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MANAGING EXTERNAL RADIATION EXPOSURE AND AREA ZONING IN INDUSTRIAL RADIOGRAPHY TRAINING: A CASE REPORT

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List of Abbreviations

ALARA	: As Low As Reasonably Achievable
BAPETEN	: Badan Pengawas Tenaga Nuklir / Nuclear Energy Regulatory Agency of Indonesia
Co-60	: Cobalt-60
Cs-137	: Cesium-137
HVL	: Half-Value Layer
IAEA	: International Atomic Energy Agency
ICRP	: International Commission on Radiological Protection
Ir-192	: Iridium-192
NDT	: Non-Destructive Testing
Pb	: Lead
PPE	: Personal Protective Equipment
RSC	: Radiation Safety Competence
SE	: Shielding Effectiveness
SSD	: Source-to-Surface Distance
Sv	: Sievert
TVEI	: Technical and Vocational Education Institution
ZORC	: Zone of Radiological Control

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ABSTRACT

Introduction: Industrial radiography training involves the use of high-activity gamma radiation sources that may pose radiation hazards to trainees and instructors if not properly controlled. Effective radiation safety management is therefore essential to minimize exposure and comply with occupational and public dose limits. **Objective:** This study aimed to evaluate radiation hazards, determine controlled and supervised area boundaries, and assess shielding effectiveness during industrial radiography training. **Methods:** A simulation-based assessment was conducted using gamma radiation sources commonly applied in industrial radiography training. Radiation dose rates were measured at various distances and compared with calculated values. Two exposure scenarios were analyzed: a large-area condition without predefined public dose constraints and a built-up area condition applying public dose limits. The effectiveness of lead, brick, steel, and wood shielding was evaluated based on dose attenuation and half-value layer (HVL) characteristics. **Results:** Measured and calculated dose rates showed close agreement. Area boundary distances varied by radiation source and exposure scenario, with larger distances required under the large-area condition. Lead provided the highest attenuation at relatively small thicknesses, whereas brick, steel, and wood required greater thicknesses. **Conclusion:** Appropriate area zoning, distance control, and shielding selection are essential to ensure radiation safety during industrial radiography training.

Keywords: Industrial Radiography; Occupational Radiation Exposure; Radiation Protection; Dose Calculation; Safety Management

INTRODUCTION

Non-Destructive Testing (NDT) is used in many industries such as oil and gas, construction, manufacturing, military maintenance (where NDT is performed on aircraft) and power generation. This procedure applies ionizing radiation in the form of gamma ray and X-ray to non-destructively test the internal condition of materials. Although highly efficient, the industrial radiography is ranked as one of the highest risk activities in occupational radiation exposure due to the application of high-activity sources, mobile environment and sometimes working under uncontrolled or temporary enclosures (1). As a consequence, radiation protection failures can result in overexposures of workers or unintentional exposures of others in addition to larger public health effects.

From a disaster health management point of view, radiological industrial accidents present a major challenge within the preparedness and risk mitigation context. Lost or abandoned radioactive sources, poor control of radiation area and lack of suitable safety training have been cited as factors contributing to radiologic emergencies with possible societal consequences beyond the workplace (2). Therefore, capacity building of radiation workers in the area of radiation safety prior to deployment in industries is a critical preventive strategy for avoiding flooding of disasters attributed to ionizing radiations.

Good handling of external irradiation is based on the application of basic radiation protection principles such as: exposure time reduction, distance maximization from radiation sources, shielding and identification of controlled areas. These principles are firmly anchored in international radiation safety standards, and constitute the very essence of the ALARA (As Low As Reasonably Achievable) philosophy (3). But, the practical application of these principles is often complicated in industrial radiography because of its dynamic operation (changing source descriptions and work conditions) along with temporary facilities which are commonly used therein as one may be working on different sites constantly causing a problems for inexperienced operators.

It has been documented in various articles that although the dose received by occupational personnel working with industrial machines tends to be within regulatory limits, some overexposure occurs as a result of procedural error, lack of situational awareness and lack of training (4). One notable case is provided by the radiological accident related to an Iridium-192 source in Nanjing, China, where deaths of patients and medical staffs indicate failure of radiation area identification and source control leading to serious exposure with delayed emergency response (5). Events such as this highlight the need for early training that focuses on hazard recognition, risk control and exercising judgment in conditions that mirror actual operations.

Training colleges and technical institutes have a strategic role to play in training future radiation workers with practical competences on radiation protection as part of disaster risk reduction. Simulation-based penetrating radiation training provides an opportunity to close the gap between understanding penetration theory and practical application; trainees can observe dose rate effects first hand, practice distance and shielding concepts, and experience delineated radiation areas in a controlled setting (6). At the level of disaster health management, this type of capacity building contributes to workforce resilience and strengthens preparedness for radiological emergencies, as well as the prevention of occupational radiation incidents.

However, the empirical basis for explaining how hands-on simulator training experiences in industrial radiography assist with management of external radiation exposure is not well-documented, especially in relation to Technical and Vocational Education Institution (TVEI) training settings within low- and middle-income countries. The literature in the field has tended to concentrate on regulatory compliance or reviews of historical dose, with less attention given to training processes and what these imply for preparation towards safety culture (7). This void underscores the importance of case-based evaluations that illustrate how radiation protection principles are applied in training and the degree to which they comply with internationally established safety protocols.

Due to this, the purpose of this case report is to investigate how external radiation exposure and radiation area identification can be dealt with practically in an industrial radiography training exercise in a vocational nuclear technology institution. By critically examining hazard identification, distance and time planning, shielding effectiveness and the designation of controlled and supervised areas in this paper we attempt to contribute with regards the role of applied radiation safety training as a prevention approach in disaster health management and occupational health context.

METHODS

Study Design

Method The study was designed as a qualitative observational case report with nested quantitative measurements of radiation doses. The method was aimed at assessing the operational performance of external radiation exposure control and radiation area identification during a planned practical industrial radiography training exercise. Such a study was chosen to reflect the timely application of radiation protection practice in response/ recovery and also to applicable for work force readiness, disaster health management.

Study Setting

The research was carried out at a Vocational Nuclear Technology institution (Vocational of Nuclear Technology X), which has the industrial radiography process as part of its curriculum. All the activities were performed in a restricted training area, and it simulated industrial radiography situations respecting national nuclear safety regulations.

Participants

The study included 21 students of vocational nuclear technology profile. Subjects who were registered for the industrial radiography training module were included in the study. During the practical simulation, every participant had already been exposed to theoretical training concerning radiation principles (time, distance and shielding; ALARA; classification of radiation areas).

Radiography Simulation and Radiation Sources

The training simulation is using small sealed gamma sources, frequently used for industrial radiography. These sources were manipulated only under supervision and were used to simulate common X-ray exposure in industrial non-destructive testing. Source manipulation, placement and exposure times were pre-determined to maintain uniformity throughout all subject tasks as well as safety.

Instruments and Materials for Radiation Protection

Measured ambient dose equivalent rates were obtained at specific distances from the source using calibrated portable radiation survey meters. Doses were also measured at different distances (50 cm, 75 cm and 100 cm) to study impact of source-to-surface distance (SSD) on dose rate.

The effectiveness of different shielding materials were investigated: lead sheet, brick, wood and steel i.e commonly found or potential industrial/structure material. Shield thicknesses were set according to existing training devices and appropriate safety regulations.

Training Tasks and Data Collection

Tasks Participants were asked to complete the following structured practical tasks:

1. Detection of potential radiation hazards associated with the industrial radiography activities;
2. Establishment of controlled and supervised radiation zones by sampling of the dose rate and regulatory dose limits;

3. A study of the dose rate variation with distance and exposure time-being- a preliminary note.
4. Comparison of dose rates with and without shields (shielding effectiveness (SE)).

Dose rate data were gathered by both actual in-situ field measurements and theoretical dose rate calculations applying gamma constants and the inverse square law in water. This parallel unfolding verified measurement accuracy and strengthened concept understanding of radiation protection principles.

Data Analysis

Data analysis was performed using a thematic analysis. Observational results, measurements and participant task performances were collated under a priori themes of analysis (hazard identification, application of time/distance principles, shielding efficacy, and precision in categorizing radiation field size). The quantitative values of dose rate were used to help describe and understand the qualitative interpretations, not for statistical hypothesis testing which was inappropriate given the case report design.

Ethical and Radiation Safety Oversight

Radiation safety instruction was given to all training participants by institutional radiation safety officers in accordance with national regulations on radiation protection and IAEA safety standards. The radioactive sources used were limited to educational purposes and any participant was obliged to wear appropriate personal protective equipment as well as to behave in accordance with safety rules when using them. Personal identity details were not retrieved and no additional radiation risk was incurred beyond standard training exposure.

RESULTS

Detailed numerical datasets and dose calculation tables are presented in the Appendix to enhance the clarity and coherence of the Results section while maintaining full data transparency. This approach enables a stronger focus on the interpretation of key patterns observed during the industrial radiography training simulation, emphasizing their relevance to radiation safety management, occupational exposure control, and practical decision making in real world radiographic operations.

Radiation Hazard Identification

The industrial radiography training simulation began with the identification of radiation hazards. The potential radiography hazards analysed and classified by the workers under study as internal, external and contamination are organised in Table 1. The internal threats were mainly associated with source manipulation and working practices, emphasizing the requirements for personal protection (shielding), suitable source containers and radiation protection. Open hazards were related to the gamma radiation emitted during source operation, and focused on distance control, exposure time and the boundaries of radiation area. Source-storage and work area control were identified as having a higher risk due to contamination-related hazards.

The discovery of a range of hazard classes suggests that participants perceived radiation risk to be multifaceted, rather than a single point. This result is in line with the international radiation safety recommendations, as recognition of hazards is considered as a fundamental principle of the occupational radiation protection (1). These findings indicate that realistic simulation improves situational awareness and can help to create a preventive radiation safety culture.

Table 1. Classification of Radiation Hazards During Industrial Radiography Training

Potential hazards	Handling management
Internal hazards	- Use of Personal Protective Equipment (PPE) such as disposable gloves, full length lab coat, safety glasses, closed toed shoes when handling radioactive substances - Installation of shielding materials - Use of personal dosemeters
Contamination hazards	- Determine and manage safe area of the radiation sources - Avoid direct contact with the radiation sources - Limit the work area - Utilize a containers for radioactive substances
External hazards	- Manage distance, safe area, and time - Utilize shielding when measure the dose rate

Source: Arifin et al., 2026

Determination of Controlled and Supervised Areas

The definition of controlled and supervised areas for radiation was considered in two modes of operation and is summarized in Table 2 and Table 3. In the first scenario, radiation area boundaries were determined using predefined occupational dose limits for radiation workers. Controlled areas were established in zones where projected exposure could exceed regulatory thresholds, whereas supervised areas were identified where exposure remained below occupational limits but still required routine monitoring.

In the second scenario where particular occupational dose limits were not preserved the public dose limit could be conservatively used as a guide for radiation area classification. The respective boundary distances obtained from measurements depended on source activity as well as the amount of work being performed; however, measured dose rates continuously proved that zone definition was in line with the specified dose limits. Small discrepancies between theoretical values and measurements in situ were noted, but not enough to compromise the safety margins.

That participants can identify and modify radiation area limits based on their operational conditions demonstrates functional proficiency with radiation zoning controls. This flexible approach is particularly suitable in industrial radiography 3 workplaces which have mobile sources, the work areas are temporary and in line with international guidance on radiation area control (8).

Table 2. Determination of Controlled and Supervised Area Boundaries Under Scenario 1

Radiation Source	Controlled Area Boundary (m)	Supervised Area Boundary (m)
Source 1	3.35	8.20
Source 2	2.42	5.92

Note: Detailed dose calculations and boundary derivations for Scenario 1 are provided in Appendix (Table A2).

Source: Arifin et al., 2026

Table 3. Determination of Controlled Area Boundaries Under Scenario 2

Radiation source	Controlled area boundary (m)
Source 1	1.22
Source 2	1.22

Note: Detailed dose calculations for Scenario 2 are presented in Appendix (Table A3).

Source: Arifin et al., 2026

Effect of Distance and Exposure Time on Dose

Detailed dose rate measurements and corresponding theoretical calculations at varying distances and exposure times are presented in Appendix (Table A1). The following section summarizes the observed trends and their implications for radiation exposure control.

Doserate clearly decreased with increasing distance as confirmed by measurements. Considering the dose rate, a clear decrease was observed at the measurement points furthest from the source of radiation (more than 70% comparing the nearest and farthest), especially as they were placed at greater distances with respect to supply doors. The present result is a demonstration that the inverse square law can be applicable under simulated industrial radiography conditions. Concomitantly, reductions in beam-on time led to proportional decreases in the cumulative dose delivered, highlighting the relevance of optimization of timing parameters in radiographic procedures.

The agreement between the measured values and their theoretical calculation is the evidence that radiation protection principles were well implemented by participants in practice. Real-time variation in dose enabled participants to better grasp changes over the exposure time and aids in making informed decisions on matters of radiation safety. These findings are in line with known principles of radiation protection and previous academic literature emphasising the educational potential for work-based learning (3, 6).

Shielding Effectiveness Against Gamma Radiation

The complete shielding data for various materials and thicknesses is detailed in Appendix (Tables A2–A6). In this section, the relative effectiveness of each material against gamma-radiation is summed up.

The lead shield was found to have the best attenuation efficiency and could reduce the dose rate by ±50% even at a low thickness. This result is due to the relative high density and atomic number of lead, which make it more interacting with gamma radiation. Common building materials including brick and steel had moderate attenuation that led to useful dose reduction though these needed to be of greater thickness than found for lead. Wood only provided a poor protection effect, suggesting that it is not suitable as the main shielding material against gamma-ray exposure.

These results underline that material shielding selection for industrial radiography should be based on both attenuation efficacy and real-world practical limitations such as ready availability of materials and ease of construction. Participants capacity to interpret the performance of shielding within such constraints suggests that an applied competence in radiation protection was developed with direct relevance to industrial practice.

Interpretation of Protective Measures in Relation to Each Other

All of the data collected indicate that subjects were able to develop a consistent radiation protection strategy by integrating four discretely addressed themes: (a) identifying the radiation hazard, (b) classifying areas according to their levels of radiation; (c) optimizing time and distance between themselves and a possible source of radiation exposure; and (d) using shielding. The high-quality correlation between theoretical estimates and measurement results within the whole result space of the two measurement parameters shows for practical purposes that simulation-based training can be used as a tool to link theoretical knowledge (derived by modelling) with practical examples.

From the perspective of disaster health management, these results underscore the importance of vocational radiation safety training as a preventive intervention that would improve workforce readiness for an emergency, situational awareness and decision-making. These professionals acquire skills to minimize radiation incidents in the workplace and lower potential for radiological accidents.

DISCUSSION

The results of this study show that structured, simulation based industrial radiography training serves as an efficient medium for supporting application of basic radiation protection principles such as identification and delineation of hazards, area classification with respect to radiation exposure, optimization time and distance rules, and selection of shielding. The results lend support to the effect of hands on training on Radiation Safety Competence (RSC), a domain that is increasingly considered as integral part of occupational health, disaster risk reduction and radiological emergency preparedness (8, 1).

The Awareness of Radiation Risk and the Safety Culture Against Radiation Hazard

The systematic exploration of radio-hazard sources based on internal, external and contamination-related hazards indicated a better radiation safety awareness among respondents. Hazard Identification is broadly recognized as the first stage of defence against workplace radiation accidents since a lack of Hazard Awareness often precedes unsafe working practices and unintended exposures (1, 9). Results It was found that simulation-based training helped to increase radiation-related situational awareness, as participants were able to link the concept of abstract risk with real-life scenarios.

Several studies demonstrated that an improved knowledge of radiation protection is closely related to a better safety attitude and adherence to protective measures (3, 10). Similar results have been described in both industrial and health sectors where low awareness of risks exposure has been reported to suboptimal radiation protection habits (11, 12). From a disaster health management standpoint, enhanced perception of hazards helps to prevent small dispersion and/ or exposure events that might lead to larger scale toxic exposures.

Zone of Radiological Control (ZORC) and Exposure Restrictions

The participants' ability to draw controlled and supervised radiation areas in different dose constraint cases reflect the successful translation of regulatory doses constraints into practical decisions. These comparisons demonstrate that real area boundaries are delineated in a transparent and reproducible fashion based on sound calculations with proportions between area dose rates and values measured, rather than arbitrary judgment. This alleviates criticism commonly raised on the practical implementation of radiation zoning in temporary industrial radiography workplaces (8, 13).

Industrial radiography is frequently performed in temporary workplaces using transportable radiation sources, making it difficult to ensure a uniform level of protection against exposure. International guidance therefore stresses conservative but flexible zoning strategies to avoid unintended exposure of workers and the public (8, 9). The results also extend previous evidence on the ability of training to reduce radiological risk by promoting workers ‘capability to manage and deploy radiation zoning strategies according to changing operational conditions and in the framework of occupational safety as well situation awareness for abnormal events (14).

Application of principles for optimizing time and distance

The findings of decreasing dose rates with increasing distance and reduced exposure time further re-emphasize the applicability of time–distance principles in radiation protection. While these principles are all established in theory, the Results show their practical effect in simulated industrial radiography. The agreement of the results appears to imply that subjects actually could use these principles in practice rather than just recall them as concepts.

Compared to didactic instruction only, experiential learning has been reported as an efficient method to enhance the understanding, retention and application of radiation safety knowledge (3, 6). A study among radiography students and radiation workers has also found that hands-on training and ongoing education can help reduce occupational doses and enhance observance with radiation protection standards (10, 11). These are important competencies for mitigating accumulated exposure and avoiding unsafe work in high risk radiological occupations.

Shielding Selection and Practical Constraints

The estimate of attenuation effectiveness via shielding shows large differences between colour and common materials. Lead outperformed brick and steel when used at thicknesses well below those required for an equivalent dose reduction. Wood was found quite ineffective, which reconfirmed its unsuitability as an efficient shielding material for the protection from gamma radiation. These results are in accordance with the established laws of radiation physics and other comparative work on shielding (9, 13).

In addition to sound engineering design considerations, the choice of a shield material for industrial radiography applications is driven by practical factors such as availability, structure feasibility and ability to be moved. Research on radiation safety management systems has identified that lack of proper or ad hoc shielding solutions is a common contributor to occupational exposure events (15, 16). Training with these programs can not only provide the level of technical competency required, but may also assist in making informed decisions under actual field and logistical conditions.

Disaster Health Management and Workforce Preparedness Considerations

Although performed in a controlled simulation setting, the results have wider implications regarding disaster health management. If poorly controlled, incidents in the field of industrial radiography can lead to high occupational exposure and also have public health implications. Developing technical capacity through the use of simulation-based training reduces risk throughout the disaster cycle, particularly in prevention and preparedness as highlighted by (8, 14).

Combining hazard identification, radiation zoning, time–distance optimization and shielding analysis within the same training structure, it encourages a general view of radiation safety. It is a key element in building a workforce that is adaptable to daily operations, as well as an unexpected radiological incident. There is also growing evidence that more sophisticated teaching tools like real-time visualization, augmented reality and virtual reality could improve radiation safety training outcomes and ensure preparedness (6).

LIMITATION

This study has several limitations that should be considered when interpreting the findings. First, the industrial radiography training was conducted under simulated conditions, which may not fully represent the complexity, variability, and environmental constraints encountered in actual field operations. Consequently, participant performance in real-world industrial radiography settings may differ from that observed during the simulation.

Second, the study was limited by its sample size and training duration, which may affect the generalizability of the results to broader industrial radiography populations. The assessment focused primarily on short-term application of radiation protection principles, and long-term retention of competencies was not evaluated.

Finally, the scope of this study emphasized technical radiation protection outcomes rather than behavioral or organizational factors, such as safety culture development or institutional policy implementation. Future research should incorporate longitudinal designs and field-based evaluations to assess sustained training effectiveness and its integration into comprehensive occupational and disaster preparedness programs.

CONCLUSION

This study demonstrates that structured, simulation-based approach to teaching industrial radiography through training is successful for explaining practical applications of basic radiation protection concepts such as hazard identification, radiation area zoning, and optimization of time and distance; in addition to selection of proper shielding. The concordance of theoretical calculations with experimental observations suggests radiation safety concepts were translated into decisions during training activities by participants.

The results demonstrate the importance of incorporating technical radiation protection training in a wider disaster health management context. By enhancing awareness, exposure control tactics and material selection expertise, such training can help reduce occupational hazard of radiological exposures and increase readiness in case of possible radiological incidents. The results are especially important for the field of industrial radiography which includes mobile sources of ionizing radiation and non-permanent workplaces.

As a whole, the study reinforces that simulation-based training is an efficient method of developing radiation safety capacity and staff morale. Adoption of similar training programmes in vocational education and occupational safety programs might serve a preventive function, reducing risks from radiological hazards and strengthening industrial disaster preparedness.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable. This study was based on an industrial radiography training simulation and did not involve human participants, patients, or human subject research.

APPENDIX

Detailed numerical data, measurements results and dose calculation tables supporting the Results section are found in this section. These tables are presented as supplementary material to facilitate data transparency and reproducibility without compromising the emphasis of the Results section on that interpretation of main trends with significance for education in radiation safety management during industrial radiography training.

Table A1. Measured and Calculated Dose Rates at Varying Distances During Industrial Radiography Training

Distance (cm)	Dose rate (Measurement)	Dose rate (Calculation)	Dose rate (Measurement)	Dose rate (Calculation)
50	71.62	5.60	11.80	11.93
75	35.03	3.10	6.10	5.83
100	18.86	1.90	3.90	3.14

Source: Arifin et al., 2026

Table A2. Detailed Calculation of Controlled and Supervised Area Boundaries Under Scenario 1

Parameter	Source 1	Source 2
Radiation energy (keV)	1173 & 1332	662
Dose limit applied	Occupational limit	Occupational limit
Calculated controlled area boundary (m)	3.35	2.42
Calculated supervised area boundary (m)	8.20	5.92

Source: Arifin et al., 2026

Table A3. Detailed Calculation of Controlled Ares Boundaries Under Scenario 2

Parameter	Source 1	Source 2
Radiation energy (keV)	1173 & 1332	662
Dose constraint	Public dose limit	Public dose limit
Calculated controlled area boundary (m)	1.22	1.22

Source: Arifin et al., 2026

Table A4. Dose Rate Attenuation Using Lead (Pb) Shielding

Radiation Source	Energy (keV)	Thickness (cm)	Dose rate	Half-value layer (HVL, cm)
Source 1	1173 & 1332	0	100	1.0
		0.4	78.02	
		0.8	59.81	
		1.0	50	
Source 2	662	0	40	0.6
		0.4	25.63	

	0.6	20.42	

Source: Arifin et al., 2026

Table A5. Dose Rate Attenuation Using Brick and Steel Shielding (Radiation Source 2, 662 keV)

Shielding	Thickness (cm)	Dose Rate	HVL (cm)
Brick	0	40	8
	4	29.64	
	8	20.60	
Steel	0	40	18
	6	33.65	
	12	26.41	
	18	20.78	

Source: Arifin et al., 2026

Table A6. Dose Rate Attenuation Using Wood Shielding (Radiation Source 2, 662 keV)

Thickness (cm)	Dose rate	Half-value layer (HVL, cm)
0	40	16
4	34.61	
8	29.34	
12	26.29	
16	20.36	

Source: Arifin et al., 2026

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