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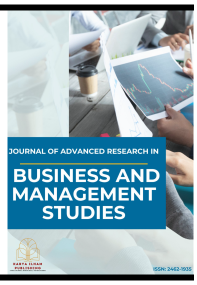

Decontamination and Dismantling Strategy for Radioisotope and Radiopharmaceutical Facilities

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ABSTRACT

The national demand for radioisotopes and radiopharmaceuticals (RIRP) continues to increase along with the development of the utilization of nuclear science and technology in various fields, especially nuclear medicine. Most RIRP products are currently imported. These needs could initially be met when the Indonesian Nuclear Industry (PT INUKI) was still operating. However, the facility was discontinued in April 2023 for several reasons and will be transferred to the National Research and Innovation Agency (BRIN). BRIN will revitalize the RIRP facility to meet domestic demand for RIRP. The revitalization effort is hindered by potential contamination discovered during the evaluation of the current condition of RIRP facilities. Radiological and physical surveys of the structures, systems and components to be decontaminated can be the first step to determine the Decontamination and Dismantling (D&D) plan and technology selection. This research aims to propose a D&D strategy along with appropriate technology recommendations for installation and risk analysis during the process. A comprehensive literature review on the latest D&D technologies was conducted to identify faster, cheaper, and more efficient methods. The D&D methods are evaluated based on safety, efficiency, cost effectiveness, waste minimization, and feasibility of industrialization. HAZOP study was conducted to identify potential hazards, level of risk, and provides risk control during the D&D process of RIRP facility. Chemical and electrochemical methods, such as acid cleaning, effectively decontaminate metal surfaces with minimal waste and cost efficiency. Physical methods such as dry ice blasting, abrasive blasting, ultrasonic, and laser cleaning are preferred for their safety, efficiency, and cost-effectiveness. Techniques such as diamond wire, plasma arc cutting, hydraulic bursting, and sawing were chosen to minimize radioactive waste and ensure safety during the dismantling process. The results of the HAZOP analysis show that the D&D process for the RIRP facility to be carried out has 7 processes with several potential hazards. The risk

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level of overall area shows 15 very high categories, 22 high categories, 13 medium category, and 7 low categories. Risk control during the D&D process is proposed to ensure operational safety and security.

Keywords:
RIRP facility ; revitalitation; safety

1. Introduction

Radioisotopes are isotopes that can undergo spontaneous decay and emit certain particles from the nucleus, resulting in changes in the number of protons or neutrons or energy levels [1]. Radioisotopes for radiopharmaceutical preparation can be produced using research reactors, cyclotrons, generators, and linear accelerators. Based on the application, they can be used for preparation of diagnostic and/or therapeutic radiopharmaceuticals [2]. Gamma Camera, SPECT, and PET are some of the important imaging techniques being employed currently for the diagnosis of diseases [3].

The national demand for radioisotopes and radiopharmaceuticals (RIRP) continues to increase along with the development of the utilization of nuclear science and technology in various fields, especially nuclear medicine. However, most of the RIRP products available today are still fulfilled from imported products. The insufficient available capacity for radiopharmaceutical production leads to long waiting times for patients seeking cancer diagnosis and treatment services, unable to meet national demand. These needs could initially be met when the Indonesian Nuclear Industry (PT INUKI) was still operating. However, the facility has been discontinued in April 2023 for several reasons and will be transferred to the National Research and Innovation Agency (BRIN).

BRIN is planning to revitalize RIRP facility after changing ownership from PT INUKI to support the radioisotope production program through the Multipurpose Reactor - G.A. Siwabessy (RSG – GAS) in the BJ Habibie Science and Technology Area. However, these revitalization efforts face significant challenges related to radioactive contamination from past radioisotope production activities. Contamination varies in extent and type, including high-radioactivity waste from radioisotope production and unidentified contaminated areas. Radiological and physical surveys of the structures, systems and components to be decontaminated are a very important key step in the initial planning stage. This is to know and record the level of radiation and contamination as well as physical conditions before determining the decontamination plan and technology selection.

Decontamination and dismantling are activities used to revitalize or decommission nuclear facilities. Decontamination is defined as the removal of contamination from the surface of facilities or equipment by washing, heating, chemical or electrochemical action, mechanical cleaning, or other techniques [4]. The purpose of this action is to reduce radiation exposure, salvage equipment and materials, decrease the volume of equipment and materials requiring storage and disposal in licensed facilities, restore the site and facility to a state of unconditional use, remove loose radioactive contaminants and secure any remaining contamination in place in preparation for protective storage or permanent disposal, and reduce the magnitude of the residual radioactive source in protective storage mode for public health and safety reasons or shorten the protective storage period [5]. Dismantling is a crucial part of the decommissioning process involving the disassembly and removal of any structure, system, or component. This stage is a key element of the radioactive waste minimization strategy. Specific factors such as the shape, activation level, or disposition of the contamination can limit the effectiveness of pre-dismantling decontamination. Consequently, even if decontamination methods cannot reduce radioactivity levels to permit materials' return to the public domain, components and structures must still be cut and size-reduced to minimize the volume of materials before storage or disposal as radioactive waste.

The pre-selection of decontamination techniques is based on general characteristics that must meet fundamental requirements, such as radiation protection and the specific conditions of the facility [6]. For the final decision on which technique to use, a more detailed analysis is necessary. The safety assessment should identify the necessary preventive, protective, and mitigating measures and justify that these measures will be suitable and sufficient to ensure safety during D&D process, in compliance with the relevant safety requirements and criteria [7]. The primary purpose of the safety assessment is to demonstrate that residual risks have been reduced to As Low As Reasonably Achievable (ALARA) and meet nationally prescribed safety criteria. The risk assessment provides essential information for developing risk management options for environmental hazards [8].

Despite numerous studies on decontamination and dismantling (D&D) techniques, there remains a gap in systematically integrating hazard assessment methodologies, such as HAZOP, with the selection of decontamination methods tailored specifically for radioisotope and radiopharmaceutical production (RIRP) facilities. Additionally, limited research has explored the comparative effectiveness of different techniques in achieving optimal ALARA implementation within these facilities. A comprehensive literature review on the latest decontamination and dismantling technologies is needed to identify faster, cheaper, and more efficient methods. This paper aims to review the current status of decontamination and dismantling technologies for restoring the potential of RIRP production functions and ensuring operational safety and security in the future through comparing methods, techniques, tools, and materials used. In addition, the HAZOP study considers and reviews potential hazard management strategies to fulfill the ALARA principle when selecting decontamination and dismantling techniques for the RIRP facility.

2. Methodology

2.1 Literature Review

A comprehensive literature review was conducted on decontamination and dismantling (D&D) techniques for the RIRP facility. This review aimed to gather information on various techniques, their applications, and effectiveness. The selection process description outlines the decision-making aspects applied during the practical selection of techniques, focusing on the general requirements and principles influencing the selection within the framework of the project strategy. The technical features of D&D techniques are detailed, providing a thorough understanding of each method's capabilities and limitations. The recommended decontamination techniques will be adapted to the potential types of contamination present in the RIRP facility. Additionally, the dismantling techniques will be proposed based on the structure, system, and components (SSC's) within the RIRP.

The types of radioactive contamination may vary depending on the radionuclide involved, the contamination source, and environmental conditions. The following are some common types of radioactive contaminants found on material surfaces.

- Radioactive Particles:
  Radioactive particles are small particles containing radioactivity that adhere to material surfaces. These particles may originate from dust, smoke, or aerosols containing radionuclides.
- Radioactive Film:
  A radioactive film is a thin layer of radioactive material that adheres to surfaces such as metal or glass.
- Radioactive Liquids:
  Radioactive liquids are fluids containing radionuclides that adhere to surfaces due to spills or leaks, such as radioactive coolants or solvents.
- Radioactive Corrosion or Scale:
  Radioactive corrosion or scale refers to corrosion layers or deposits containing radionuclides that form on metal or other materials due to chemical reactions or radiolytic processes.

- Absorption into Materials:
  This occurs when radionuclides penetrate the structure of materials, such as concrete or plastic.
- Oily Contamination:
  Oily contamination refers to radioactive contamination mixed with oil or other chemicals, forming a sticky layer on material surfaces.
- Residual Contamination:
  Residual contamination is the remaining radioactive contamination that persists after production, testing, or processing of radioactive materials.

When selecting a specific technique for system and/or component decontamination, several key requirements shall be taken into account [4]:

- Safety: The chosen method should not increase radiation hazards, such as external contamination of workers or inhalation of radioactive dust and aerosols formed during its implementation. It should also avoid introducing additional hazards, such as chemical or electrical risks.
- Efficiency: The method should effectively remove radioactivity from surfaces to levels that enable hands-on work instead of relying on robots, permit the recycling or reuse of materials, or allow assignment to a lower waste treatment and disposal category.
- Cost-Effectiveness: Whenever possible, equipment should be decontaminated and repaired for reuse. However, the method should not incur costs that exceed those of waste treatment and disposal of the material.
- Waste Minimization: The method should not generate large quantities of secondary waste, as treating and disposing of this waste would increase personnel requirements and costs, leading to additional exposures.
- Feasibility of Industrialization: Given the large quantities of contaminated materials, the methods or techniques should not be labor-intensive, difficult to handle, or challenging to automate.

2.2 Risk Analysis

To ensure the selection of appropriate decontamination and dismantling techniques, a risk analysis was conducted using Hazard and Operability Study (HAZOP) method. This method involved systematically reviewing potential hazard management strategies to fulfill the ALARA principle. The HAZOP study considered various factors, including safety, efficiency, and compliance with relevant safety requirements and criteria, to identify suitable and sufficient measures to ensure safety during decommissioning. The purpose of HAZOP is to investigate the basic set of operation of the system being assessed, considering deviations that may occur in normal operation and identifying their potential hazardous effects [9]. Several HAZOP procedures will be outlined, including identification of nodes, the application of keyword, hazard identification, and the determination of protection and mitigation measures. These steps are critical for systematically analyzing potential risks and ensuring comprehensive safety during the revitalization process.

The following steps should be iteratively applied to identify accident scenarios that could lead to the exposure of workers and the public or have adverse environmental consequences [7]:

- Identification of Hazards and Initiating Events: Evaluate the activity and location of radioactive sources at the facility and any additional hazards from decommissioning. Identify events that could cause harm to workers, the public, or the environment.
- Hazard Screening: Quantify and screen the identified hazards to focus safety efforts on the significant and relevant hazards and initiating events for the facility.
- Identification of Scenarios: Perform a safety analysis to identify all relevant scenarios, including those from decommissioning activities or accidents, where the screened hazards could occur.

Consideration of conditions as a result of risk identification of the decontamination and dismantling process in the RIRP facility is as shown in Table 1.

Table 1
Condition assessment of risk analysis

Condition	Symbol	Remark
Normal	N	Daily work and according to the procedure
Abnormal	A	The work is not according to the procedure
Emergency	E	Uncontrollable circumstances

Risk is analysed by combining consequences and their likelihood. Consequence refers to the impact or outcome of an event, while likelihood indicates the frequency or probability of damage or hazard occurring. The table of consequences in Table 2 and likelihood level in Table 3 are adapted from the AS/NZS 4360:2004 standard [10]. It is used to determine the rating scale to assess the acceptability of the risk during the D&D process. The level of risk is proportional to likelihood and consequence. This can be mathematically represented as the product of the risk matrix. It can be shown mathematically as :

$$Risk = Consequence \times Likelihood \tag{1}$$

The results of the risk assessment are then presented in the risk assessment matrix in Table 4, and the corresponding risk indicators are shown in Table 5.

Table 2
Likelihood criteria of D&D process [10]

Level	Likelihood	Qualitative Description	Quantitative Description
1	Rare	Almost certainly will not occur	Never occurred during D&D process
2	Unlikely	Less likely to occur	Occurs 1 - 2 times during D&D process
3	Possible	Likely to occur or not occur	Occurs 2 - 3 times during D&D process
4	Likely	Most likely to occur	Occurs >3 times during D&D process
5	Almost certain	Almost certainly will occur	Occurs >5 times during D&D process

Table 3
Consequences criteria of D&D process [10]

Level	Consequences	Description
1	Insignificant	Risk impact is acceptable or can be mitigated by routine activities
2	Minor	Risk impact is acceptable or can be mitigated with minimal effort
3	Medium	The impact of the risk has the potential to degrade the objectives of the D&D process. Handling or mitigation required
4	Significant	The impact of the risk has the potential to inhibit the objectives of the D&D process. Requires special handling or mitigation
5	Fatal	Risk impact has the potential to fail the objectives of the D&D process. Special handling required

Table 4
Risk assessment matrix of D&D process

Likelihood	Consequences 1	2	3	4	5
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5

Table 5
Indicator of the risk assessment matrix D&D process

Color	Symbol	Indication	Conclusion
Green	L	Low	Risk is acceptable. Control measures are considered effective
Yellow	M	Medium	The risk is not yet acceptable. Additional control measures required
Orange	H	High	Risk is unacceptable. Control measures must be taken
Red	VH	Very High	Risk is highly unacceptable. Immediate control measures must be taken

3. Results

The decontamination and dismantling process for the RIRP facility requires a strategy focusing on efficiency, effectiveness, cost, and risk analysis. The initial step is compiling a list of available methods, followed by a preliminary selection based on the project's strategic approach.

3.1 Selection of Decontamination Techniques for the Revitalization of RIRP Facility
3.1.1 Chemical/Electrochemical decontamination of metal

Chemical methods are mainly based on reactions such as dissolution, oxidation/reduction, complexation, and sequestration to remove contaminants from the surface [11]. Chemical decontamination offers advantages such as applicability to inaccessible surfaces, reduced work hours, remote decontamination, and minimal airborne hazards. Additionally, it uses readily available chemical agents, generates wastes, and allows for remote recycling of wash liquids. However, it can produce large volumes of waste, may generate mixed wastes, cause corrosion and safety issues, requires different reagents for different surfaces, requires drainage control, and requires large-scale operations [12].

Electrochemical decontamination primarily uses electrolysis to dissolve the metal anode and remove contaminants from metal surfaces or dissolve them in the electrolyte. This technique is effective for removing radionuclide contamination from conductive surfaces like iron-based alloys, copper, aluminum, lead, and molybdenum. However, its effectiveness is limited by adhering materials, bath size, and surface geometry, making it impractical for industrial decontamination of complex geometries. Table 6 provides an overview of the characteristics and applications of mild and aggressive chemical decontamination methods, as well as electrochemical decontamination of metal.

Table 6
Overview of chemical/electrochemical decontamination of metal

Technique/reagent	Field of application	Advantages	Limitations	Remarks
Mild chemical decontaminations: •Detergents •Creams •Foams •Dilute acids/alkalis •Chemical gel •Pastes	Decontamination of large flat pieces on-site; Decontamination of doors, pools, liners, reactor containment in situ.	Easy to use, Inexpensive, Low exposure of workers	Only remove loose contamination; High secondary waste generation, if additional wet cleaning is needed (pads, brushes, rubber, gloves, etc.); Not applicable to porous surfaces	Measures needed to prevent recontaminations
Aggressive chemical decontaminations: •Concentrated acids/alkalis •Oxidizing/reducing reagents	Removal of thin layers of metal surfaces; Decontamination of relatively complex components and shapes.	Removal of highly contaminated surface; Decontamination to release limits feasible if sufficient material is removed; Commercially available, relatively inexpensive; Low secondary waste production if reagent is reused	Dismantling, segmentation, etc., required; Application on-site usually necessitates use of baths to achieve effective decontamination; Higher exposure of workers	Additional ventilation required; Possible increased hazard from toxic/corrosive gases or solutions; Multistep/alternate treatments often used
Electrochemical decontaminations: •Bath operations •Pad operation	Decontamination of disassembled components; Decontamination of localized 'hot spots' and regular surfaces.	Fast with high DF Low volume of secondary waste production	May not be effective for hidden surfaces having poor electrolyte contact; Possible high exposure of workers; Not applicable to complex or inaccessible surfaces	

3.1.2 Physical decontamination process

In addition to chemical and electrochemical methods for comprehensive decontamination, physical processes are also employed. These tend to be simpler to implement but are usually less intensive compared to electrochemical and chemical methods. An overview of the characteristics and applications of the physical decontamination process is shown in table 7.

3.1.3 Decontamination of buildings and concrete

During NPP decommissioning, over 70% of intermediate- and low-level solid radioactive waste comprises concrete and metal building materials [13].

Table 7
Overview of physical decontamination process

Technique	Field of Application	Advantages	Limitations	Remarks
Ultrasound Cleaning	Decontamination of pieces with unstable contamination	Fast, enhances chemical effects, synergy with chemicals	Limited to light contamination, not for deep cleaning	Often used post chemical cleaning
CO2 Ice Blasting	Removal of contamination from various surfaces	High speed, effective, minimal secondary waste	Loud, requires safety measures due to CO2, test needed	CO2 pellets evaporate, leaving no residue
Ice Blasting	Similar to CO2 blasting but uses ice crystals	Easier setup than CO2, effective contaminant removal	Less aggressive, liquid effluent treatment needed	Similar to CO2 but uses water ice
Pressurized Water Jet	Cleaning pool walls, dismantled pieces, tools	Can use low to high pressure, adjustable temperatures	Generates aerosols, high water use	Effective for various contamination levels
Abrasive Techniques	Decontamination with recycling of abrasives	Dry and wet methods, various materials can be used	Needs recycling to limit waste, potential cross contamination	Used in ventilated areas, automated systems available
Vibration Abrasive Techniques	Decontamination of removable pieces	Effective for a range of materials	Size limitations, machine-specific	Can cut large components for processing
Flushing with Water	Large areas not suitable for scrubbing	Simple, uses solvent action of water	Potential for erosion, debris collection needed	Flooding surfaces with hot or cold water
Dusting/Vacuuming/Wiping/Scrubbing	Removal of loose contaminants from surfaces	Direct removal of particles, adjustable techniques	Pre-treatment, not for ingrained contaminants	Common cleaning techniques used
Strippable Coatings	Wide range of surfaces, especially non-porous	High decontamination factors, no liquid waste	Requires setting time, surface accessibility	Easy disposal of waste with stripped
UV-Curing	Surface coating, adhesive applications, printing industry, automotive, electronic devices, aerospace	Fast curing process, high efficiency, environmentally friendly, energy-saving, high productivity, cost-effective	Limited penetration depth, may require specific formulations	Ideal for applications requiring quick turnaround times and high precision
Steam Cleaning	Complex shapes and large surfaces with grease	Low secondary waste, effective removal	Requires vacuum extraction for waste	Combines kinetic and solvent actions of hot water

Table 8
Overview of building and concrete decontamination techniques

Technique	Field of application	Advantages	Limitations	Remarks
Scabbling	Removal of upper concrete layers	Dry process, no water or chemicals needed, effective for thin layers	Work rates vary with concrete composition, not suitable for deeply contaminated surfaces	Suitable for large and small areas
Milling/Shaving	Removal of concrete layers up to a few millimeters	Produces smooth surface finish, effective for larger surfaces	Limited to shallow depths, requires diamond-tipped tools	Remote-controlled systems available for large areas
Rock Breaker/Jackhammer	Deep decontamination of floors and potentially walls	Effective for deep contamination	Labour-intensive, may produce a lot of secondary waste	Suitable for floors with deep contamination

The selection of the right decontamination technique for building and concrete is necessary because the waste from decommissioning in the form of concrete and metal must be handled properly. Table 8 provides an overview of the building and concrete decontamination techniques.

3.1.4 Recommendation of decontamination techniques for the revitalization of the RIRP Facility

For chemical and electrochemical decontamination of metal in Tabel 6, chemical decontamination methods such as acid cleaning should be used in controlled environments to minimize exposure to hazardous chemicals and ensure proper ventilation. This method is effective at removing contaminants from metal surfaces, enabling hands-on work, and is relatively low cost compared to waste disposal. It generates liquid waste that can be treated and neutralized and can be automated and scaled for large volumes.

Research on decontamination methods using chemicals was conducted by Maengkyo *et al*., [14] focused on the chemical decontamination of radioactive concrete, specifically utilized potassium ferrocyanide for the removal of ^{137}Cs and ^{60}Co, while ^{90}Sr was removed through co-precipitation with BaSO4 from acidic wastewater generated during the treatment process. The chemical precipitation method successfully reduced the radioactivity of ^{137}Cs and ^{60}Co to levels below the discharge criteria. While the removal efficiency of 90 Sr significantly increased to 98.8% when 0.02 M of Ba^{2+} was injected.

Electrochemical decontamination presents lower chemical risks but requires safe handling of electrical equipment. It is highly effective in decontaminating metal surfaces, suitable for recycling and reuse, with minimal secondary waste compared to chemical methods, and is suitable for industrial-scale applications and automation. The research conducted by Lu *et al*., [15] investigated the electrochemical decontamination method with ultrasonic technology and compared its effectiveness with electrochemical decontamination only. The result demonstrated that the ultrasonic-assisted method offered good decontamination efficiency, required simpler equipment, and used fewer chemical reagents.

Physical decontamination processes as shown in Table 7, dry ice blasting is recommended for its safety, as it does not generate hazardous secondary waste, and its effectiveness in removing contaminants without damaging surfaces. It has moderate equipment costs with low operational costs and minimal secondary waste since dry ice sublimates, making it easily scalable and automatable. Masserant in his patent [16] developed a system for cleaning components contaminated with radioactive materials using dry ice blasting within a chamber. This method employed bead reaction and thermal quenching via dry ice blasting to effectively remove oxide layers from stainless steel and carbon steel surfaces. EDX analysis verified the successful removal of these oxide layers from the sample. Abrasive blasting, while very effective in cleaning surfaces, requires proper containment and protective equipment to prevent dust inhalation. It is cost-effective for large-scale operations but generates significant secondary waste that requires disposal and is suitable for large-scale operations with proper waste management.

For building and concrete decontamination techniques in Table 8, scabbling can be used to remove surface contamination on concrete, while a jackhammer can be employed to eliminate contamination within the concrete. Both techniques can be applied to small or large areas. In comparison, milling/shaving requires additional cutting components, which can impact the costs involved in the decontamination process. The potential types of contamination and the recommended decontamination methods for each room and/or component within the RIRP facility are presented in Table 9

Table 9
Decontamination technique recommendations

No	SSC	Types of Contamination*	Decontamination Methods **
1	**Hotcell:**		
	• Floor	1, 2, 3, 5, 7	1.b, 1.e, 1.f, 3
	• Wall	1, 2, 3, 5	1.b, 1.e, 1.f, 3
	• Roof	-	1.b
	• Equipment	1, 2, 3, 5	1.b, 1.e, 1.f
2	**Radioisotope Lab:**		
	• Floor	1, 3, 5, 7	1.b, 1.e, 1.f, 3
	• Wall	1, 3, 5	1.b, 1.e, 1.f, 3
	• Roof	-	1.b
	• Equipment	1, 3, 5	1.b, 1.e, 1.f
3	**Radiopharmacy Lab:**		
	• Floor	1, 3, 5, 7	1.b, 1.e, 1.f
	• Wall	1, 3, 5	1.b, 1.e, 1.f
	• Roof	-	1.b
	• Equipment	1, 3, 5	1.b, 1.e, 1.f
4	**Quality Control Lab:**		
	• Floor	1, 3, 5, 7	1.b, 1.e, 1.f
	• Wall	1, 3, 5	1.b, 1.e, 1.f
	• Roof	-	1.b
	• Equipment	1, 3, 5	1.b, 1.e, 1.f
5	**Target Preparation Area:**		
	• Floor	1, 2, 3, 5, 7	1.b, 1.e, 1.f, 3
	• Wall	1, 2, 3, 5	1.b, 1.e, 1.f, 3
	• Roof	-	1.b
	• Equipment	1, 2, 3, 5	1.b, 1.e, 1.f
6	**Irradiated Target Reception Area:**		
	• Floor	1, 2, 3, 5, 7	1.b, 1.e, 1.f, 3
	• Wall	1, 2, 3, 5	1.b, 1.e, 1.f, 3
	• Roof	-	1.b
	• Equipment	1, 2, 3, 5	1.b, 1.e, 1.f
7	**Waste Storage:**		
	• Floor	1, 2, 3, 5, 7	1.b, 1.e, 1.f
	• Wall	1, 2, 3, 5	1.b, 1.e, 1.f
	• Roof	-	1.b
	• Equipment	1, 2, 3, 5	1.b, 1.e, 1.f
8	**Corridor:**		
	• Floor	1, 3, 5	1.b
	• Wall	1, 5	1.b
	• Roof	-	1.b
9	**Employee Room:**		
	• Floor	1	1.a, 1.b
	• Wall	1	1.a, 1.b
	• Roof	-	1.a, 1.b
	• Equipment	1	1.a, 1.b

3.2 Selection of Dismantling Techniques for the Revitalization of RIRP Facility

Dismantling means the complete or partial dismantling of a building structure. It excludes refurbishment, provided the work does not involve the alteration of existing structural components [17]. The selection of these technologies involves assessing factors like cutting speed, radiation exposure, maintenance frequency, dust emissions, contamination, secondary waste generation, fire hazards, rigging requirements, noise levels, and industrial safety issues related to heights, especially in congested areas.

3.2.1 Concrete cutting and dismantling techniques

Most of the waste generated from the dismantling process is contaminated concrete. Therefore, the selection of appropriate techniques is necessary to safely address these issues. A brief review of concrete cutting and dismantling techniques are shown in Table 10.

Table 10
Overview of concrete cutting and dismantling techniques

Technique	Fields of Application	Advantages	Limitations	Remarks
Controlled Blasting	Heavily reinforced concrete sections	High cutting rate	Requires a blasting expert, significant preparation, potential for high noise and vibration	Effective for large-scale demolition, uses delayed firing techniques to control fragmentation
Wrecking Ball or Slab	Non-reinforced or lightly reinforced concrete structures	Suitable for low structures and breaking rubble	Slow, not recommended for radioactive structures	Limited to about 15 m height due to crane instability
Flame Cutting	Situations where vibration is not permissible	Effective for thick concrete	Produces large amounts of smoke	Uses a thermite reaction to decompose concrete, requires efficient exhaust system
Thermite Reaction Lance	Cutting holes or slits in nuclear facilities	Effective for precision cuts	Produces large amounts of smoke	Used for cutting reinforced concrete, requires exhaust system
Rock Splitter	Fracturing concrete in limited access areas	High cutting rate, minimal noise and vibration	Not suitable for thick reinforced concrete	Uses hydraulic expansion to fracture concrete, requires multiple splitters for long sections
Circular Diamond or Carbide Saws	Removing entire wall or floor sections	Medium cutting rate, dust control with water spray	Slow cutting reinforcing bars, limited to 40% of blade diameter	Suitable for concrete up to 1 m thick
Core Stitch Drilling	Precision cuts in complex geometries	Medium cutting rate, low disturbance to surroundings	Requires rock splitter and reinforcing bar cutter	Used for precision removal of beams and other structures
Wire Cutting	Cutting large blocks of reinforced concrete	Precise cuts, low debris, high cutting rates	Requires initial drilling to feed the wire	Uses diamond wire, suitable for nuclear and non-nuclear applications

3.2.2 Segmenting metal component

Large metal component is decided to be segmented, a segmentation strategy, which can be defined as a process to find a set of lengths and/or angles to segment an object with a view to optimizing subsequent management of resulting segmented pieces, should be considered early in planning for decommissioning. A brief review of segmentation processes for metal components of varying thicknesses is presented in Table 11.

Table 11
Overview of segmentation processes for metal components

Technique	Fields of application	Advantages	Limitations	Remarks
Arc saw cutting	Cut any conductive metal without contacting the workpiece	Faster cutting rates, no contact with workpiece	Practical problems with large blade access and positioning, large containment envelopes required	Good for underwater operation, some development required for large scale operation
Oxygen burning	Cutting of metals uses a torch assembly carrying a flowing mixture of fuel gas and oxygen	Good for mild steel, equipment readily available, easy setup	Good only for mild steel, requires suitable ventilation, dust and aerosols generation	Easy adaptation to remote operation, commonly used in maintenance
Plasma arc torch	Rapid cutting of all conductive metals	High current densities and temperatures, breaks gas molecules into plasma	Requires well-ventilated workspace, produces large quantities of aerosol, smoke and dust	Different gases can be used, producing various results
Thermite reaction lance	Cut through most kinds of metal	Can cut through most kinds of metal	Handheld operation, extensive ventilation required	Effective for cutting reinforcing bars, thermite reaction
Explosive cutting	Cutting pipes from the outside as well as from the inside using shaped charges	Only a few grams of explosive required, can cut pipes from inside or outside	Used only in special cases, not practical for all scenarios	Effective for cutting concrete beams, minimal explosive required
Laser cutting	Cutting of metals	High precision cutting	Under development, relatively large equipment needed	Effective for precision cutting of various metals
Mechanical nibbler	Cut plates and tanks	Effective for cutting thin sheets, easy debris management	Limited to thin sheets, small amounts of aerosols	Effective for small parts, easy debris management
Shears	Cut sheet metal, pipes and small rods and bars	No dust or smoke, only large debris	Limited to thin materials, low wall thickness cutting	Effective for small metal parts, no dust generation

Circular cutting machines	Cut cylindrical components	Can cut thick pipes with multiple passes, maintains contamination control	Needs vacuuming of chips, lubricants recycling	Effective for cylindrical parts, maintains contamination control
Abrasive cutters	Segment all types of component	Effective for segmenting components, can use water lubricants	Produces sparks and dust, not suitable near consumables	Effective for stationary setup, easy contamination control
Hacksaw, guillotine saw	Cut all types of metal pieces	Relatively inexpensive, high cutting speeds, reduced fire hazards	Requires setup and clamping, may need lubrication	Effective for both portable and stationary use, easy setup
Abrasive water jet	Cut metals using abrasive water jet technique	Uses high velocity water jet with abrasives for cutting	Nozzle life is short, under development	Effective for various metal types, needs further development
Fissuration cutting	Cutting metal components without producing secondary waste	Produces low aerosols and smoke, low temperature process	Under development, can only cut up to 10 cm thick	Produces low secondary waste, low aerosol generation

3.2.3 Recommendation of dismantling techniques for the revitalization of the RIRP Facility

Concrete cutting and dismantling techniques in Table 10, such as diamond wire cutting and hydraulic bursting, offer various benefits. Diamond wire cutting is safe due to low dust and noise levels, highly efficient with precise cutting, and cost-effective for large-scale projects despite moderate to high initial costs. It also produces minimal secondary waste and is scalable and suitable for automation. Hydraulic bursting is safe with a low risk of airborne dust, efficient in breaking down large concrete structures, and cost-effective by reducing labor-intensive work. It generates minimal secondary waste and is easily industrialized and scalable.

For metal components segmentation in Table 11, plasma arc cutting and mechanical cutting are effective techniques. Plasma arc cutting requires proper ventilation to manage fumes but offers high precision and speed, making it effective for metal segmentation. Despite high initial costs, it reduces overall labor costs and generates minimal secondary waste, making it suitable for automation and large-scale use. Mechanical cutting is safe with proper protective equipment, effective for various metal types, and has a lower initial cost compared to plasma arc cutting. It produces manageable secondary waste and is feasible for industrial applications. Other options that can be used as demolition techniques at the RIRP facility are shown in Table 12 as follows.

Table 12
Dismantling option for the RIRP Facility

No	Structure, System, Component	Release Manually	Segregation			Demolition
			Arc cutting	Abrasive Cutting	Cold Cutting	
1	Hotcell:					
	- Hand Manipulator	•		•	•	
	- Conveyor	•		•	•	
	- Plugin door	•	•	•	•	
2	VAC system	•	•	•	•	
3	Pipe, pump, valve, etc.	•	•	•	•	
4	Building structure (roof, wall, floor, fondation)	•		•	•	•
5	Equipment and furniture (Glove box, lab furniture, fume hood etc.)	•	•	•		

3.3 HAZOP Application for Decontamination and Dismantling Project of RIRP Facility

The main focus of the HAZOP study conducted in this paper is to analyze the major hazards with potentially significant consequences related to D&D activities. This is due to the varying levels and types of contamination, including waste from radioisotope production processes that may have relatively high radioactive activity, as well as various areas of contamination and radiation. There is a division of working areas in the RIRP facility to facilitate dose monitoring consisting of contamination zones in Table 13 and radiation zones in Table 14.

Table 13
Division of contamination in the RIRP facility

Division of contamination zones in IPRR:	
Zone A	Contamination Free
Zone B (Low)	< 0.37 Bq/cm^2 : alpha < 3.7 Bq/cm^2 : beta
Zone C (Medium)	0.37 Bq/cm^2 ≤ CL< 3.7 Bq/cm^2: alpha 3.7 Bq/cm2 ≤ CL< 37 Bq/cm2: beta
Zone D (High)	≥ 3.7 Bq/cm^2: alpha ≥ 37 Bq/cm2: beta

Table 14
Division of radiation in the RIRP facility

Division of radiation zones in IPRR:	
Zone I	Work area with radiation exposure R ≤ 0.5 mrem/h (5 µSv/h)
Zone II	Work area with radiation exposure R ≤ 2.5 mrem/h (25 µSv/h)
Zone III	Work area with radiation exposure R ≤ 50 mrem/h (500µSv/h)
Zone IV	Work area with radiation exposure R ≥ 50 mrem/h (500µSv/h)

Based on the potential contaminated areas within the RIRP facility, the respective contamination and radiation zones are applied as Table 15 shows follows.

Table 15
Potential contaminated area within radioisotope and radiopharmaceutical facility

Area	Contamination zone	Radiation zone
Hot Cell	Zone D	Zone IV
Receiving and Storage Area	Zone D	Zone IV
Target preparation area	Zone D	Zone IV
Irradiated Target Receiving Area	Zone D	Zone IV
Radioisotope Lab	Zone D	Zone IV
Radiopharmaceutical Lab	Zone C	Zone III
Quality Control Lab	Zone C	Zone III
Corridor	Zone B	Zone II
Staff room	Zone A	Zone I

3.3.1 HAZOP nodes of D&D project for RIRP facility

Nodes are defined as manageable sections with definite boundaries, created by breaking down the design into smaller, clearly defined parts [18]. Determination of study points or nodes based on the sequence of activities to be carried out during the D&D process on the RIRP facility is shown in table 16.

Table 15
List of nodes for HAZOP study for the RIRP facility

Revitalization Stage	Node	Title
Radiological survey and characterization	1	Collect all relevant data regarding the status of factories entering the safe enclosure or demolition phase, including inventory of non-radioactive hazardous materials and radionuclides in buildings, equipment and other materials
Decontamination and Dismantling	2	Building preparatory work (Structures such as tents or barriers)
	3	Fans, vents, and HVAC controls for managing airflow and contaminant control
	4	Clean/remove the air filter
	5	Remove small items, drives/motors from areas
	6	Remove/size reduce large items
	7	Remove steel platforms, power distribution panels, emergency power systems, and grounding
	8	Decontamination and monitoring of cut sections
	9	Clean/decontaminate room
Waste management	10	Place all waste collection in containers, transport systems, and temporary storage areas
	11	Pathways for moving materials and equipment
Final survey	12	Monitoring facility
	13	Preparation of the final report
	14	Coordination with stakeholders

3.3.2 Selection of process keyword

Keywords are terms associated with hazards that initiate hazard identification when applied to nodes. Hazard-based keywords are used to discuss the credibility or possible causes of hazards, qualitative consequences for operators, on-site workers, general public, protection or mitigation measures to reduce frequency, and manage hazards. HAZOP studies for D&D projects of RIRP facility utilized standard keywords based on the revitalization stage to analyze the design, facilitating discussions that identified potential hazards and operational challenges. This process led to the removal of hazards and the implementation of safety measures. The keywords for D&D projects are listed in Table 17.

Table 17
HAZOP study keyword

1	Radiation	16	Dropped loads
2	Critically incident	17	Conventional hazards
3	Shielding	18	Ergonomic hazards
4	Chemical spill	19	Loss of power supply
5	Effluents	20	Loss of communication
6	Airborne contamination	21	Human error
7	Toxicity	22	Control and instrumentation
8	Fire	23	Personal Protective Equipment
9	Explosion	24	Confined space
10	Corrosion exposure	25	Extreme weather
11	Noise exposure	26	Structural collapse
12	Ventiilation failure	27	Waste mismanagement
13	Enviromental impact	28	Maintainability

3.3.3 Hazards identification, risk assessment, and risk control

Protection and mitigation measures are essential components of risk management, which involve implementing controls to minimize identified hazards, reduce exposure levels, and protect sensitive populations from adverse health outcomes. In its classical meaning, mitigation refers to a sustained action taken to reduce or eliminate risk to people and property from hazards and their effects [19]. Identification of hazards during the D&D process to identify any potentially hazardous and accidental work areas in the RIRP facility. The result of the hazard identification is as shown in Table 18.

Table 18
Hazard identification during D&D process

No.	Process	Hazard	Risk	Condition
1	Characterization	Excessive radiation exposure, toxic chemical exposure, airborne contaminant	Exposed to excess radiation, contamination, lack of oxygen, slip, fall	N
2	Waste removal, loading into containers	Excessive radiation exposure, container leakage, toxic chemical exposure, dropped highly contaminated items	Exposed to excess radiation, contamination, lack of oxygen	E
3	Removing/cutting/deconta-minating components	Radioactive dust, contaminant, hard and heavy objects, dropped heavy loads, electric current, noise, restricted access	Inhalation of radioactive dust, contamination, lack of oxygen, electrocution, crushed, fall, worker injury or fatality	E
4	Clean/replace the air system filter	Airborne contaminant, failure/malfunction of building ventilation system, wastes, noise	Inhalation of radioactive dust, contamination, electrocution, fall, slip, worker injury or fatality	A
5	Handling of reagents and chemical	Chemical spill, toxic fumes, fire/explosion	Contamination, chemical burns, inhalation of toxic fumes	N
6	Decontaminating and dismantling walls and floors	Radioactive dust, contaminant, fire/explosion, wastes, noise, building collapse	Inhalation of radioactive dust, contamination, lack of oxygen, slip, fall,crushed, worker injury or fatality	A
7	Secondary waste transfer and management	Radiation exposure, container leakage, toxic chemical exposure, dropped heavy loads	Exposed to excess radiation, contamination, environmental pollution	N

Meanwhile, risk assessment used to determine the level of risk during the D&D process in each area of the RIRP facility are shown in Table 19 to 27.

Table 19
Risk assessment of D&D process in the Hot Cell

Area	Process	Likelihood	Consequence	Risk rating	Result
Hot Cell	Characterization	2	5	10	High
	Waste removal, loading into containers	3	5	15	Very High
	Removing/cutting/decontaminating components	3	5	15	Very High
	Clean/replace the air system filter	3	5	15	Very High
	Decontaminating and dismantling walls, and floors	3	5	15	Very High
	Secondary waste transfer and management	3	4	12	High

Table 20
Risk assessment of D&D process in the Receiving and Storage Area

Area	Process	Likelihood	Consequence	Risk rating	Result
Receiving and Storage Area	Characterization	2	5	10	High
	Waste removal, loading into containers	2	5	10	High
	Removing/cutting/decontaminating components	3	5	15	Very High
	Clean/replace the air system filter	2	5	10	High
	Decontaminating and dismantling walls, and floors	3	5	15	Very High
	Secondary waste transfer and management	2	5	10	High

Table 21
Risk assessment of D&D process in the Target Preparation Area

Area	Process	Likelihood	Consequence	Risk rating	Result
Target Preparation Area	Characterization	2	5	10	High
	Waste removal, loading into containers	3	5	15	Very High
	Removing/cutting/decontaminating components	3	5	15	Very High
	Clean/replace the air system filter	3	4	12	High
	Decontaminating and dismantling walls, and floors	3	5	15	Very High
	Secondary waste transfer and management	2	5	10	High

Table 22
Risk assessment of D&D process in the Irradiated Target Receiving Area

Area	Process	Likelihood	Consequence	Risk rating	Result
Irradiated Target Receiving Area	Characterization	2	5	10	High
	Waste removal, loading into containers	3	5	15	Very High
	Removing/cutting/decontaminating components	3	5	15	Very High
	Clean/replace the air system filter	3	5	15	Very High
	Decontaminating and dismantling walls, and floors	3	5	15	Very High
	Secondary waste transfer and management	3	4	12	High

Table 23
Risk assessment of D&D process in the Quality Control Lab

Area	Process	Likelihood	Consequence	Risk rating	Result
Quality Control Lab	Characterization	2	5	10	High
	Waste removal, loading into containers	2	4	8	Medium
	Handling of reagents and chemical	3	3	6	Medium
	Removing/cutting/decontaminating components	2	5	10	High
	Clean/replace the air system filter	2	4	8	Medium
	Decontaminating and dismantling walls, and floors	2	5	10	High
	Secondary waste transfer and management	2	4	12	High

Table 24
Risk assessment of D&D process in the Radiopharmaceutical Lab

Area	Process	Likelihood	Consequence	Risk rating	Result
Radiopharmaceutical Lab	Characterization	2	5	10	High
	Waste removal, loading into containers	2	5	10	High
	Handling of reagents and chemical	2	4	8	Medium
	Removing/cutting/decontaminating components	3	5	15	Very High
	Clean/replace the air system filter	2	4	8	Medium
	Decontaminating and dismantling walls, and floors	2	5	10	High
	Secondary waste transfer and management	2	4	8	Medium

Table 25
Risk assessment of D&D process in the Radioisotope Lab

Area	Process	Likelihood	Consequence	Risk rating	Result
Radioisotope Lab	Characterization	2	5	10	High
	Waste removal, loading into containers	3	4	12	High
	Handling of reagents and chemical	2	4	8	Medium
	Removing/cutting/decontaminating components	3	5	15	Very High
	Clean/replace the air system filter	2	4	12	High
	Decontaminating and dismantling walls, and floors	3	4	12	High
	Secondary waste transfer and management	2	4	8	Medium

Table 26
Risk assessment of D&D process in the Corridor

Area	Process	Likelihood	Consequence	Risk rating	Result
Corridor	Characterization	2	3	6	Medium
	Waste removal, loading into containers	1	4	8	Low
	Removing/cutting/decontaminating components	2	3	6	Medium
	Clean/replace the air system filter	1	3	3	Low
	Decontaminating and dismantling walls, and floors	2	3	6	Medium
	Secondary waste transfer and management	1	3	3	Low

Table 27
Risk assessment of D&D process in the Staff Room

Area	Process	Likelihood	Consequence	Risk rating	Result
Staff Room	Characterization	1	3	3	Low
	Waste removal, loading into containers	1	4	8	Low
	Removing/cutting/deconta-minating components	2	3	6	Medium
	Clean/replace the air system filter	1	3	3	Low
	Decontaminating and dismantling walls, and floors	2	3	6	Medium
	Secondary waste transfer and management	1	3	3	Low

Risk assessments of the D&D process for the RIRP facility indicate that these activities require hazard mitigation or control. Table 28 shows the risk control of each process during the decontamination and dismantling activities of the facility.

Table 28
Risk control of D&D process for the RIRP facility

No.	Process	Hazard	Risk	Controlling
1	Characterization	Excessive radiation exposure, toxic chemical exposure, airborne contaminant	Exposed to excess radiation, contamination, lack of oxygen, slip, fall	SOP, PPE, operator certification and regular training, appropriate and addquate equipments, Clear signage and communication of hazard zones
2	Waste removal, loading into containers	Excessive radiation exposure, container leakage, toxic chemical exposure, dropped highly contaminated items	Exposed to excess radiation, contamination, lack of oxygen	SOP, PPE, operator certification and regular training, appropriate and adequate equipments, provision of adequate waste containers, protection of waste containers during the transfer process, maintenance and testing of lifting or transport equipment, proper labeling and documentation of waste.
3	Removing/cutting/deconta-minating components	Radioactive dust, contaminant, hard and heavy objects, dropped heavy loads, electric current, noise, restricted access	Inhalation of radioactive dust, contamination, lack of oxygen, electrocution, crushed, fall, worker injury or fatality	SOP, PPE, operator certification and regular training, appropriate and adequate equipments, maintenance and testing of lifting or transport equipment, installation of plastic/dust collector in the work area, maintenance of tools
4	Clean/replace the air system filter	Airborne contaminant, failure/malfunction of building ventilation system, wastes, noise	Inhalation of radioactive dust, contamination, electrocution, fall, slip, worker injury or fatality	SOP, PPE, operator certification and regular training, appropriate and adequate equipments, maintenance of equipment, installation of plastic/dust collector in the work area, immediate replacement or repair of malfunctioning systems, regular air quality monitoring
5	Handling of reagents and chemical	Chemical spill, toxic fumes, fire/explosion	Contamination, chemical burns, inhalation of toxic fumes	SOP, PPE, operator certification and regular training, appropriate and adequate equipments, proper storage and labeling of chemicals, implementation of fire and explosion prevention measures, availability of MSDS and emergency response plans
6	Decontaminating and dismantling roofs, walls, and floors	Radioactive dust, contaminant, fire/explosion, wastes, noise, building collapse	Inhalation of radioactive dust, contamination, lack of oxygen, slip, fall,crushed, worker injury or fatality	SOP, PPE, operator certification and regular training, appropriate and adequate equipments, maintenance and testing of lifting or transport equipment, installation of plastic/dust collector in the work area, maintenance of tools, continuous air monitoring for radioactive dust and other contaminants, coordination with structural engineers to ensure building integrity
7	Secondary waste transfer and management	Radiation exposure, container leakage, toxic chemical exposure, dropped heavy loads	Exposed to excess radiation, contamination, environmental pollution	SOP, PPE, operator certification and regular training, appropriate and adequate equipments, provision of adequate waste containers, protection of waste containers during the transfer process, maintenance and testing of lifting or transport equipment, proper labeling and documentation of waste, regular environmental monitoring for potential contamination.

4. Conclusions

This research aimed to identify and recommend the most effective techniques for decontamination and dismantling, along with conducting a risk analysis and HAZOP study, specifically for the revitalization of RIRP facility. For decontamination, chemical and electrochemical methods such as acid cleaning and electrochemical processes are effective for metal surfaces, offering low-cost solutions and minimal secondary waste. Physical methods like dry ice blasting, abrasive blasting, ultrasonic cleaning, and laser cleaning are recommended for their safety, efficiency, and cost-effectiveness in different contamination scenarios. For dismantling, techniques such as diamond wire cutting, hydraulic bursting, plasma arc cutting, and sawing are chosen to minimize radioactive waste and ensure safety, with methods tailored to specific contamination and activation levels, allowing efficient management for storage or disposal. A comprehensive HAZOP study was conducted, systematically reviewing potential hazards and implementing preventive, protective, and mitigating measures to ensure safety during decommissioning. The results of the HAZOP analysis show that the D&D process for the RIRP facility to be carried out has 7 processes with several potential hazards. The risk level of overall area shows 15 very high categories, 22 high categories, 13 medium category, and 7 low categories. Risk control during the D&D process has been proposed to ensure operational safety and security.

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