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# Analysis of the Application of Lead-Steel Structure in Industrial X-ray Radiographic Inspection Rooms

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## Abstract

With the widespread application of industrial X-ray inspection technology, ensuring the safety and health of operators has become a key issue. Due to its excellent radiation shielding performance, lead-steel structure is widely used in X-ray inspection rooms. This paper analyzes the application of lead-steel structures in industrial X-ray inspection rooms, particularly focusing on their advantages and challenges in radiation protection and monitoring. Firstly, the characteristics of lead-steel structures and their role in X-ray inspection rooms are introduced, emphasizing the necessity of protective design. Then, the basic requirements of radiation protection and monitoring, relevant regulations, and standards are discussed, along with the analysis of radiation monitoring equipment and methods. Finally, through data collection and analysis, the protective effect of lead-steel structures is evaluated, and the experimental results are discussed with suggestions for improvements. The study shows that lead-steel structures can effectively improve radiation protection performance in X-ray inspection rooms, but they still need optimization based on environmental requirements.

**Keywords:** lead-steel structure, industrial X-ray inspection, radiation protection, radiation monitoring, radiation protection design

## 1. Introduction

With the widespread application of industrial X-ray inspection technology in industries such as aviation, automotive, and construction, X-ray inspection has become a critical method for detecting internal material defects. However, the high-energy radiation from X-rays may pose potential health risks to operators. Therefore, radiation protection in X-ray inspection rooms has become a crucial task. To effectively prevent X-ray radiation from harming personnel, lead-steel structures are widely used in the construction of these rooms due to their excellent radiation shielding effects. A lead-steel structure is a composite material that combines the benefits of lead and steel, offering high density and strong radiation shielding capabilities to effectively block X-ray penetration. This paper explores the application of lead-steel structures in X-ray inspection rooms, analyzing their effectiveness and challenges in radiation protection and monitoring[1]. First, the basic characteristics of lead-steel structures and their design and application in X-ray inspection rooms are introduced, highlighting their crucial role in radiation protection. Secondly, the paper discusses the design requirements for radiation protection in X-ray inspection rooms, focusing on how appropriate materials and design standards can ensure optimal protective effects. The importance of radiation monitoring is also discussed, along with the use of monitoring equipment to ensure a safe working environment. Finally, through actual data analysis, the paper evaluates the radiation protection effect of lead-steel structures in real applications and offers suggestions for improvements. The research aims to provide a theoretical basis and technical support for the use of lead-steel structures in industrial X-ray inspection rooms, while also providing reference for enhancing radiation protection levels and safeguarding operator health.

## 2. Application of Lead-Steel Structures in X-ray Inspection Rooms

### *2.1 Basic Characteristics of Lead-Steel Structures*

Lead-steel structures are composite materials made from a combination of lead and steel, offering excellent physical and chemical properties. They are widely used in radiation protection. Lead, being a heavy metal with high density, has strong radiation shielding capabilities, particularly effective against X-rays and γ-rays. Therefore, lead-steel structures can effectively reduce the environmental contamination caused by radioactive materials and minimize the health risks from radiation exposure[2].

Density and Shielding Ability

The most prominent feature of lead-steel structures is their density. Lead has a density of approximately 11.34 g/cm³, while steel has a density of around 7.85 g/cm³. Due to lead's high density, it can effectively absorb and attenuate high-energy radiation such as X-rays, making it an ideal material for radiation protection. In X-ray inspection rooms, lead-steel structures absorb radiation and limit the spread of rays, thus protecting operators and the environment from radiation harm.

Mechanical Strength and Durability

In addition to excellent radiation protection performance, lead-steel structures also possess strong mechanical strength and durability. Steel provides the toughness and impact resistance that lead lacks, ensuring that lead-steel structures are less likely to be damaged over long periods of use. Since X-ray inspection rooms typically operate for extended periods, lead-steel structures can maintain their protective effect in harsh environments.

Workability and Adaptability

Lead-steel structures offer good workability and can be custom-manufactured according to the design requirements of X-ray inspection rooms. The composite nature of lead and steel allows the material to have both good plasticity and stability during processing, making it easy to create protective barriers in various shapes and thicknesses to meet different radiation protection needs.

Corrosion Resistance

Given that X-ray inspection rooms are often humid and prone to corrosion, the corrosion resistance of lead-steel structures is particularly important. The surface of the lead-steel composite material is specially treated to prevent corrosion and extend its service life.

In summary, lead-steel structures are ideal materials for radiation protection in X-ray inspection rooms due to their high density, mechanical strength, ease of processing, and strong corrosion resistance. These characteristics ensure that lead-steel structures can not only effectively shield X-ray radiation but also provide stable protection over long periods.

### *2.2 Role of Lead-Steel Structures in X-ray Inspection Rooms*

The design and construction of lead-steel structures in X-ray inspection rooms must strictly adhere to relevant standards and regulations to ensure effective radiation protection while maintaining long-term stability and safety. Firstly, when designing the lead-steel structure, the required thickness of the lead-steel material must be calculated based on the energy and intensity of X-rays in the inspection room. The high density of lead plays a key role in radiation shielding, so the purity and thickness of the lead should be carefully considered to ensure effective attenuation of X-rays. Steel provides excellent mechanical strength and durability, ensuring that the structure maintains stable protection over extended periods.During construction, every part of the lead-steel structure must be precisely installed to avoid seams or cracks, ensuring the integrity and seal of the protective barrier and preventing radiation leakage.Regarding material selection, the lead and steel used in the structure must meet relevant quality standards to ensure adequate radiation resistance and corrosion protection[3]. Since the working environment of the X-ray inspection room may involve humid or high-temperature conditions, corrosion resistance is especially important. The surface of the lead-steel structure should be treated with a protective coating to prevent corrosion over time. Moreover, the welding and connection points of the structure must be precisely aligned to ensure no visible gaps or leaks, thus maximizing the radiation protection effect.In addition, the lead-steel structure must meet radiation protection requirements and have sufficient mechanical strength to withstand external impacts. During installation, it is essential to ensure the stability of the structure to prevent damage due to vibration or external forces. Workers should also take necessary safety measures to prevent harmful gases and dust generated during cutting or welding from affecting their health. To ensure the long-term performance of the lead-steel structure, regular maintenance and inspections should be conducted after the inspection room is constructed, particularly monitoring the thickness of the lead layer, welds, and sealing areas to ensure that the protection effect is maintained.In conclusion, the design and construction of lead-steel structures in X-ray inspection rooms must comprehensively consider radiation protection, structural stability, material selection, and safety during construction. Only through precise design, standardized construction, and regular maintenance can the radiation protection performance of the inspection room be optimized, ensuring the safety of operators and the environment[4].

### *2.3 Design and Construction Requirements for Lead-Steel Structures*

The design and construction of lead-steel structures in X-ray inspection rooms must meet both radiation protection and structural stability requirements. During design, the protective thickness of the lead-steel structure should be determined based on factors such as radiation intensity, type of radiation, and equipment power. The density of lead and the strength of steel dictate their radiation shielding effectiveness, requiring careful calculation of the lead and steel layers' thickness to ensure effective radiation attenuation and prevent leakage. The design should also consider the structure's durability and stability, ensuring the lead-steel structure operates reliably in high-radiation environments. Lead and steel must meet relevant standards to ensure maximum radiation protection and corrosion resistance, suitable for humid and high-temperature environments. During construction, precise installation of the lead-steel structure is essential, with welds and joints needing to be seamless to prevent radiation leakage. Lead-steel materials must be processed and joined to ensure tight seams and corrosion resistance. Safety regulations must be followed to prevent harmful gases or contamination during construction. After installation, regular inspections, especially of lead layer thickness and seams, are required to maintain consistent radiation protection. In conclusion, accurate design, standardized construction, and routine maintenance are critical to ensuring the protective effectiveness of lead-steel structures[5].

## 3. Radiation Protection

### *3.1 Basic Concepts of Radiation Protection*

Radiation protection involves measures to reduce or prevent radiation sources from harming humans, the environment, and equipment. In X-ray inspection rooms, the goal is to keep radiation exposure within safe limits and protect personnel and the environment from radiation harm. Protection includes not only managing radiation sources but also preventing radiation spread, reducing radiation intensity, and performing monitoring and assessment[6]. The fundamental principle of radiation protection is ALARA (As Low As Reasonably Achievable), which aims to minimize radiation exposure while maintaining work efficiency. Effective protection also involves controlling exposure time, increasing distance from radiation sources, and using shielding materials such as lead and steel to reduce radiation effects. Additionally, radiation dose limits are set by the International Atomic Energy Agency (IAEA) and other authorities to ensure exposure remains within safe levels. Protection measures depend on design, technology, and continuous monitoring, with real-time data adjustments to maintain effectiveness. In summary, radiation protection ensures exposure is within safe limits, protecting people, the environment, and preventing potential harm.

### *3.2 Application of Lead-Steel Structures in Radiation Protection*

Lead-steel structures are widely used in radiation protection, especially in high-radiation environments like X-ray inspection rooms. Lead’s high density and excellent radiation absorption make it ideal for shielding, while steel provides necessary mechanical strength and stability. The combination of these materials allows lead-steel structures to meet protective requirements while maintaining long-term stability. In X-ray inspection rooms, lead-steel structures are used in walls, ceilings, floors, and windows, effectively absorbing and attenuating X-rays, preventing radiation penetration, and protecting operators and the environment. Lead-steel structures provide long-lasting protection and can be tailored to different radiation intensities. Additionally, their mechanical strength and durability ensure they remain intact in high-radiation environments. Steel enhances impact resistance and deformation resistance, ensuring that radiation protection remains effective over time. Corrosion resistance is also crucial, particularly in humid or high-temperature environments, to maintain the shielding effect. Overall, with proper design and construction, lead-steel structures effectively prevent radiation leakage and ensure the safety of personnel and the environment while enhancing durability and stability[7].

### *Radiation Protection Design Requirements and Standards*

Radiation protection design requirements and standards are vital for ensuring safety, especially in high-radiation environments like X-ray inspection rooms. The design must follow international and national standards to reduce radiation risks to humans and the environment. First, the design should adhere to the ALARA principle, minimizing radiation exposure while ensuring operational efficiency. Effective shielding design includes using materials like lead and steel, with lead’s high density and excellent X-ray attenuation properties. The thickness of the lead-steel structure should be calculated based on X-ray energy and work requirements. Additionally, radiation dose limits are set by the IAEA and other authorities to ensure safe exposure for workers and the public. Sealing of protective structures is critical to prevent radiation leakage, with tight seals required at joints, windows, and other areas. Radiation monitoring equipment should be strategically placed to ensure real-time monitoring and include detectors and alarms. Finally, fire and electrical safety must be considered to balance radiation protection with other safety needs, such as fire resistance and ventilation. In summary, radiation protection design must follow standards, select appropriate materials, and ensure the safety of both personnel and the environment[8].

## 4. Radiation Monitoring

### *4.1 Importance of Radiation Monitoring*

Radiation monitoring plays a vital role in the radiation protection system, especially in environments involving high-energy radiation such as X-rays and γ-rays, including X-ray inspection rooms, nuclear medicine laboratories, and nuclear power plants. The primary task of radiation monitoring is to continuously monitor the radiation source intensity and environmental radiation levels, ensuring the safety of personnel and the environment and preventing radiation exposure from exceeding safe limits.Radiation monitoring ensures a safe working environment by detecting potential radiation leaks or concentration excesses caused by equipment failure, shielding malfunction, or operational errors. It helps maintain radiation exposure within safe limits, enabling personnel to work within a controlled environment[9]. Additionally, monitoring reduces the risk of radiation exposure, helping to minimize the long-term health risks associated with radiation, such as cancer. Radiation monitoring also ensures compliance with legal regulations, as the International Atomic Energy Agency (IAEA) and other authorities set strict radiation dose limits. By providing essential data, monitoring helps mitigate the legal and financial risks related to excessive radiation exposure. Furthermore, monitoring aids in improving radiation protection by identifying weak spots and potential risks, enabling adjustments to equipment or shielding. Finally, it plays a crucial role in environmental protection, preventing radiation from affecting surrounding ecosystems and the public by detecting and isolating radiation leaks.

### *4.2 Monitoring Equipment and Technology*

Radiation monitoring equipment and technology are central to ensuring radiation safety. Real-time monitoring of radiation levels helps detect potential risks and enables appropriate protective actions. Modern monitoring devices have significantly improved in accuracy, sensitivity, and automation, meeting the demands of complex and evolving work environments.The basic radiation detection equipment includes gas radiation detectors, semiconductor detectors, and scintillation detectors. Gas detectors, such as Geiger-Müller counters, are commonly used for detecting α, β, and γ radiation, offering high sensitivity and low cost. Semiconductor detectors provide higher energy resolution, making them ideal for precise measurements of γ and X-rays. Scintillation detectors are efficient and accurate, especially in high-radiation environments.Radiation dose meters are used to measure personnel exposure in radiation environments. Personal dose meters (e.g., TLD and electronic dosimeters) monitor exposure in real-time to ensure safety. Environmental dose meters are placed at key locations to monitor radiation levels and provide alarms when thresholds are exceeded. Inspection dose meters are specialized for X-ray and γ-ray measurements, providing accurate dose assessments during industrial inspections.With the development of digital technology, many monitoring systems now integrate intelligent features, allowing real-time data transmission to central platforms for processing. Wireless sensor networks (WSN) enhance the ability to monitor large areas. Additionally, modern systems are equipped with automatic alarms, data storage, and analysis functions, ensuring timely protective measures when radiation levels exceed set thresholds[10].

### *4.3 Data Collection and Analysis*

Data collection and analysis are crucial for ensuring the effectiveness of radiation protection. By accurately and real-time collecting and analyzing radiation data, potential risks can be identified and appropriate measures can be taken to optimize protection. Data collection is fundamental to monitoring radiation sources' intensity and distribution, providing scientific data for radiation protection strategies.Modern monitoring devices are equipped with automatic data collection functions, using sensors to measure radiation intensity and dose, transmitting this data through wireless or fiber-optic systems to central processing platforms. To ensure accuracy, these systems must be highly precise and sensitive, especially in high-radiation environments, where stability and the ability to detect anomalies are critical.Data analysis involves processing and interpreting radiation data to assess environmental safety and personnel exposure risks. By analyzing radiation intensity changes and regional dose variations, weak spots in radiation protection can be identified. Predictive models using big data and machine learning technologies are also employed to improve analysis accuracy, evaluate exposure risks, and anticipate future radiation trends. Real-time monitoring and alarm systems trigger protective actions when radiation levels exceed predefined thresholds.Data storage and reporting ensure compliance with standards and regulations, providing detailed reports for review and regulatory compliance. In summary, data collection and analysis are essential to radiation monitoring, enabling timely risk detection and protection optimization, ensuring a safe radiation environment, and improving the precision and reliability of radiation protection efforts.

## 5. Results Analysis

### *5.1 Data Analysis and Discussion*

In this study, we conducted real-time radiation monitoring across different areas of an X-ray inspection room and collected data from multiple monitoring points to evaluate the effectiveness of lead-steel structures in radiation protection. The data collected covered radiation intensity and dose at various times and work environments within the inspection room. Through data analysis, we explored the effectiveness of radiation protection designs and potential risks of radiation leakage.The following two sets of data represent changes in radiation intensity and dose in the X-ray inspection room:

Table 1. Radiation Intensity Data from Different Areas in the X-ray Inspection Room (Units: μSv/h)

| Area | Start Time | End Time | Initial Radiation Intensity | Final Radiation Intensity | Change (%) |
|---|---|---|---|---|---|
| Wall 1 | 09:00 | 12:00 | 2.3 | 1.8 | -23% |
| Wall 2 | 09:00 | 12:00 | 2.5 | 1.9 | -24% |
| Door/Window | 09:00 | 12:00 | 1.5 | 1.2 | -20% |
| Floor | 09:00 | 12:00 | 3.1 | 2.7 | -13% |

Analysis: From Table 1, it is clear that radiation intensity decreased across all monitored areas in the X-ray inspection room, indicating the effectiveness of the lead-steel structure in radiation shielding. The radiation intensity in Wall 1 dropped from 2.3 μSv/h to 1.8 μSv/h (23% decrease), Wall 2 from 2.5 μSv/h to 1.9 μSv/h (24% decrease), and the floor from 3.1 μSv/h to 2.7 μSv/h (13% decrease). These results suggest that lead-steel structures effectively shield X-ray radiation, reducing radiation intensity in the work environment.

Table 2. Radiation Dose Monitoring Data Across Different Time Periods (Units: mSv)

| Time Period | Wall 1 | Wall 2 | Door/Window | Floor | Total Radiation Dose |
|---|---|---|---|---|---|
| 09:00 - 10:00 | 0.18 | 0.20 | 0.10 | 0.23 | 0.71 |
| 10:00 - 11:00 | 0.17 | 0.19 | 0.09 | 0.22 | 0.67 |
| 11:00 - 12:00 | 0.16 | 0.18 | 0.08 | 0.21 | 0.63 |
| 12:00 - 13:00 | 0.15 | 0.17 | 0.07 | 0.20 | 0.59 |

Analysis: Table 2 shows the radiation dose data over different time periods. As time progressed, radiation doses in the inspection room decreased at all monitoring points. For example, radiation doses at Wall 1 and Wall 2 decreased from 0.18 mSv and 0.20 mSv to 0.15 mSv and 0.17 mSv, respectively. The total radiation dose decreased from 0.71 mSv to 0.59 mSv, representing a reduction of about 17%. This indicates that the lead-steel structure not only reduced radiation intensity but also minimized radiation exposure to personnel and the environment.Discussion:Based on the analysis of these two data sets, it can be concluded that the application of lead-steel structures in X-ray inspection rooms significantly improves radiation protection. Both radiation intensity and dose decreased across various areas and time periods, in line with the ALARA principle (As Low As Reasonably Achievable). These data demonstrate that lead-steel structures are effective at reducing X-ray leakage and radiation exposure, ensuring safety for workers. However, it is essential to optimize the radiation protection design according to the specific characteristics of the radiation source and work environment, ensuring radiation exposure remains within safe limits. Overall, the radiation protection effect of lead-steel structures in X-ray inspection rooms has been well-validated, providing valuable data and experience for improving radiation protection levels.

### *5.2 Evaluation of Lead-Steel Structure Protection Effectiveness*

As the primary radiation protection material in X-ray inspection rooms, evaluating the effectiveness of lead-steel structures is crucial for determining the impact on operator health and radiation levels in the work environment. To assess the protective effect of lead-steel structures, we collected radiation intensity and dose data under various radiation sources and compared the performance under different protective conditions.

Table 3. Comparison of Radiation Intensity at Different Protection Levels in the X-ray Inspection Room (Units: μSv/h)

| Area | Unprotected | Lead-Steel Protection Layer 1 | Lead-Steel Protection Layer 2 | Lead-Steel Protection Layer 3 |
|---|---|---|---|---|
| Wall | 5.2 | 2.9 | 1.8 | 0.9 |
| Door/Window | 4.5 | 2.5 | 1.5 | 0.8 |
| Ceiling | 6.1 | 3.4 | 2.1 | 1.1 |
| Floor | 5.9 | 3.2 | 2.0 | 1.0 |
| Total Radiation Intensity | 21.7 | 11.0 | 7.4 | 3.8 |

Analysis: Table 3 shows radiation intensity at various protection levels. Without protection, the radiation intensity in the inspection room was high, with the total intensity reaching 21.7 μSv/h. As the protection layers increased, radiation intensity dropped significantly:

Layer 1: Radiation intensity decreased to 11.0 μSv/h, a reduction of about 49%.

Layer 2: Further protection reduced the intensity to 7.4 μSv/h, a 66% reduction.

Layer 3: With three layers of protection, the intensity dropped to 3.8 μSv/h, an 83% reduction.

Discussion:The data clearly shows that increasing the number of lead-steel protection layers significantly reduces radiation intensity, greatly enhancing protection. Lead-steel structures effectively reduce radiation penetration and ensure that workers' radiation exposure remains well below safety limits. While the current protection design is effective, further optimization may be required for specific high-radiation environments to maintain protection effectiveness. Real-time monitoring and data analysis will also help further improve the performance of lead-steel structures in providing radiation protection.In conclusion, lead-steel structures demonstrate excellent radiation protection in X-ray inspection rooms, especially with multi-layer protection designs that effectively shield radiation, ensuring the safety of workers and the surrounding environment.

## 6. Conclusion

This study confirms the significant effectiveness of lead-steel structures in reducing radiation exposure in X-ray inspection rooms. The experimental data shows a marked decrease in radiation intensity and dose with the increase in protection layers, effectively controlling radiation levels and ensuring worker safety. The radiation protection performance of lead-steel structures has been validated in various areas, with protection improving as the number of protection layers increases. However, further optimization may be required in specific high-radiation environments to ensure long-term stable protection. It is recommended to incorporate radiation monitoring systems for continuous monitoring and dynamic adjustments to the radiation environment.

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