

RADIATION SAFETY PROCEDURES FOR FLOODED MEMBER INSPECTION USING GAMMA TRANSMISSION TECHNIQUE: A COMPREHENSIVE REVIEW

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ARTICLE INFO	ABSTRACT
Received: 05/9/2024	This paper provides a comprehensive review of radiation safety procedures in Flooded Member Inspection using the gamma transmission technique, a key nondestructive testing method in offshore oil and gas industries. This technique involves utilizing high-energy gamma-emitting isotopes, specifically Cobalt-60, to assess the integrity of submerged structures. The associated risks of using such radioactive materials demand the strict adherence to safety protocols to protect personnels, equipments, and the environment. This review outlines the methods for preparing, handling, transporting, and storing radioactive sources, emphasizing the importance of the As Low As Reasonably Achievable principle in minimizing radiation exposure. Additionally, the paper discusses the calculated foundations of radiation protection and dose management, illustrating how these principles ensure compliance with international safety standards. The results underscore the effectiveness of existing safety measures and provide recommendations for improving radiation protection practices in the FMI operations, having implications for enhancing offshore inspection safety and reliability.
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QUY TRÌNH AN TOÀN BỨC XẠ TRONG KIỂM TRA CẤU KIỆN NGẬP NƯỚC BẰNG KỸ THUẬT TRUYỀN GAMMA: ĐÁNH GIÁ TOÀN DIỆN

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THÔNG TIN BÀI BÁO	TÓM TẮT
Ngày nhận bài: 05/9/2024	Bài báo này cung cấp một đánh giá toàn diện về các quy trình an toàn bức xạ trong Kiểm tra cấu kiện ngập nước sử dụng kỹ thuật gamma truyền qua, một phương pháp kiểm tra không phá hủy quan trọng trong ngành công nghiệp dầu khí ngoài khơi. Kỹ thuật này sử dụng các đồng vị phát gamma năng lượng cao, đặc biệt là Cobalt-60, để đánh giá độ toàn vẹn của các cấu trúc chìm dưới nước. Các rủi ro liên quan đến việc sử dụng các vật liệu phóng xạ như vậy đòi hỏi phải tuân thủ nghiêm ngặt các quy trình an toàn để bảo vệ nhân sự, thiết bị và môi trường. Bài đánh giá này trình bày các phương pháp chuẩn bị, xử lý, vận chuyển và lưu trữ các nguồn phóng xạ, nhấn mạnh tầm quan trọng của nguyên tắc Giảm phơi nhiễm tới mức thấp nhất có thể đạt được nhằm giảm thiểu phơi nhiễm bức xạ. Ngoài ra, bài báo còn thảo luận về nền tảng tính toán trong bảo vệ bức xạ và quản lý liều, minh họa cách các nguyên tắc này đảm bảo tuân thủ các tiêu chuẩn an toàn quốc tế. Kết quả nghiên cứu nhấn mạnh hiệu quả của các biện pháp an toàn hiện tại và đưa ra các khuyến nghị để cải thiện thực hành bảo vệ bức xạ trong các hoạt động FMI, góp phần tích cực vào việc nâng cao an toàn và độ tin cậy của quy trình kiểm tra ngoài khơi.
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Quản lý nguồn phóng xạ	
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1. Introduction

Flooded member inspection was a critical nondestructive testing (NDT) technique widely applied in the offshore oil and gas industry to ensure structural integrity and prolong the lifespan of oil platforms. Submerged structures, particularly load-bearing members, if not properly monitored and maintained, could be damaged due to water ingress, leading to reduced load capacity and even structural failure. This instability posed significant threats not only to occupational safety but also to the environment and could result in substantial economic losses. Flooded member inspection (FMI), with its ability to detect internal defects within submerged members early without requiring the shutdown of the platform, was the optimal solution to this issue [1], [2].

In the FMI technique, gamma radiation was widely utilized, with Cobalt-60 being the isotope of choice due to its ability to emit high-energy gamma rays (1.17 MeV and 1.33 MeV) and its half-life of 5.27 years. Cobalt-60 could penetrate thick materials and allow for detailed data collection on the integrity of submerged structures without the need for complex surface treatments. This optimized the inspection process in harsh offshore environments, where time and working conditions were limited, ensuring long-term effectiveness and sustainability of the system [3], [4].

However, the use of ionizing radiation in such inspections not only offered high efficiency but also posed significant challenges in radiation safety. Ionizing radiation could cause serious harm to the health of on-site personnel, such as radiation exposure, damage to living tissues and nervous systems, along with the risk of environmental contamination if not properly managed and controlled. Therefore, the as low as reasonably achievable (ALARA) principle became central to minimizing radiation exposure during operational processes [5], [6].

While the ALARA principle had been widely applied in industries involving radiation, its implementation in offshore environments faced numerous challenges due to the specific conditions present. Several studies had addressed the technical aspects of FMI using gamma radiation, such as the ability to detect water ingress within structures [7], [8], but they lacked comprehensive guidelines covering the entire lifecycle management of Cobalt-60, from preparation, handling, transportation, to storage. This gap prevented the optimization of radiation safety protocols for offshore operations, where working environments were constrained by space and time, and required highly effective and optimized radiation protection procedures [9].

Another significant challenge faced by FMI was the practical application of the inverse square law regarding radiation intensity. According to this principle, radiation intensity decreases with the square of the distance from the source. While this theory was well understood, its implementation on confined offshore platforms was often impractical due to limited working areas. This required innovative technical solutions to adjust and optimize radiation protection principles in specific working conditions, ensuring radiation exposure levels remained within permissible limits without affecting the inspection process [10], [11].

This research introduced a novel approach by providing a comprehensive evaluation of radiation safety procedures in FMI using the gamma transmission technique, focusing on the management of radioactive sources. The study delved into the preparation, handling, transportation, and storage of Cobalt-60, which had not been thoroughly analyzed in previous research. Additionally, the integration of mathematical principles and modeling, particularly the calculation and application of the inverse square law, helped optimize radiation safety procedures in offshore environments – unique and challenging conditions [12], [13].

The necessity of this research was underscored by the urgent need to ensure safety for personnel and the environment, given the increasing offshore oil and gas activities. Offshore environments not only presented significant technical challenges but also heightened safety risks, particularly when working with high-energy radioactive sources like Cobalt-60. Establishing

comprehensive radiation safety procedures was critical to protecting personnel and mitigating risks to the surrounding environment.

The primary objective of this study was to develop a safety framework aligned with international radiation safety standards, such as those set by the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) [12], [13]. The research provided detailed guidelines on the entire process of managing and operating radioactive sources in offshore environments and offered recommendations for improvements to enhance the safety and efficiency of FMI operations.

2. Materials and Methods

This study adopted a comprehensive approach, combining a literature review and mathematical analysis to thoroughly evaluate radiation safety procedures during FMI using gamma transmission techniques. The focus of the research was on the management of Cobalt-60, a high-energy gamma-emitting isotope, commonly used in NDT of submerged structures in the oil and gas industry.

Firstly, a literature review was conducted to collect and analyse previous studies related to the use of Cobalt-60 in offshore inspections. This review helped to identify the most effective methods for the preparation, handling, transportation, and storage of Cobalt-60, as well as the potential radiation exposure risks associated with operations in the confined environments of offshore platforms [1], [3], [5]. From the gathered studies, radiation safety procedures were synthesised and analysed to clarify any gaps and highlight areas for improvement.

In addition to the literature review, the study incorporated mathematical analysis to model and accurately calculate radiation intensity during FMI operations. One of the key mathematical models employed was the inverse square law, which was used to calculate the decrease in radiation intensity as a function of distance from the radiation source. This law helped determine the exposure dose based on the distance between personnel and the radiation source, thus assisting in optimising protection measures in offshore work environments with limited space [4], [6].

To minimise radiation exposure for personnel, the ALARA principle was integrated into the analysis. This principle required the optimisation of exposure time and the implementation of appropriate protective measures to ensure the safety of workers while complying with international standards such as those set by the ICRP and the IAEA [4], [6], [11]. Mathematical models were used to calculate cumulative radiation doses over the operational period, ensuring that all activities were performed within safe exposure limits.

One major challenge of the study was the application of the inverse square law in offshore environments. The confined space on offshore platforms made it difficult to maintain a safe distance from the radiation source. To address this issue, the study analysed and proposed technical solutions aimed at adjusting and optimising radiation protection measures, including:

- Lead aprons: To reduce the radiation intensity that personnel were exposed to, the study recommended the use of lead aprons for workers operating near the radiation source. Lead aprons, made from materials with high radiation-absorbing capacity, provided protection against gamma radiation. This solution was both practical and flexible, suitable for inspection tasks in the confined spaces of offshore platforms [7].

- Optimising work shifts: To minimise cumulative radiation exposure for personnel, the study proposed carefully structured work schedules, limiting the time spent in radiation-exposed areas and rotating personnel for tasks with higher exposure levels. This ensured that no individual was overexposed during the working period [8].

- Continuous training and monitoring: A crucial aspect of reducing exposure risk was to enhance the knowledge and skills of the workforce. The study recommended strengthening radiation safety training programmes, including the use of dosimeters and exposure management.

Additionally, continuous monitoring systems needed to be deployed to track individual radiation doses during the course of work [9].

- Utilising simulation and pre-calculation technology: The use of computer simulation tools to predict radiation distribution before actual operations took place was suggested. These simulations helped to identify high-risk areas and optimise the deployment of protective measures. This technology not only ensured effective radiation shielding but also enhanced the efficiency of the inspection process in real-world conditions [10].

Finally, based on a comprehensive analysis of the literature review and mathematical models, the study provided recommendations for improving existing radiation safety procedures in FMI offshore inspections. The results of this research aimed to improve both operational efficiency and personnel safety in the oil and gas sector

3. Results and Discussion

3.1. Control of exposure dose and contingency plan

The management of radiation exposure during FMI operations was rigorously governed by the ALARA principle, which required that exposure to ionizing radiation be minimized to the lowest feasible levels, considering economic and social factors. This was particularly crucial within the context of gamma transmission techniques, where a gamma radiation source, typically the Cobalt-60 isotope, was employed to assess the internal condition of submerged structures.

Before the FMI device descended underwater for inspection, the radioactive source had to be affixed to the FMI measurement frame. During this phase, the radiation dose rate directly impacted radiation safety personnel due to the close proximity required for handling and installation. Personnel were required to ensure that this process was carried out swiftly and safely by implementing appropriate protective measures, maintaining sufficient distance, and minimizing exposure time. Once this setup was complete, the FMI measurement system, together with the radioactive source, would be deployed to depth with an Remotely Operated Vehicle (ROV) for inspection. At that point, the dose rate in the surface work area decreased to background levels and posed no impact on personnel.

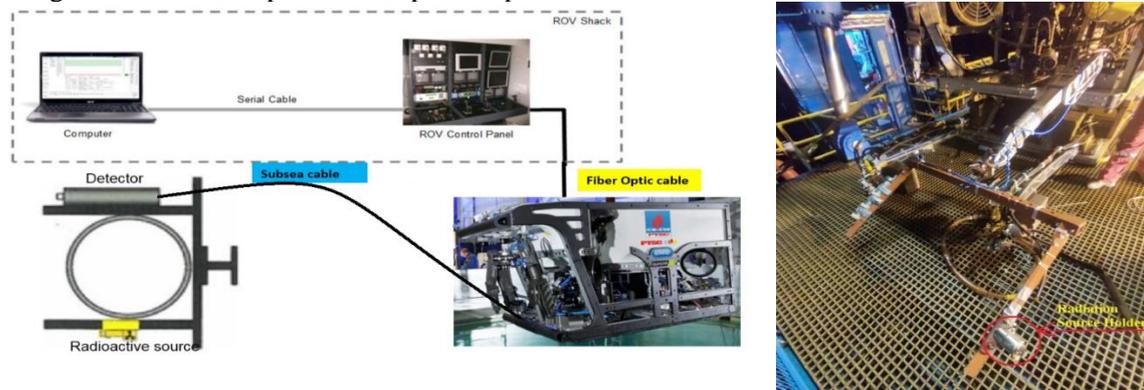


Figure 1. Radiation source holder for FMI measurement frame installed on ROV

The gamma transmission technique was functioned by directing a gamma beam through a structural member, where it interacted with the material and any present fluids, such as water. The gamma radiation, after passing through the member, was detected on the opposite side, enabling an assessment of the internal structure, including detection of water ingress or other defects.

The dose rate \dot{D} at a distance r from a point source of gamma radiation was described by the inverse square law:

$$\dot{D} = \frac{\Gamma \times A}{r^2} \quad (1)$$

where:

- Γ is the specific gamma-ray constant for the isotope, typically expressed in $\text{mSv}\cdot\text{m}^2/\text{Ci}\cdot\text{h}$, which accounts for the energy and intensity of the gamma radiation emitted by the isotope.
- A is the activity of the radioactive source, measured in curies (Ci), indicating the rate of radioactive decay events per second.
- r is the distance from the source to the point where the dose rate was measured, expressed in meters.

This inverse square relationship underscored the importance of maintaining a sufficient distance from the radioactive source to reduce exposure. Specifically, doubling the distance from the source decreased the dose rate by a factor of four, thereby significantly enhancing safety. This principle was fundamental in determining controlled areas around the radiation source and implementing appropriate safety measures.

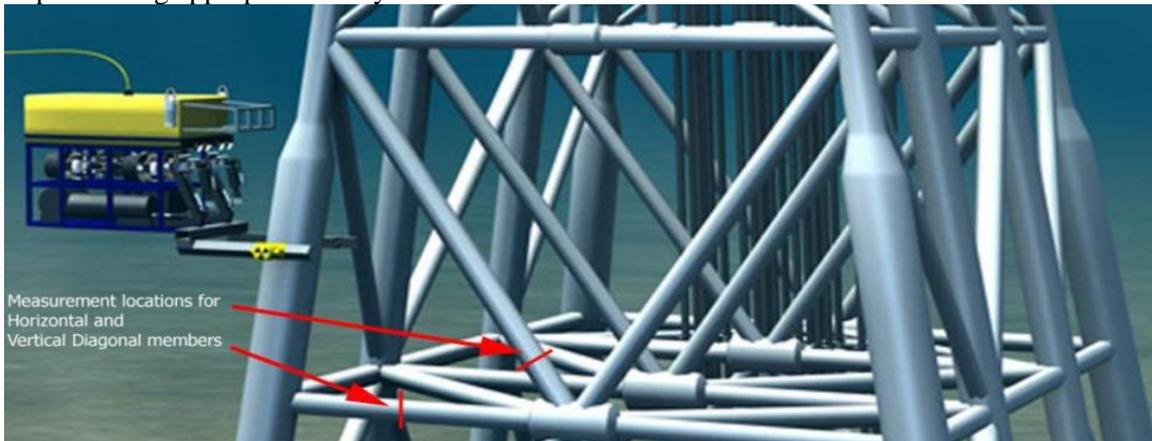


Figure 2. The ROV device dives underwater to measure the offshore platform structures

The total radiation dose D received by personnel over a period t was calculated via the following equation:

$$D = \dot{D} \times t = \frac{\Gamma \times A \times t}{r^2} \quad (2)$$

where:

- D represents the cumulative radiation dose received over time, measured in millisieverts (mSv).
- t represents the duration of exposure to the radiation source, expressed in hours.

This equation was essential for calculating the permissible exposure time for workers near the radiation source, ensuring that the cumulative dose remained within regulatory limits, typically set at 20mSv per year for radiation workers according to the recommendations of the International Commission on Radiological Protection (ICRP). Managing radiation dose over time allowed adjustments to be made in factors such as distance, exposure time, and shielding to ensure compliance with these limits.

Adherence to international regulations, such as those established by the ICRP and the International Atomic Energy Agency (IAEA), required continuous monitoring and assessment of radiation exposure via advanced dosimetry equipment and sophisticated risk assessment procedures to anticipate and mitigate potential radiation incidents. This included the use of personal dosimeters for workers, environmental monitoring, and the implementation of protective measures such as radiation shields and exclusion zones to minimize exposure.

In the event of an emergency, such as a radiation leak or an unexpected increase in radiation levels, the incident response plan is activated immediately to protect personnel and the environment. Emergency measures include evacuation of the area, isolation of the radiation source, and notification of relevant authorities to take appropriate action. This plan is designed to ensure that any incident is handled promptly and effectively, minimising impact on safety and operations.

Based on the FMI Emergency Response Plan, additional procedures are implemented as follows:

1. Management of radioactive package and transport vehicle:

- The radioactive source (Co-60) is secured within a lead container with 40mm shielding thickness, ensuring safety and compliance with surface dose rate standards.
- The transport vehicle is clearly marked with radiation hazard warnings, ensuring safe distance and stability of the package throughout transit.

2. Exposure control measures during transportation:

- The radiation protection supervisor regularly monitors surface dose rates at various positions within the transport vehicle, including the seat of drivers, both sides, and beneath the vehicle.
- Personal dosimeters (TLD) are issued to all personnel involved, with dose measurements conducted hourly to confirm adherence to safety thresholds.
- In the event of vehicle malfunction, strict protocols for area isolation and radiation source handling are immediately implemented.

3. Response measures in case of a source drop:

- Should the radioactive source fall onto the seabed outside of its housing, procedures are followed to ensure safe recovery, under the direction of the Radiation Protection Supervisor and FMI technical team. If classified divers are available, they are equipped with protective gear, radiation monitoring devices, and information on radiation levels at various distances.
- In the absence of classified divers, alternative recovery protocols are prepared, including the use of dose-monitoring equipment and strict safety procedures.

4. Dose control for rescue personnel:

- All personnel involved in retrieval or incident response are equipped with individual radiation dosimeters, and activities are conducted within safety zones designated by the FMI engineer.
- Detailed records of personnel names and time spent on task are maintained to assess and manage radiation exposure, in strict adherence to the ALARA principle.

5. Other emergency response measures:

- In the case of fire or traffic collisions, standardised procedures for public safety and affected area isolation are implemented, supported by coordination with relevant authorities and radiation safety teams.
- Any incident involving the loss or misplacement of radioactive material activates search and recovery measures, coordinated closely with police and other relevant entities.

These protocols and measures ensure maximum safety for personnel and the environment throughout the inspection and transport of radioactive sources, while enabling swift and effective incident handling to minimise impact on operational and overall safety.

3.2. Safety procedures

These guidelines are the result of our team's research and development process, derived from successful implementations for oil and gas clients in Vietnam since 2016. We have collected and analyzed evidence and results to demonstrate the effectiveness of these guidelines, as outlined in the following sections of this paper.

3.2.1. Assembling equipment

The assembly of FMI equipment must be conducted with meticulous attention to ensure safety and functionality. The radiation protection supervisor (RPS) is responsible for gathering and inspecting all necessary equipment prior to deployment. This includes verifying the calibration of radiation survey meters and ensuring the availability of personal protective equipment (PPE) such as the following:

- Hard hats
- Flame-resistant coveralls
- Safety boots
- Safety spectacles

- Barrier tape and radiation warning signs

The equipment must be packaged appropriately for air, sea, and road transportation, with special attention given to the shielding and containment of the radioactive source to prevent any accidental exposure during transit.

3.2.2. Radioactive source preparation

The preparation of the radioactive source, typically Cobalt-60, is a critical step that requires strict compliance with safety protocols. The RPS is tasked with removing the source from the radiation storage facility, conducting thorough inspections to confirm the source's integrity, and verifying its activity via calibrated instruments. The source is then placed in a Type A or Type B container, depending on its activity level, designed to contain the radiation and prevent leakage [16]. The container is labelled with internationally recognized radiation symbols and transported under conditions that comply with the IAEA Regulations for the Safe Transport of Radioactive Material, as shown in Figure 3.



Figure 3. Handling and assembly of the radioactive source

3.2.3. Arrival of radioactive source on site

Upon arrival at the offshore platform, the RPS must conduct a thorough inspection of the radioactive sources. This involves the use of radiation survey meters to ensure that the sources have not been compromised during transport and that the containment integrity remains intact. Any discrepancies, such as signs of damage or abnormal radiation levels, must be reported immediately, and the area must be secured. The RPS must liaise with the Offshore Platform Safety Department and relevant regulatory bodies to determine the appropriate corrective actions.

3.2.4. Storage of radioactive sources on site

When not in use, the radioactive sources must be stored in a secure, shielded area, typically within a designated storage container that restricts access to authorized personnel only. The storage area should be designed to prevent unauthorized entry and should be equipped with continuous radiation monitoring devices to detect any breaches during containment. According to IAEA guidelines, the dose rate within the storage area should not exceed $10\mu\text{Sv/hr}$, and barriers should be erected at a distance where the dose rate at the boundary does not exceed this threshold [15].

3.2.5. Permit to work

Before initiating any FMI operation, the RPS must obtain a permit to work, issued by the platform's safety personnel. This permit ensures that all safety conditions are met and that the work is conducted under strict supervision. The RPS is also responsible for establishing controlled areas around the gamma source, marked with barriers and warning signs, to restrict access to nonessential personnel. The dose rate within these controlled areas must be continuously monitored, ensuring that it does not exceed $10\mu\text{Sv/hr}$ at the boundary [15].

3.3. Procedure for handling radioactive sources

3.3.1. Preparation of tools

The safe handling of radioactive sources during FMI operations requires specialized tools and procedures. The following tools are essential:

- A 20 – 30 cm long clamp was designed for secure handling of the source to minimize direct contact.

- The lead bricks create temporary shielding around the source during assembly and disassembly.
- Lead coats and dosimeters are used protect personnel and monitor exposure levels.

3.3.2. Attaching the radioactive source to the source holder

The procedure for attaching the radioactive source to the FMI source holder, as shown in Figure 4, was as follows:

1. The area around the source container was shielded, and lead bricks were used to reduce radiation exposure.
2. The protective screw cap was carefully remove from the source container via a wrench, ensuring minimal handling.
3. The radioactive is secured onto the source holder, ensuring that it is properly aligned and fastened to prevent movement during operation.
4. A dosimeter was used to verify that the radiation levels around the holder were within safe limits, confirming that the source was securely positioned.
5. The completion of the task is report to the team leader, ensuring that all safety protocols have been followed.

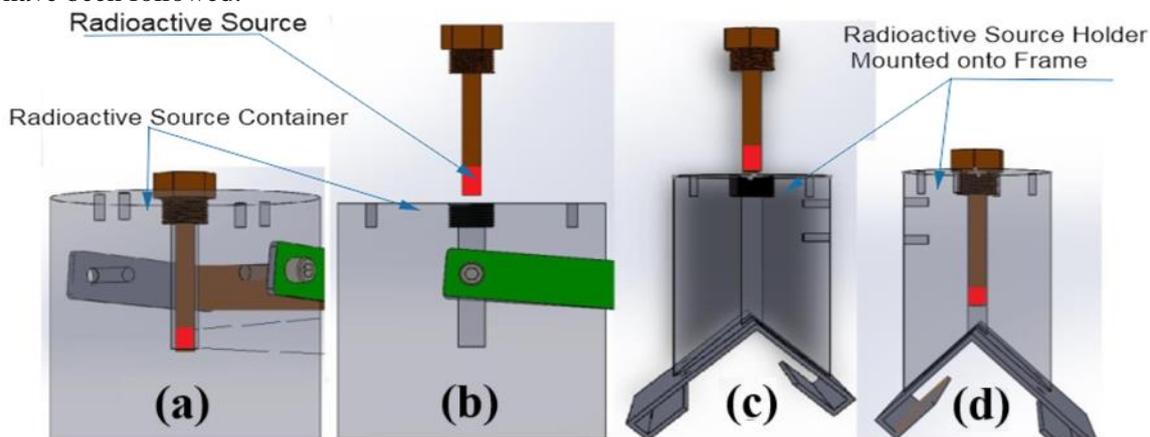


Figure 4. Illustration of source attachment process - (a) shield with lead bricks, (b) unscrew the cover, (c) remove the source bar, and (d) insert it into the holder, ensuring proper alignment

3.3.3. Removing the radioactive source

The removal of the radioactive source from the holder follows a similarly meticulous process:

1. The area shielded with lead bricks as described during the attachment process.
2. The source is carefully removed from the holder and placed back into the designated container, ensuring that it is fully secured.
3. A dosimeter was used to confirm that the source was securely contained and that the radiation levels were within safe limits.
4. The team leader should be notified upon successful completion of the task, ensuring that all safety measures have been adhered to.

3.4. Safety considerations

3.4.1. Radiation safety

The transfer and deployment of gamma sources within FMI equipment require strict adherence to radiation safety protocols. A controlled area is established around the gamma source during its transfer, with barriers positioned to maintain a safe distance from the source. The FMI engineer is responsible for ensuring that the dose rate at the boundary of the controlled area does not exceed $10\mu\text{Sv/hr}$ [15]. Additionally, during operations involving simultaneous diver

activities, a minimum safe working distance from the ROV carrying the gamma source must be maintained. This distance is determined on the basis of the specific activity of the source and the potential exposure to personnel.

3.4.2. Electrical safety

The FMI equipment is designed to withstand harsh offshore environments, with considerations for both radiation and electrical safety. The electronic components, including the radiation detector pod, are housed within insulated casings to prevent any electrical hazards, such as arcing or sparking, especially in oxygen-rich atmospheres, the procedure for attaching the radioactive source to the FMI source holder, as shown in Figure 5. The equipment operates within a temperature range of -10°C to 40°C , ensuring reliable performance under varying conditions.

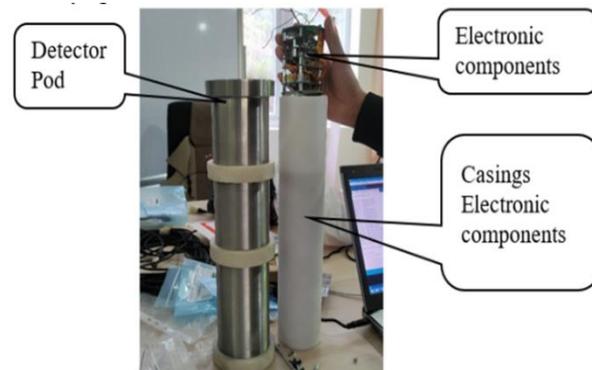


Figure 5. *Electrical safety considerations in FMI equipment*

Upon the completion of FMI operations, the RPS is responsible for ensuring that all controlled area barriers and warning signs are removed, and that the site is returned to its original state. The radioactive sources are securely packaged and transported back to the storage facility under the same stringent conditions as during deployment. A detailed report is prepared, documenting the inspection process, radiation safety measures, and any incidents or anomalies that occurred during the operation. This report is submitted to the ROV contractor and platform operator for review and record-keeping.

In the event of a radiation incident, such as a breach in containment or an unexpected increase in radiation levels, the FMI team follows a predefined emergency response plan. This plan includes immediate evacuation of the affected area, activation of containment protocols, and communication with local and national radiation safety authorities. The RPS coordinates the response efforts, ensuring that all personnel are accounted for and that the incident is mitigated with minimal impact on safety and the environment. Regular drills and simulations are conducted to ensure that all team members are proficient in emergency procedures.

4. Conclusion

This study provided a comprehensive review of radiation safety procedures in FMI using the gamma transmission technique, a key NDT method in the offshore oil and gas industry. This technique utilized the high-energy gamma-emitting isotope Cobalt-60 to assess the structural integrity of submerged components, yet also presented significant radiation safety challenges. To manage and mitigate radiation exposure risks to personnel and the environment, the ALARA principle and advanced radiation protection measures were strictly adhered to, ensuring compliance with international safety standards established by the ICRP and IAEA.

Detailed protocols were established for the preparation, handling, transportation, and storage of Cobalt-60, incorporating radiation intensity and safe distance calculations to optimize protection. Notably, the inverse square law for radiation was applied to calculate radiation intensity at various distances from the source, where the intensity decreases inversely with the square of the distance. This principle demonstrated that doubling the distance from the source reduces radiation intensity to one-quarter, allowing for safe zone calculations and enhanced shielding strategies to keep exposure within permissible limits.

Additionally, it was shown that controlling exposure time and using cumulative dose rate calculations were essential in restricted offshore environments such as oil rigs and vessels.

Through dose rate calculations, exposure levels were tightly managed, enabling optimized distance, exposure time, and shielding that aligned with ICRP safety limits.

To further improve safety, continuous training programs and exposure monitoring with advanced dosimetry equipment were recommended, ensuring that personnel maintained proficiency in radiation safety protocols. In case of an incident, an emergency response plan was outlined in detail, including evacuation procedures, source containment, and notifications to regulatory authorities to minimize impact.

The recommendations of the study contributed to the improvement of radiation safety protocols in FMI operations, ensuring sustainability and operational effectiveness in offshore inspections. Ultimately, this research not only enhanced efficiency and safety in submerged structure inspections but also provided a scientific foundation and practical framework for advancing radiation safety standards in the offshore oil and gas industry.

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