Investigation of X-ray Penetration Characteristics of Fuel Rods and Radiation Protection Conditions

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Abstract

Fuel rods are one of the core components of nuclear reactors, and their structural stability directly affects the operational stability of nuclear reactors. Non-destructive testing of fuel rod structure and defects is crucial for ensuring nuclear safety. Employing X-ray based non-destructive testing and flaw detection techniques, such as Digital Radiography (DR) and Computed Tomography (CT), for structural and defect inspection of fuel rods can provide high resolution and defect detection capabilities, offering a promising solution to high-level quality control challenges for fuel rods. Regarding X-ray flaw detection for fuel rods, this paper first analyzes the physical process of interaction between X-rays and atoms in matter during penetration, then quantitatively analyzes the attenuation of X-ray intensity in fuel rods based on the Lambert-Beer law. Based on this, the relationship between X-ray energy and its penetration capability for fuel rods is clarified, indicating that X-rays with energy not lower than 200 keV should be selected to meet the weld inspection requirements for this type of fuel rod. Additionally, since radiation protection is required for X-ray non-destructive flaw detection of fuel rods, this paper also analyzes the selection of lead plate thickness for radiation protection based on the energy of the aforementioned X-ray source. For adequate protection, the thickness should be selected as at least 20 mm. In summary, this paper clarifies the X-ray penetration characteristics for implementing non-destructive testing and flaw detection of fuel rods, and analyzes the corresponding radiation protection conditions, which provides guidance for fuel rod production practice.

Full Text

Investigation of X-Ray Penetration Characteristics and Radiation Protection Conditions for Fuel Rods

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Abstract

Fuel rods are one of the core components of nuclear reactors, and their structural stability directly affects reactor operational stability. Non-destructive testing (NDT) of fuel rod structures and defects is crucial for ensuring nuclear safety. X-ray-based NDT and inspection techniques, such as Digital Radiography (DR) and Computed Tomography (CT), offer high resolution and defect detection capabilities for fuel rod inspection, promising to address high-level quality control challenges. This paper first analyzes the physical processes of X-ray interactions with atoms in matter during penetration, then quantitatively examines X-ray intensity attenuation in fuel rods based on the Lambert-Beer law. This analysis clarifies the relationship between X-ray energy and penetration capability, establishing that X-rays with energy no less than 200 keV are required to meet weld inspection needs for this fuel rod type. Additionally, since radiation protection is necessary for fuel rod X-ray NDT, this paper analyzes lead plate thickness selection for the aforementioned X-ray source energy, concluding that a thickness of at least 20 mm should be selected for adequate protection. In summary, this work clarifies the X-ray penetration characteristics required for fuel rod NDT and analyzes corresponding radiation protection conditions, providing guidance for fuel rod production practices.

Keywords: X-ray inspection; Non-destructive testing; Fuel rod; Lambert-Beer law

1. Introduction

As the core unit of nuclear reactors, fuel rods host nuclear fission reactions and conduct the released heat to coolant [?, ?]. Operating for extended periods in high-temperature, high-pressure, and radiation environments, fuel rods undergo complex physical and chemical changes during service, including thermal expansion, irradiation annealing, surface corrosion, crack propagation, and internal pressure variations [?, ?]. These changes can lead to structural damage such as rupture, swelling, and leakage, which, if undetected, severely impacts reactor safety and stability [?, ?]. Meanwhile, fuel rod structures and internal defects may significantly affect surrounding environments and equipment, potentially causing nuclear accidents.

X-ray-based NDT and inspection technology, as a representative NDT method, enables high-precision imaging and has been widely applied in industrial component internal structure analysis and material characterization. This technique provides internal information such as voids, cracks, and defects without destroying the test object, offering non-destructive and high-precision characteristics [?]. Applying X-ray inspection technology to fuel rod quality control not only enhances service life and reduces accident risks but also provides critical data support for fuel management, nuclear power plant maintenance, and operational optimization. For instance, through regular NDT, fuel replacement cycles can be optimized, reactor power distribution adjusted, and fuel rod health status monitored in real-time, thereby improving nuclear energy utilization efficiency and economics. Furthermore, NDT reduces maintenance and downtime, lowering operational costs. Thus, it plays a vital role in ensuring safe nuclear power plant operation and enhancing the competitiveness of the nuclear energy industry [?].

This paper conducts feasibility analysis for fuel rod NDT based on X-ray inspection, first investigating the relationship between X-ray energy and penetration capability for fuel rods, confirming the feasibility of high-precision inspection using X-ray technology, and analyzing the corresponding radiation protection requirements.

2. X-Ray Inspection Basic Process

The basic structure of X-ray-based NDT and inspection equipment consists of three core units: the radiation source, test object, and detector (or film), as shown in [Figure 1: see original paper]. The fundamental detection process involves the source emitting X-rays that penetrate the test object and reach the detector to form a transmission image. During X-ray transmission, structural and material differences in various parts of the test object cause different degrees of X-ray absorption, with corresponding intensity detected by detector units at each position. After image processing, internal details of the test object can be obtained.

Unlike other inspection methods, X-ray inspection offers significant advantages for fuel rod structure and internal defect detection. First, it is non-destructive, enabling full inspection of fuel rods before use. Second, DR technology enables rapid NDT, while high-resolution CT can precisely capture structural details of minute defects, making it suitable for complex internal structure analysis. Consequently, X-ray inspection technology has been widely applied in fuel rod NDT and quality control.

3. X-Ray Penetration Characteristics Analysis

3.1 X-Ray Penetration Mechanism Analysis To ensure good detection results for fuel rods, X-ray penetration capability must first be evaluated. This assessment involves ray propagation and attenuation within fuel rods, including the effects of different tube voltages and currents on penetration depth and image quality. Only with clear understanding of ray penetration capability can X-ray transmission imaging effectively reveal internal structural features, defects, or other critical issues. Therefore, studying the mechanisms of X-ray interaction with fuel rods and attenuation patterns under different conditions is key to ensuring effective NDT.

When X-rays penetrate matter, they interact with atoms through several primary mechanisms:

1. **Photoelectric Effect:** The photoelectric effect is a major X-ray-matter interaction where X-ray photons are absorbed by atoms, causing electron ejection.

2. **Compton Scattering:** Compton scattering is another primary interaction between X-rays and free or weakly bound electrons. In this process, X-ray photons collide with electrons, causing ejection while partially transferring photon energy to the electron. Compton scattering significantly affects high-energy X-rays; scattered X-rays have lower energy and altered propagation direction. This scattering is an important cause of attenuation during X-ray-matter interaction.

3. **Electron Pair Production:** Pair production occurs only at extremely high photon energies (greater than 1.022 MeV). In this process, X-ray photons convert their energy into an electron-positron pair in the atomic nuclear electric field. This interaction probability increases with X-ray energy but becomes significant only at very high energies.

4. **Thomson and Rayleigh Scattering:** These are elastic scattering processes of X-rays with atomic nuclei or electrons, where Thomson scattering approximates Compton scattering at low energies. Thomson and Rayleigh scattering involve no energy loss [**?**, **?**].

Through these mechanisms, X-rays interact with fuel rod materials, undergoing attenuation and energy transfer that affect transmission imaging quality. The Lambert-Beer law is typically used to characterize X-ray absorption and attenuation during penetration [**?**]. The core principle is that X-ray intensity attenuates with increasing penetration depth, with the degree of attenuation affected by the material' s atomic composition and density.

According to the Lambert-Beer law, X-ray intensity attenuation in an object follows:

$$I = I_0 e^{-\mu T}$$

where I_0 is incident photon intensity, T is material thickness, and μ is the linear attenuation coefficient of the penetrated material.

For more direct correlation with atomic properties, the mass attenuation coefficient μ_m is typically used to characterize photon absorption:

$$\mu_m = \frac{\mu}{\rho}$$

where ρ is material density.

For a specific element, its mass attenuation coefficient depends on X-ray energy, with specific values available in public databases. The XCOM database, developed by the National Institute of Standards and Technology (NIST), is an authoritative tool for calculating X-ray interaction coefficients in elements, compounds, and mixtures. Covering energies from 1 keV to 100 GeV, it provides mass attenuation coefficients and component data for major interaction mechanisms including photoelectric effect, Compton scattering, and pair production [?]. In this study, XCOM database data were used to calculate ray penetration and attenuation characteristics in fuel rods, providing precise theoretical support for NDT feasibility analysis.

For the fuel rods discussed in this paper, which are mixtures of multiple elements, the mixture' s mass attenuation coefficient is the sum of each element' s mass attenuation coefficient multiplied by its mass fraction [?]:

$$\mu_m = \sum_i w_i \mu_{mi}$$

where μ_{mi} is the mass attenuation coefficient of each element in the mixture and w_i is the mass fraction of each element.

Substituting the mixture' s mass attenuation coefficient yields:

$$I = I_0 e^{-\mu_m \rho T}$$

where ρ is the test object' s density, and multiplying the mass attenuation coefficient by density gives the linear attenuation coefficient.

In practical applications, test objects are often assemblies of multiple mixtures. While obtaining the overall elemental mass fractions and density for the entire object is difficult, the elemental composition and density of each component are relatively easy to obtain. Therefore, the elemental composition and density of each component can substitute for the overall elemental mass fractions and density.

Assuming the test object has a regular shape (i.e., the cross-sectional area penetrated by X-rays remains constant for each component), introducing the penetration cross-sectional area S yields:

$$I = I_0 e^{-\sum_i \mu_{mi} \rho_i T_i}$$

which finally gives:

$$I = I_0 e^{-\sum_i \mu_{mi} m_i}$$

where m_i is the mass per unit area of each component. This equation shows that when the penetration cross-sectional area of each component is constant, the overall residual ray intensity can be determined using each component' s thickness and density, thereby evaluating the penetration characteristics of different X-ray energies. This enables analysis of X-ray penetration characteristics for fuel rods.

3.2 X-Ray Penetration Characteristics for Fuel Rods Based on fuel rod structural characteristics, this section analyzes penetration characteristics of different X-ray source voltages in various fuel rod regions using the conclusions from Section 3.1. After welding end plugs to the cladding tube, weld quality must be strictly controlled. The following analysis examines X-ray penetration characteristics for both the fuel rod weld region and pellet-filled region.

Fuel rods are cylindrical with approximately 9.5 mm diameter, primarily consisting of zirconium alloy cladding, UO_2 pellets filling the interior, and end plugs at both ends. The cladding wall thickness is about 0.6 mm, and the pellet layer thickness is about 8 mm. The weld between the end plug and cladding tube can be simplified as a pure zirconium cylinder with 9.5 mm diameter. For the pellet-filled region, the elemental composition can be approximated as 15.51% Zr by volume fraction and 84.49% UO_2 by volume fraction.

Under these conditions, mass attenuation coefficients for each layer at different ray energies can be obtained from XCOM. [Figure 2: see original paper] and [Figure 3: see original paper] show the mass attenuation coefficients for the fuel rod weld region and pellet-filled region, respectively.

According to the previous analysis, residual ray intensity after passing through multiple material layers can be calculated using the Lambert-Beer law:

$$I = I_0 e^{-\sum_i \mu_{mi} \rho_i T_i}$$

This yields the relationship curves between residual ray intensity and ray energy for different source voltages in the active region, as shown in [Figure 4: see original paper].

Based on the Lambert-Beer law, X-ray penetration capability is related to tube voltage, which represents the maximum X-ray energy the source can emit. Therefore, penetration capability increases with tube voltage [?]. Generally, a penetration rate no less than 20% is considered necessary for good imaging quality. Combined with actual fuel rod inspection requirements, X-rays with energy no less than 200 keV can meet weld inspection needs. In actual production, considering long-term stability and efficiency, X-ray sources with maximum voltage of 320 kV are typically adopted.

4. X-Ray Radiation Protection Conditions Analysis

The previous section analyzed the relationship between X-ray penetration capability and energy by calculating residual ray intensity after passing through fuel rods, providing theoretical basis for source energy selection. However, since X-rays pose radiation hazards, protective measures are required to ensure operator safety and minimize environmental impact, typically implemented using lead shielding. Lead' s radiation shielding effectiveness is inversely proportional to X-ray energy [?]. Medium-to-high-energy X-rays (e.g., 200 keV) require thick lead shielding to effectively reduce radiation intensity. Based on the derived equations, this section analyzes protective lead housing thickness. For commonly used 200 kV X-ray sources, calculations show that residual intensity after penetrating 10 mm lead plate is about 1%, and about 0.1% after 15 mm lead plate.

In practice, when using 200 kV X-ray sources, common protective lead housing thickness typically ranges from 10 mm to 15 mm. In specific cases requiring further radiation leakage reduction or handling high-dose requirements, thickness may reach 20 mm or more. When designing protective lead housing for X-ray inspection equipment, international radiation protection standards must be followed, such as those from the International Commission on Radiological Protection (ICRP) and International Electrotechnical Commission (IEC) [?].

Theoretical analysis of ray attenuation and penetration reveals that X-rays with approximately 200 keV energy possess sufficient penetration capability to penetrate high-density metal cladding and other materials in fuel rods. To ensure on-site personnel safety, equipment protective lead housing thickness should be at least 20 mm.

References

[1] Zheng Saichun, Zhang Xiaogang, Zhang Fan, Wang Shaoxing, Guo Mengya. Positioning detection system for the core of tubular nuclear fuel elements[J]. Nondestructive Testing, 2024, 46(7): 12–18.

[2] Li Guanxing. Manufacturing Technology of Research and Test Reactor Fuel Elements[M]. Beijing: Chemical Industry Press, 2007.

[3] Frost B R T. Nuclear Fuel Elements: design, fabrication and performance[M]. Elsevier, 2013.

[4] Cui Yao, Zhang Xiangyang, He Gaokui. Design of non-destructive testing detection system for nuclear fuel assemblies[J]. Isotopes, 2015, 28(3): 167–170.

[5] Zhang Xiaogang, Yu Dongbao, Tang Hui, Zhu Yongli, Ge Teng. Boundary identification and positioning detection system for the core inside the cladding of plate-type nuclear fuel elements[J]. Nondestructive Testing, 2023, 45(1): 58-61+71.

[6] Choi H-J, Chung Y S, Kim H, Kwak S-W, Chung H, Baek H-K, Shin J, Chung Y H, Min C H. Performance evaluation of Yonsei Single-photon Emission

Computed Tomography (YSECT) for partial-defect inspection within PWR-type spent nuclear fuel[J]. Nuclear Engineering and Technology, 2024, 56(11): 4471–4480.

[7] Parker H M O, Joyce M J. The use of ionising radiation to image nuclear fuel: A review[J]. Progress in Nuclear Energy, 2015, 85: 297–318.

[8] Katsuyama K, Nagamine T, Matsumoto S, Sato S. High energy X-ray CT study on the central void formations and the fuel pin deformations of FBR fuel assemblies[J]. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 2007, 255(2): 365–372.

[9] Cai Yawen, Wang Xiangke. Research progress on nuclear radiation detection technology and devices[J]. Journal of Instrumental Analysis, 2024, 43(10): 1512–1524.

[10] Interaction of X-rays with matter[J]. Journal of Engineering, 1979, (03): 93–115.

[11] Li Zhefu, Xue Xiangxin. Photon mass attenuation coefficients of boron-containing minerals and epoxy resin[J]. Atomic Energy Science and Technology, 2011, 45(9): 1147–1152.

[12] Berger M J, Hubbell J H. XCOM: Photon cross sections on a personal computer[R]. National Bureau of Standards, Washington, DC (USA). Center for Radiation Research, 1987.

[13] Tang Yahui. X-ray detection system for pipeline wall thickness and detection method[D]. Tianjin University, 2023.

[14] Chen Jun. Radiation protection analysis of X-ray inspection work for steel structures[J]. Engineering Technology Research, 2023, 8(20): 42–44.

[15] Li Dawei, Ji Yunlong, Zhou Hongmei, et al. Measurement and protection evaluation of pulsed X-ray radiation field caused by a certain equipment[J]. Chinese Journal of Radiological Health, 2020, 29(01): 53–56.

[16] Lu Xiaoqian, Li Lingling. Radiation protection and safety evaluation of X-ray flaw detection devices under special shielding conditions[J]. Guangdong Chemical Industry, 2019, 46(13): 40–41+48.

[17] Zheng Cheng. Research on radiation shielding and protection of industrial X-ray flaw detection devices[J]. China Strategic Emerging Industries, 2018, (16): 180+182.

[18] Wang Sainan, Deng Chenyang. Radiation protection and environmental impact analysis of industrial X-ray devices[C]//Chinese Nuclear Society. China Nuclear Science and Technology Progress Report (Volume 8): Proceedings of the 2023 Annual Conference of the Chinese Nuclear Society on Nuclear Chemical and Radiation Protection. China Nuclear Mining Technology Group Co., Ltd.; China Nuclear Strategic Planning Research Institute, 2023: 5.

[19] Hu Jian. Exploration of X-ray radiation protection standards and regulations[J]. Popular Standardization, 2022, (02): 114-115+118.

[20] Jia Pengjun, Liu Yan, Yao Huan, et al. Discussion on radiation protection and safety management of X-ray flaw detection[J]. Inner Mongolia Petrochemical Industry, 2018, 44(11): 52-58.

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Note: Figure translations are in progress. See original paper for figures.