoint of the decommissioning phases, and the assessment output. In the TRIGA 2000 research reactor decommissioning plan, the starting point for the safety assessment needs to be clearly defined. For example, starts at the end of the installation operation.

The information/documentation of the reactor operation also should be collected to make a comprehensive record [9, 11]. In TRIGA 2000 research reactor, the objectives are to ensure that exposure to the workers and general public do not exceed the limits, so that the decommissioning plan will focus to achieve this objective.

In conducting a risk assessment on the decommissioning process, to ensure that the exposure does not exceed the limits, three safety categories need to be considered:

Radiological safety; i.e., the safety aspect related to radiation exposure received by workers.

Occupational Safety; i.e., the safety aspect related to the interaction of workers with the equipment used and environmental conditions while working.

Process safety; i.e., the safety aspects related to the processes that occur when the system or installation operates.

Timeframes for TRIGA 2000 research reactor decommissioning are adapted to the activities in decommissioning which involve Planning, Characterization, Decontamination, Dismantling, and Safe Storage [4]. In planning for TRIGA 2000 decommissioning, a decision-making process is carried out to determine the strategies, methods, and techniques selected for decommissioning. The allocation of costs and methods of funding are also decided. In doing characterization, relevant data and information related to TRIGA 2000 are collected, covering the source inventory, the amount of radioactive exposure of systems and components, the layout of an installation, and other important information. The information obtained from the characterization process is needed to decide strategies, methods, costs, and the amount of waste generated during the dismantling process. Information on room layout, system and component layout, and source estimates as well as the amount of radiation exposure at each position will make the dismantling process effective and efficient [6, 12].

At this stage, it is necessary to determine the method of decontamination, dismantling option, and safe storage place. The decontamination process is usually carried out on floors, walls, pipes, etc., and uses mechanical materials, chemicals, water, etc. For example, contamination on the concrete surface can be removed by vacuuming, brushing, cleaning, washing, and spraying methods, or by using chemicals. The dismantling process involves cutting and dismantling building components and structures, using conventional techniques and even advanced and remote technologies. Conventional cutting processes are usually carried out using plasma cutting, thermal cutting, electrical cutting, laser cutting, sawing, oxyacetylene torches, etc. The demolition process is usually carried out by blasting, drilling, rock splitting, etc [13]. The waste resulting from decommissioning or dismantling must be stored in safe storage. The waste from TRIGA 2000 research reactor can be stored temporarily at the installation site and can also be in a permanent waste storage area outside the site. When the second option is decided, using a permanent waste facility in Serpong nuclear area, the process of transferring the waste from the site to a permanent storage area will involve additional aspects, such as the safety aspect of transportation of radioactive waste materials [14].

3.2 Description and Decommisioning Activities of TRIGA 2000 Research Reactor

The TRIGA 2000 research reactor is a TRIGA Mark II-type reactor. It was constructed in 1961 and reached criticality for the first time in 1964. On February 1965, the reactor was inaugurated, which was operated on a power level of 250 kW. The reactor power was upgraded two times, i.e. from 250 kW to 1000 kW in 1972 and from 1000 kW to 2000 kW in 2000. The TRIGA 2000 research reactor uses light water as moderator and coolant, graphite as the reflector [6].

The key components of the reactor consist of the reactor core, control rods, reactor tank, primary and secondary cooling system, emergency core cooling system, emergency ventilation, and instrumentation system. Figure. 2 shows the reactor in vertical diagram.

The key component of the TRIGA 2000 needs to be divided, based on the contamination level, into metal apparatus (reactor vessel, reactor core), internal mechanicals (pipes, tanks, parts of the machine), and concrete structures. The level of contamination is to be considered in determining the method of decontamination and dismantling option. The low contaminated parts, can be disassembled with hands-on equipment and technique. However, most of the metal and internal machinery must be disassembled with a remote operating method since they were highly radioactive.

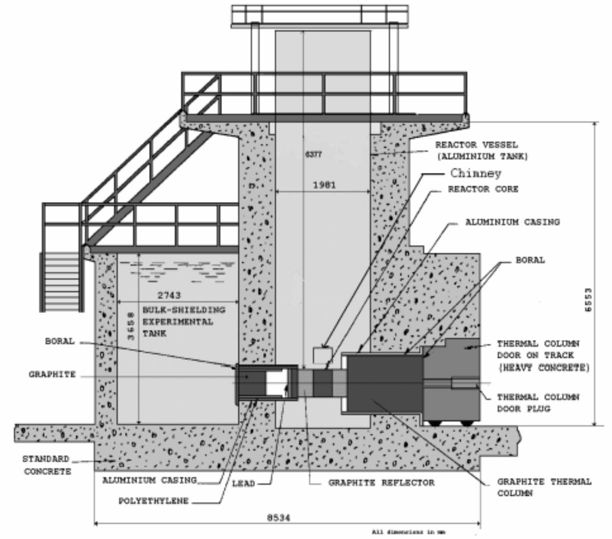

Fig. 2. Vertical section of the TRIGA 2000 Research Reactor [15]

TRIGA 2000 research reactor facilities and decommissioning activities are a potential hazard, so it is important to know the component of the facilities and determine whether a decommissioning activity has the potential to give a probability rise to a hazardous situation [16].

Non-technical information is also needed. TRIGA 2000 research reactor implements a management system, which guarantees the availability of safety measures, covers the existence of procedures, preserves the equipment, training, maintenance programs, etc. This information should be included in the hazard analysis.

3.3 Hazard Identification and Screening

The first concern for the TRIGA 2000 research reactor was when the reactor was upgraded. A detailed calculation of the reactor core criticality and spent fuel element storage facility were performed to improve nuclear safety from radiological and non-radiological hazards. These activities also involved the removal of fuel elements from and into the reactor core, disassembling of the old reactor core, installation of the new reactor core, and other components that happened in a very high radiation environment [6]. The second concern for the TRIGA 2000 research reactor is the decommissioning plan. Learning from the experience, radiological and non-radiological hazards will arise during decommissioning activities, so the worker needs to be protected by eliminating and reducing them.

For that purpose, hazards in TRIGA 2000 research reactor need to be identified. The qualitative methods to evaluate the potential hazards and operability problems of decommissioning operations also need to be applied. We recommend Hazard and Operability study (HAZOP) methods to identify the hazards combined with a database from the decommissioning experience of another nuclear reactor. The HAZOP technique is a team-based structured method that consists of identifying hazards, contributory causes, and operability problems in plans and procedures. One of the advantages of HAZOP is that the process is systematic dan comprehensive [17–19]. The HAZOP technique was applied in some NPP decommissioning projects [20, 21].

The main approach from HAZOP is how to divide the system into nodes, define a keyword, identification, and analysis the hazard from the keyword and suggest protection or mitigation measures (Figure 3). If implemented in the HAZOP approach, the key components of the TRIGA 2000 research reactor are a node, i.e reactor core, control rods, reactor tank, primary and secondary cooling system, emergency core cooling system, emergency ventilation, and instrumentation system. For application in the nuclear industry, the keyword and parameter have been modified, to accommodate the specific hazards related to radiation. By applying these keywords, we can identify and evaluate the hazards.

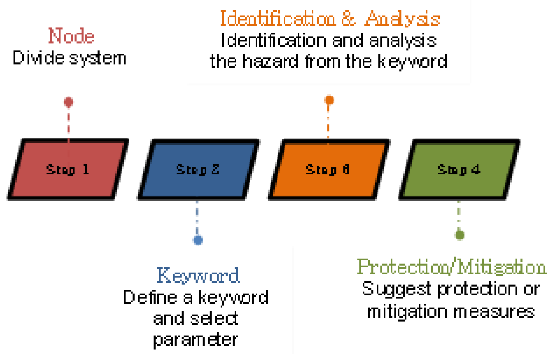

Fig. 3. HAZOP Approach

As a reference or verification, we can use the data from the decommissioning project of KRR-2 (TRIGA Mark-III type), which combines HAZOP and data from the experiences. Hazards from a decommissioning project were summarized in Table 1.

Table 1. Hazards from a decommissioning project [17, 22]

Radiological hazard	Non-radiological hazards
• External exposure • Internal exposure • Criticality • Loss of containment	• Elevation • Hand handling • Toxic and hazardous materials • Falling object • Electricity • Machinery

• Ingestion and inhalation of radionuclides	• Toxic and hazardous materials
• Loss of services	• Fire/explosion
• Ventilation	• Noise
	• Slippery place
	• Confined space
	• Dust
	• Unsafe act

3.4. Hazard Analysis

In decommissioning, a comprehensive safety assessment of the hazards involved should be conducted to define protective measures, as a part of defense-in-depth system that takes into account the specifics of decommissioning. The measures may be different from the condition during the operation of the installation [23].

In this stage, radiological and non-radiological hazards in TRIGA 2000 research reactor were evaluated and risk analysis was conducted. The risk analysis is determined by the frequency and potential impact of hazards on workers, society, environment, and stakeholders [24]. Historical operation conditions and similar occurrences happening in other NPPs are also examined and analyzed. Risk analysis can be done by qualitative, quantitative, or semi-quantitative methods. Qualitative analysis uses words to describe the likelihood and severity. Semi-quantitative uses scale, value, and rank [25]. Meanwhile, a quantitative analysis can be obtained by calculating the risk value. Hazard analysis is carried out by quantifying the probabilities and consequences of the identified hazards. The multiplication between Probability and Consequence represents risk value [7, 26].
Korean Occupational Safety and Health Agency (KOSHA) has been assigning the value of probability and consequences using data collected from the U.S. Nuclear Regulatory Commission (NRC) and the International Atomic Energy Agency (IAEA). U.S. NRC collected their data from twenty U.S. plants that both have completed and still begun their decommissioning. Probability is the likelihood or possibility of the hazard to occur. The more often it happens, the higher the probability level will be. Meanwhile, consequences are the amount or how severe the damage or harm resulted from the even. The higher the resultant damage, the higher the level of consequences will be. Both values are often provided as ranking or leveling and obtained from the experiences, expert judgments, or spesific references [27]. For TRIGA 2000 research reactor, we recommend the use of level of probability, level of radiological and non-radiological consequences, and risk matrix, as shown in Tables 2-5. Since the decommissioning of TRIGA 2000 research reactor is the first decommissioning for Indonesia, and all the hazards (radiological and non-radiological) need to determine the likelihood and consequences level, so we recommend searching from the literature, or experiences during operating conditions [7, 26].

Table 2. The level of probability/likelihood [7]

Likelihood	Level of Likelihood	Likelihood Level
Highly Unlikely	< 20%	1
Reasonably Likely	20 – 40 %	2
Even Chance		
Highly Likely	40 – 60 %	3
Almost Certain	60 – 80 %	4
	>80 %	5

Table 3. The level of radiological consequences[7]

Radiological Consequences	Level of Exposure	Consq. Level
Insignificant	<0.1 mSv onsite <0.01 mSv offsite	1
Minor Exposure	0.1-1 mSv onsite 0.01-0.1 mSv offsite	2
Moderate Exposure Under Dose Limit	1-20 mSv onsite 0.1-1 mSv offsite	3
Major Exposure Above Dose Limit	20-50 mSv onsite 1-5 mSv offsite	4
Critical Exposure	>50 mSv onsite >5 mSv offsite	5

Table 4. The level of non-radiological consequences[7]

Non-radiological Consequences	Level / Duration of Treatment	Consq. Level
Insignificant Injury (no treatment required)	No treatment	1
Minor Injury	< 1 month	2
Moderate Injury	1-6 month	3
Serious (major) Injury	6 month – 1 year	4
Fatality (long-term illness or death)	1 year or fatal	5

The multiplication of probability and consequence gives a four-risk value categorization, which are represented by four different colors. The green color represents a risk value of 1-5, which means low risk. The yellow color represents a value of 6-10, which means medium risk. The orange color represents a value of 11-15, which have high risk, and the red color represents an extreme risk with risk value of 20-25.

Table 5. Risk Matrix [7]

		Radiological Consequences	Insignificant	Minor Exposure	Moderate Exposure	Major Exposure	Critical Exposure
		Non-radiological Consequences	Insignificant Injury	Minor Injury	Moderate Injury	Major Injury	Fatality
Likelihood		Level	<0.1 mSv onsite <0.01 mSv offsite	0.1-1 mSv onsite 0.01-0.1 mSv offsite	1-20 mSv onsite 0.1-1 mSv offsite	20-50 mSv onsite 1-5 mSv offsite	>50 mSv onsite >5 mSv offsite
			No treatment	< 1 month	1-6 month	6 -12 month	1 year / fatal
	Level		1	2	3	4	5
Higly Unlikely	< 20%	1	1	2	3	4	5
Reasonably Likely	20 – 40 %	2	2	4	6	8	10
Even Chance	40 – 60 %	3	3	6	9	12	15
Highly Likely	60 – 80 %	4	4	8	12	16	20
Almost Certain	>80 %	5	5	10	15	20	25

Compared to an NPP, the power capacity and complexity of a research reactor is clearly lower, and hence, has lower risk potential. For developing a risk matrix, NPPs data are still relevant for the research reactors, since the potential hazards are almost the same, such as from radiological, chemical, and mechanical materials. When the data of the research reactor are implemented to this leveling and matrix, it can be seen that the research rector has a lower risk than NPP.

3.5 Engineering Analysis

The hazard analysis must accommodate the engineering analysis by conducting engineering codes and standards to determine whether the existing SSCs are appropriate with all assumptions in the hazard analysis. Engineering analysis also identifies the function of the safety required for new engineered SSCs, to ensure that these will meet the safety requirements and criteria [28]. Based on the IAEA safety series, for complex assessment, the engineering document is better to separate from the others report, to give a functional specification for the engineering specialist [9, 11].

The TRIGA 2000 research reactor SSCs need to be grouped by the category of the safety function. For example, the requirement for SSCs category 1, those are important for preventing or mitigating major exposure. All category 1 components also require an assessment. This assessment is supported by complete engineering calculations, codes and standards assessment, and others.

However, category 1 is not expected in the safety assessment of the decommissioning. For SSCs category 3, they only have a little contribution to prevent or mitigate the exposure. This category is also frequently found in decommissioning safety assessments because the requirement is related to functionality and performance just based on records and/or a structured facility walk-down. The safety functions must be ensured continuously throughout the decommissioning plan, taking into account aging, degradation mechanisms, and others [29].

In TRIGA 2000 research reactor, engineering analysis also have a big role when the reactor was upgraded. During the upgrade, almost all reactor systems were refurbished, modified, and changed. The removal of the old core structure was difficult, even impossible to reassemble the core structure, this is why an engineering design needs to be applied to the new core structure. Another new engineered safety future was also provided for the reactor system. To prevent the release of gaseous fission products into the environment, an emergency ventilation system was assembled [9, 11].

Learning from all experiences, we recommend in decommissioning TRIGA 2000 research reactor a series of engineering workshops and calculations should be made to ensure the arise of radiological and non-radiological hazards will not affect the workers.

3.6 Evaluation of Result and Identification of Safety Measures

The TRIGA 2000 research reactor risk matrix must be evaluated, and need to take any action to eliminate the hazard or minimize the risk. The technique for safety evaluation proposed by IAEA is a graded approach. The hazards are graded based on the severity using a simplified method with the residual radioactivity equivalent to the dose from the viewpoint of public exposures [30, 31]. Evaluation results must meet regulatory requirements regarding dose acceptance for workers and the public. To reduce the dose that comes from radiological hazards, the following factors can be taken [26, 30, 32]:

- Time. Time is directly proportionate with dose, so the dose can be effectively reduced by limiting the working time in radiation facilities [33].
- Distance. Increasing the distance will be more effective because the amount of radiation exposure is inversely proportional to the square of the distance. When the worker moves away from the source, the radiation level drops rapidly, so the worker can complete the work with a lesser amount of dose.
- Shielding. Some materials can reduce the dose rate. The types of shielding depend on the type of radiation and its energy levels [34].
- Source reduction. This means that if the amount of radioactive material can be reduced so the radiation and contamination levels will be lower and the worker will receive a lesser amount of dose.

In addition, the impact of the decommissioning that interfere with the public in accidents need to be evaluated, if the result is unacceptable, safety measure needs to be taken or work plans will be changed [30]. Kudo and Sugihara [30], have established the basic concept for safety evaluation by applying a graded approach.

A non-radiological hazard can be controlled by a principle called ‘‘System Safety Precedence’’. This system works in sequence because the previous ways are more effective than the next, as follows [22]. Elimination of the hazards and risks, Incorporate safety devices, Provide warning system, Provide PPE, Apply administrative controls.

For the general industry, the control concept that is mostly used is according to ISO 45001:2018, which eliminates hazards and reduces OHS risks by using the hierarchy as shown in Figure 4. The concept of System Safety Precedence is the same as ISO 45001:2018, but the order of control is different.

We recommended applying the Graded Approach and System Safety Precedence, Hierarchy of Risk Control based on ISO 45001:2018, and basic principles of radiation protection to eliminate the hazard and control the risks that arise from decommissioning activities for TRIGA 2000.

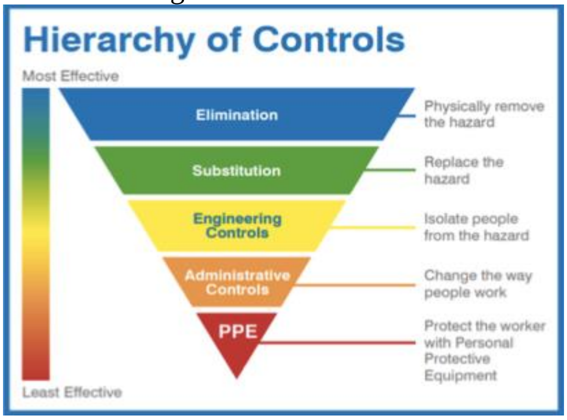

Fig. 4. Hierarchy of Risk Control in ISO 45001:2018[35]

3.7 Independent Review

An independent review should be conducted by a person or team who understand TRIGA 2000 research reactor. We recommended TRIGA 2000 research reactor safety committee as a reviewer. They should assure the validity of the data and assumptions, the accuracy of the facility and the decommissioning activities, the adequacy of safety measures, and the update of safety assessment.

CONCLUSION

Decommissioning is an option when nuclear reactors are not revitalized, either for technical or political reasons. The decommissioning activities have radiological and non-radiological hazards impact on humans and the environment. In preparing the decommissioning plan, it is necessary to pay attention to the safety assessment. Regarding the decommissioning plan for the TRIGA 2000, the concept of a safety assessment process with the stages to determine the framework, describe the detailed information about the facility and activities of the decommissioning, identify, analysis the hazards with the engineering approach, evaluate the results and identify the safety measures, and ultimately a review from the independent person or team. HAZOP methods are used to identify the hazards, which quantifies the probability and frequency to determine the level of the risk and map the risk using a risk matrix. The output of the risk matrix is the input for the evaluation stage. Evaluation stages make a decision about which risks require improvement and the priorities. To control these risks, we recommend the Graded approach and System Safety Precedence, Hierarchy of Risk Control based on ISO 45001:2018, and the basic principles of radiation protection, consisting of distance, time, and shielding. In the final step, an independent review from safety committee.

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AUTHOR CONTRIBUTION

All authors equally contribute to the study including the preparation and the approval of the final version of the manuscript.

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