

Indirect Neutron Radiography Experiment on Dummy Nuclear Fuel Rods for Pressurized Water Reactors at CMRR

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Abstract

Nuclear energy is a vital source of clean energy that will continue to play an essential role in global energy production for future generations. Nuclear fuel rods are core components of nuclear power plants, and their safe utilization is paramount. Due to its inherent high radioactivity, indirect neutron radiography (INR) is currently the only viable technology for irradiated nuclear fuel rods in the field of energy production. This study explores the experimental technique of indirect neutron computed tomography (INCT) for radioactive samples. This project includes the development of indium and dysprosium conversion screens of different thicknesses and conducts resolution tests to assess their performance. Moreover, a pressurized water reactor (PWR) dummy nuclear fuel rods have been fabricated by self-developing substitute materials for cores and outsourcing of mechanical processing. Experimental research on the INR is performed using the developed dummy nuclear fuel rods. The sparse reconstruction technique is used to reconstruct the INR results of 120 pairs of dummy nuclear fuel rods at different angles, achieving a resolution of 0.8 mm for defect detection using INCT.

Full Text

Preamble

Indirect neutron radiography experiment on dummy nuclear fuel rods for pressurized water reactors at CMRR

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Nuclear energy represents a vital source of clean energy that will continue to play an essential role in global energy production for future generations. Nuclear fuel rods are core components of nuclear power plants, and their safe utilization is paramount. Due to their inherent high radioactivity, indirect neutron radiography (INR) is currently the only viable technology for examining irradiated nuclear fuel rods in energy production applications. This study explores the experimental technique of indirect neutron computed tomography (INCT) for radioactive samples. The project includes the development of indium and dysprosium conversion screens of different thicknesses and conducts resolution tests to assess their performance. Moreover, pressurized water reactor (PWR) dummy nuclear fuel rods have been fabricated by developing substitute materials for fuel cores in-house while outsourcing mechanical processing. Experimental research on INR is performed using these developed dummy nuclear fuel rods. The sparse reconstruction technique is used to reconstruct the INR results of 120 pairs of dummy nuclear fuel rods at different angles, achieving a resolution of 0.8 mm for defect detection using INCT.

Keywords: Conversion screen, Dysprosium, Indirect Neutron Computed Tomography, Dummy nuclear fuel rods

Introduction

Rapid economic expansion has resulted in the emergence of a series of environmental issues, with global warming recently attracting significant attention [1]. Nuclear energy is expected to have a substantial impact on future global energy output because of ever-increasing human energy demands and concerns about climate change [2]. However, safety concerns surrounding nuclear energy cannot be ignored, despite its establishment as a clean energy source [3,4]. A key component of nuclear reactors is the nuclear fuel rod, which operates for several years in extremely corrosive, high-pressure, high-radiation, and high-temperature environments [5]. The structural characteristics and performance of nuclear fuel rods directly affect the vital status and safe operation of the reactor [6]. Various testing methods must be employed to ensure the safe operation and cost-effectiveness of nuclear power plants from processing through production. Traditional ultrasonic detection, eddy current detection, and other nuclear fuel element detection methods suffer from poor penetration capability and low detection efficiency.

Non-destructive testing (NDT), which includes X-ray and neutron radiography (NR), offers alternative approaches. In contrast to X-rays, the latter complements the former [7–10]. Neutron interaction is characterized by nuclear rather than electronic interactions with the medium through which it passes [11–14].

Neutrons are more suitable than X-rays for detecting fuel components for several reasons [15]. First, uranium has a high attenuation coefficient for X-rays. The attenuation coefficient for the natural composition of uranium is low for cold neutrons, allowing thicker assemblies to be transmitted without problems. Additionally, the cold neutron cross-sections of ^{235}U and ^{238}U are very different, making it easy to distinguish between the two isotopes and quantify the fissile isotope ^{235}U [16]. NR plays a crucial role in developing safer and more efficient nuclear power plants by providing valuable information for the development of new fuels, claddings, and other reactor materials.

However, analyzing irradiated nuclear fuel rods by NR is challenging because most neutron detectors used for imaging are gamma-sensitive, and gamma radiation can interfere with the analysis [17]. Activation foils are valuable when used in conjunction with films for highly radioactive objects, as in the early days of NR [2]. The earliest neutron radiographs were produced in 1935 by Kallmann, only three years after James Chadwick discovered neutrons in 1932 [18]. Subsequently, a facility built explicitly for NR at the 200 kW Juggernaut reactor provided the first NR application for studying irradiated nuclear fuel [19]. Craft et al. used dysprosium and indium conversion foils to perform NR of irradiated nuclear fuel in a NR reactor. They found that cracking of the reflector material was more visible in the dysprosium image, whereas the central void was only visible in the indium image [20].

Groeschel et al. observed the sensitivity of neutrons to hydrogen concentration in cladding samples using artificial hydride materials. The induced hydrogen content in a sample can be estimated from the obtained macroscopic cross-sections [17]. Wei et al. performed INR experiments using X-ray imaging plates (IPs) at the China Advanced Research Reactor (CARR). They used dummy nuclear fuel rods and a motor vehicle water-temperature sensor during the testing phase to conduct both qualitative and quantitative inspections. The thickness of the tape at one position on the cladding of the dummy nuclear fuel rod was quantitatively calculated to be 9.57 layers with a relative error of $\pm 4.3\%$ pellets. Meanwhile, the NCT method allows for a detailed image view of the cross-section of enriched and natural pellets, highlighting the difference in enrichment between these pellets [25].

In our previous study, we detected irradiated U-10Zr alloy using indirect NR because of the high residual dose [26]. Although some direct digital techniques have successfully examined irradiated nuclear fuels, INR remains an essential technology for detecting irradiated nuclear fuel compared to other nondestructive techniques [27].

This study developed a highly accurate and intelligent NCT experimental device for radioactive samples, ensuring safe shielding, automatic picking, high-precision control, and accurate positioning. This device aims to provide the necessary tools for NR as an NDT method for nuclear fuel components of various reactors. The NCT method for radioactive samples involves techniques for measuring, lowering noise, and calibrating digital two-dimensional (2D) indirect

neutron image data under high background radiation field conditions. These achievements include a Computed Tomography (CT) reconstruction method based on finite 2D indirect neutron image projection data, quantitative calculations, and the analysis of indirect neutron CT three-dimensional (3D) data of radioactive samples (nuclear fuel components). These methods make it possible to obtain quantitative information with multiparameter overlap, which is impossible to obtain using conventional 2D images.

II. Materials and Methods

A. Principle

As a unique NDT technique, NR has a range of applications in the nuclear and aerospace industries. When passing through an object, neutrons interact with the atomic nucleus of the object, causing a change in the transmitted neutron beam intensity (I). The Lambert-Beer law describes I by using the composite neutron interaction probability of each independent material as follows [28]:

$$I = I_0 \exp \left(\sum (N_i \sigma_i t) \right)$$

where I_0 is the incident beam intensity, N_i is the bulk density of the target nucleus for element i , σ_i is the total neutron scattering cross-section for element i , and t is the thickness of the sample in the beam direction.

Owing to the varied intensities of transmitted neutrons in inhomogeneous or faulty objects, information on the internal structure of an item may be retrieved using specific techniques to detect neutron rays penetrating the object.

Based on the different exposure methods, NR can be divided into direct neutron radiography (DNR) and indirect neutron radiography (INR), as shown in Fig. 1 [29]. In DNR, both the film (imaging plate) and the conversion screen are exposed to the neutron beam, and the film (imaging plate) absorbs the prompt radiation created by the neutron irradiation of the conversion screen [30]. While the rapid imaging speed of this technology is an advantage, it is prone to interference from gamma rays in the neutron beam, as well as those produced by the sample and neutrons, because the film (imaging plate) is also gamma-sensitive. In INR, the conversion screen, which is unaffected by γ -rays, is first placed at the back of the sample. The conversion screen absorbs neutrons from the neutron beam through the sample [31,32]. Each location on the conversion screen produces a radioactivity intensity directly proportional to the intensity of the neutrons that hit the screen. Consequently, the conversion screen develops a possibly radioactive latent image after the neutron beam penetrates the sample, which is then moved to the dark box and placed on a film (imaging plate) for re-exposure to create an image. This technique avoids γ -ray interference and is therefore suitable for imaging in strong γ -ray environments. This transfer technique is one of the few that can produce high-quality radiographic images of irradiated fuel; however, it is also time-consuming [23,33]. Conducting indirect

neutron CT is more time-consuming due to the use of multi-angle photography of the sample for 3D image reconstruction. This approach is an offline imaging technology in which the acquisition and exposure of each projected image involve replacement of the absorption foil, resulting in variations before and after imaging.

Indirect neutron CT encounters two aforementioned technical challenges. The differences between images are resolved by setting up an identifier as a reference for subsequent image adjustments. In addition, time and neutron beams are saved by optimizing the conversion screen or improving the reconstruction algorithm.

B. Dummy Nuclear Fuel Rod

1. Material and Structure Pressurized water reactors (PWRs) are the predominant reactor types employed in contemporary commercial nuclear power facilities [34]. A fuel rod in PWRs is a typical multicomponent device designed to continuously produce and transfer fission energy from fuel pellets to the coolant while safely containing fission products simultaneously [6]. These reactors contain diverse nuclear fuel components with distinct features. A typical PWR nuclear fuel rod comprises several components, including a UO_2 core block, zirconium alloy cladding, end plugs, compression springs, and helium cavity [6]. The enrichment of ^{235}U in the UO_2 core typically ranges from 3% to 5%.

As an illustrative example, we developed a substitution sample for a nuclear fuel rod from the Daya Bay Nuclear Power Station. Fig. 2 [Figure 2: see original paper] depicts the structure of the nuclear fuel rod from the Daya Bay Nuclear Power Plant. Table 1 lists the main parameters of the Daya Bay nuclear fuel rods.

2. Calculation and Production Nuclear fuels used in reactors primarily comprise fuel meat and cladding, with fuel meat containing nuclear materials that must be carefully controlled and managed because of associated risks. However, using real nuclear materials for sample preparation in INR detection of nuclear fuel rods can be challenging because of sample management, transportation, and high production costs.

This paper proposes the development of substitute samples for nuclear fuel rods. These substitute samples were specifically designed for research purposes in the field of INR. We designed a simulated sample structure that exhibited a high level of consistency with real fuel rods. Additionally, we built composite materials that could effectively substitute for real fuel rods. By manipulating the proportions of constituents in the simulated substance, it is possible to make the substance more closely match the density of the fuel core and the coefficient of neutron absorption for cold neutrons. Table 2 presents the cold neutron cross-section data for each element of the PWR nuclear fuel rod.

The cold neutron cross-sections of the remaining nuclides present in the core

material have significantly smaller values than ^{235}U and ^{10}B . Consequently, their effects are ignored during the substitute material formation procedure.

UO_2 is the core material with a density of approximately 10.60 g/cm^3 . As a result, lead with a density closer to this value was chosen as a substitute for the substrate of the composite, and boron carbide was used to simulate the macroscopic absorption cross-section of the core of cold neutrons with various ^{235}U enrichments. The relationship between the boron carbide content and ^{235}U enrichment in the core is deduced as follows:

$$\Sigma_{235\text{U}} = \sigma_{235\text{U}} \times \rho_{\text{UO}_2} \times \frac{N_A}{M_{235\text{U}}} \times p_{235\text{U}}$$

$$\Sigma_{10\text{B}} = \sigma_{10\text{B}} \times \rho_{\text{B}_4\text{C}} \times \frac{N_A}{M_{\text{B}_4\text{C}}} \times p_{10\text{B}}$$

$$\rho_{\text{B}_4\text{C}} = \sigma_{235\text{U}} \times \rho_{\text{UO}_2} \times \frac{238}{270} \times \frac{55.2}{43.2} \times \frac{10}{p_{235\text{U}}} \times \frac{3843.3}{691.7} \times \frac{10.6 \times 238}{0.198 \times 235} \approx 0.485 p_{235\text{U}}$$

where Σ_i is the macroscopic cross-section of i , σ_i is the microscopic cross-section of i , ρ_i is the density of i , p_i is the abundance of i , N_A is the Avogadro constant, and M_i is the molar mass of i .

The composition ratios and density information of dummy nuclear fuel rods with different ^{235}U enrichments, calculated using Eq. (5), are listed in Table 3. The corresponding composite materials can be used for PWR nuclear fuel rod processing.

Fig. 3 [Figure 3: see original paper] depicts the process flow of the PWR dummy fuel core preparation. The first step is to measure specific amounts of lead powder and boron carbide powder. Subsequently, a minimal coupling agent is added to the mixing tank while adhering to the prescribed material ratios for diverse enrichment fuel cores. Afterward, the powders are mixed evenly in a mixer for more than 48 hours. Finally, the mixture is loaded into a hot-press mold and compacted in a hot-press furnace to create dummy fuel cores.

Fig. 4 [Figure 4: see original paper] depicts the different components of the PWR dummy nuclear fuel rod, including aluminum gaskets, end plugs, cores, springs, and cladding tubes made of aluminum alloy. Aluminum gaskets were placed between different cores to simulate various size gaps between the cores. End plugs were used to encapsulate fuel rods. The core consisted of six distinct compositions of blended materials, with enrichments of substitute fuel cores varying from 1.8% to 4.45%. Some cores had small holes machined on two end faces with hole diameters of 2 mm, 1.5 mm, 1 mm, 0.8 mm, 0.5 mm, 0.4 mm, and 0.2 mm. The hole depths were 3 mm, which were used to simulate defects of different scales within the cores.

III. Experiment Setup

A. Neutron Beams

We installed an experimental setup for NR at the Institute of Nuclear Physics and Chemistry of the Chinese Academy of Engineering Physics using the China Mianyang Research Reactor (CMRR) [35–38]. In the CMRR, we reduced the energy of thermal neutrons by interacting them with deceleration material in the slowing chamber, resulting in the production of lower-energy cold neutrons [39]. The flight tube consisted of 11 sections of 1-m-long aluminum tubes with vacuum inside to reduce attenuation of the neutron beam by air, particularly for low-energy beams. The neutron spectra were measured using time-of-flight techniques, as shown in Fig. 5 [Figure 5: see original paper] with a peak wavelength of 2.65 Å and a spectrally weighted average wavelength of 3.99 Å. The facility also includes an object-handling system, an imaging system, a beam stop, and a shielding wall, as shown in Fig. 6 [Figure 6: see original paper].

The aperture size D directly impacts the neutron beam divergence and neutron beam intensity at the sample location. The collimation ratio of the neutron beam (L/D) directly affects spatial resolution. Increasing the L/D ratio improves spatial resolution by decreasing the aperture diameter [40,41]. However, this comes at the expense of lowering the neutron flux reaching the sample. The experimental setup used in this study had an L/D ratio of 275. The neutron flux measured at the detector for the aperture setting reported here was $\Phi_0 = 6 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$.

B. Conversion Screen

The crucial issue in the INR experimental method is determining the exposure time of the conversion screen in the neutron beam and the exposure time of the conversion screen to the NIP to ensure efficient use of the neutron beam and save time. In Eq. (6), we describe the relationship between the radioactivity of a conversion screen exposed to a neutron beam. The exposure time (t_1) [21,42] is given by:

$$A(t_1) = \delta N \Phi (1 - e^{-\lambda t_1})$$

where δ is the neutron absorption cross-section of the converter, N is the number of atoms in the converter material, Φ is the neutron flux irradiating the neutron converter, λ is the decay constant, $\lambda = 0.693/\tau$, and τ is the half-life of the converter material.

After exposure to the neutron beam, the conversion screen was transferred to a darkroom and exposed to the NIP for time t_2 . The radioactivity of the converter, $A(t_2)$, is given by [21,42]:

$$A(t_2) = (\delta N \Phi (1 - e^{-\lambda t_1})) e^{-\lambda t_2} = A(t_1) e^{-\lambda t_2}$$

Fig. 7 [Figure 7: see original paper] shows the variations in the activity of the neutron conversion screen exposed to the neutron beam and after exposure cessation, according to Eq. (6) and (7). The activity of the conversion screen reaches a saturation point as the duration of exposure to the neutron beam increases. Once exposure stops, the conversion screen's activity decays rapidly. Regardless of whether the conversion screen is exposed to the neutron beam or the film, when the exposure time reaches three half-lives of the conversion screen material, the activity is close to 90% of the saturation value.

The conversion screen used for INR should have a high neutron cross-section and be capable of generating decay particles through nuclear reactions with neutrons, which can then lead to NIP exposure. Consequently, dysprosium and indium meet these requirements, and their activation products have half-lives of approximately 1–2 hours, meeting the time requirements for second-exposure operations without resulting in excessive exposure.

In INR, the conversion screen thickness primarily affects the detection efficiency and resolution of the imaging results. Selecting an appropriate conversion screen thickness is imperative to achieve optimal imaging quality, with thicker screens being more efficient but having lower intrinsic resolution and less precision. Fig. 8 [Figure 8: see original paper] shows the substitution results, illustrating the detection efficiency of cold neutrons using indium and dysprosium neutron conversion screens of varying thicknesses. The dysprosium screen exhibited greater detection effectiveness for cold neutrons than the indium screen.

We developed 50 μm and 100 μm thick dysprosium neutron conversion screens and 100 μm and 150 μm thick indium neutron conversion screens by considering the detection efficiency of cold neutrons and the intrinsic resolution of the conversion screen. Fig. 9 [Figure 9: see original paper] illustrates the screen design. We performed a resolution test on INR converter screens using cold neutron beams in conjunction with a NIP. We then exposed the resolution test piece (Siemens Star) and INR converter screen to the neutron beam for 1 hour. Afterward, we exposed the INR converter screens for 2 hours in a second exposure with the NIP. Fig. 10 [Figure 10: see original paper] shows the test results. The 50 μm and 100 μm thick dysprosium neutron conversion screens could effectively resolve 75 μm and 200 μm slits, respectively, and the 100 μm and 150 μm thick indium neutron conversion screens could effectively resolve 75 μm slits.

Sparse Projection Data Reconstruction Algorithm

In INR, the acquisition of each projection image involves a second exposure with a single image data acquisition time of more than 1 hour. Additionally, conventional online radiographic CT detection generally requires more than 360 projection images, indicating that the efficiency of INCT is too low. Consequently, developing sparse reconstruction algorithms based on fewer images is critical. Sparse reconstruction algorithms necessitate only a limited number of images

for the reconstruction process, as opposed to a substantial quantity. This is beneficial for protecting operators from radiation risks and helpful in improving image quality and resolution, particularly when data are limited. Shortening imaging time and improving efficiency are additional advantages of reducing sampled data, and it can aid in reducing data storage and transmission costs.

Therefore, we developed a reconstruction algorithm for neutron-sparse projection data to improve INCT efficiency. We introduced projections onto convex sets (POCS) [43] using a total variance minimization (TVM) algorithm based on compressed sensing theory. We improved the algorithm for the low-gray value part of the image because the original algorithm reconstruction was unclear. The reconstruction steps of the improved POCS and TVM (POCS-TVM) algorithm are as follows:

- (1) We assign an initial value to the reconstructed image, $\text{ART} (k = 1) = 0$, where k is the number of iterations set to f_0 of the algorithm.
- (2) The iterative algebraic reconstruction technique (ART) algorithm was reconstructed once.
- (3) The non-negative constraint: if any of the ART iterative reconstruction matrices have negative values, we take the absolute value of the smallest value in matrix f ($\min(f)$). In addition to the absolute value, the value of each matrix element is given by $f_{\text{POCS}}^{(k)}(i, j) = f_{\text{ART}}^{(k)}(i, j) + f(\min(f))$.
- (4) We take f_0 as the initial value for the TVM operation: $f_{\text{TVM}}^{(k)} = f_{\text{POCS}}^{(k)}$.
- (5) We also calculate the incremental factor given by $d^{(k)} = \|f_0^{\text{ART}(k)} - f_{\text{POCS}}^{(k)}\|$.
- (6) We compute the global variational gradient and the direction of the gradient as $G_{n-1}^{(k)} = \left. \frac{\partial \|f\|_{\text{TV}}}{\partial f_{i,j}} \right|_{f=f_{n-1}^{\text{TVM}(k)}}$.
- (7) We correct the image by iterating along the direction of the decreasing gradient of the total variance, that is $f_n^{\text{TVM}(k)} = f_{n-1}^{\text{TVM}(k)} - \alpha d^{(k)} \hat{G}_{n-1}^{(k)}$, where α is an adjustment factor for controlling the search step size. An iterative calculation is performed until the number of iterations n reaches the set value N .
- (8) To determine whether the algorithm satisfies the termination condition, the common termination condition is $\|f_{\text{POCS}}^{(k+1)} - f_{\text{POCS}}^{(k)}\| < \delta$ (δ is a small positive number, e.g., $\delta = 10^{-5}$). Alternatively, the total number of iterations k reaches the set value K ; otherwise, the result of the current TVM iteration is used as the initial value of the next round of POCS iterations; that is, $\text{ART}^{(k+1)} = f_N^{\text{TVM}(k)}$.

Experimental Procedure

The experimental setup comprised a neutron beam, film stand, imaging dark box, dummy nuclear fuel rod, gadolinium sheet, in-metal conversion screen, NIP, image-reading equipment of the NIP, and a screen clearer. Fig. 13 [Figure 13: see original paper] shows the experimental setup. We used INCT, an offline imaging technique that necessitates the transfer of the conversion screen in each instance of image acquisition and exposure, thereby establishing a novel coordinate system. Therefore, we used a $5\text{ mm} \times 5\text{ mm} \times 1\text{ mm}$ gadolinium metal sheet (a strong neutron absorber) as a marker for post-image processing. The marker was independent of the sample stage and conversion screen, ensuring that it remained fixed in each image in the CT system. The sample was fixed on the INCT sample stage during the experiment to achieve a 360° rotation. We positioned the indium conversion screen within an imaging dark box on the film stands. This setup facilitated the transfer of the conversion screen, which was used for the second exposure, from the radiation environment after the first exposure to the neutron beam. After the second exposure, NIP scanning was completed using a phosphor screen laser scanner (scanning optical resolution $50\text{ }\mu\text{m}$, scanning bias voltage 600 V) with a clearing time greater than 15 minutes.

Three-dimensional reconstruction places high demands on the quality of projected images. INR requires two exposures, during which variations in parameters such as exposure time, neutron injection rate, and sample position can introduce significant errors. Therefore, 2D projection images must be subjected to background deduction, noise reduction, and data normalization prior to 3D reconstruction. We gathered 180 projected images across a 360° range for 3D reconstruction using this process.

IV. Results and Discussion

As depicted in Fig. 14 Figure 14: see original paper, the INR outcomes based on subsequent background correction are as effective as CCD digital imaging outcomes. The figure illustrates grayscale variations among cores with different enrichment levels, and gaps between the cores and springs are distinctly visible. Although larger holes in the core are easily distinguishable, discerning smaller holes is challenging. In Fig. 14(a), the grayscale curve for the red line part has been drawn by selecting it from the image, with results shown in Fig. 14(b).

We simulated cores with different enrichments by adding a certain amount of B_4C to the lead powder to achieve a neutron cross-section similar to that of a real fuel core with specific enrichment. The addition of B_4C altered the total cross-section of the lead mixture. The grayness profile of the fuel rod gradually increased as the core enrichment decreased. In the gradient curve, grayscale discernible alterations were noticeable at the junctures between the cores. Cores with high enrichment have a high mass fraction of ^{235}U and a high neutron cross-section, which increases the likelihood of neutron interactions, reducing the number of neutrons that successfully reach the conversion screen.

The defective component inside the core has a higher grayscale value than other parts. The observed difference in grayscale values in regions with the same enrichment can be attributed to the lower total cross-section of the core region with defects compared with the entire cross-section of other regions with the same enrichment. Therefore, INR techniques provide valuable insight into core measurements, internal flaws, and disparities in core enrichment.

Fig. 15 Figure 15: see original paper depicts 2D projection images of the dummy nuclear fuel rod obtained through INR at various angles. However, the projected images acquired at different angles during the offline tomography test are unsuitable for direct utilization in 3D reconstruction because they require transfer of the conversion screen to a dark room for a second exposure after each exposure. This process inevitably leads to discrepancies in before-and-after images, posing considerable challenges for 3D reconstruction. We employed a precise positioning algorithm to rectify transfer errors by recognizing localization identifiers present in the image. Fig. 15(d) shows the corrected image. After rectifying the 180 projection images obtained, the outcomes of the 3D reconstruction are depicted in Fig. 15(e). We reconstructed the 3D structure of a dummy nuclear fuel rod, distinguishing the springs, core gaps, and partial holes within the core. We then distinguished holes inside the core block with the smallest diameter of 0.4 mm from the 2D cross-section.

INR requires a second exposure for each projection, and conventional reconstruction algorithms require many projection images. Hence, reconstructing INR data using traditional reconstruction algorithms is time-consuming. Thus, we applied a background correction technique for neutron images to each projection, resulting in 120 indirect neutron projection images. Afterward, we reconstructed these images over a 360° range using the modified POCS-TVM algorithm. Fig. 16 Figure 16: see original paper shows the reconstructed results, and Fig. 16(b) and Fig. 16(c) show two of the 2D sections. Holes with diameters of 2 mm, 1.5 mm, and 1 mm are shown in Fig. 16(b), whereas only holes with diameters of 0.8 mm are displayed in Fig. 16(c). The detection technology can effectively distinguish holes with a minimum diameter of 0.8 mm and achieve the project's expected resolution index better than 1 mm.

V. Conclusion

This study successfully developed indirect conversion screens for indium and dysprosium with different thicknesses, tested their resolution, and prepared a dummy nuclear fuel rod. Using image identification and precise positioning technology, we accurately positioned the sample projection image during offline INCT. This achievement is of substantial importance, as it effectively addresses the issue of nonuniformity in offline INCT images. We acquired digitized INR projection data and performed INCT using a sparse reconstruction algorithm. This technique reduced the total acquisition time of neutron tomography. The experimental results were impressive, demonstrating a resolution of 0.8 mm, which surpassed the initially anticipated target. This work establishes China's

first internationally advanced “INCT experimental device for radioactive samples” and the corresponding “INCT measurement method for radioactive samples.” This study offers valuable tools and techniques for the NDT of nuclear fuel rods throughout their processing, production, and service stages. Our study provides fundamental guidelines for future studies on irradiated fuel rods using NR.

In light of the rapid advancement of the nuclear power sector, matters pertaining to nuclear safety have become a subject of escalating focus. In industrialized nations, NR is widely used for research on nuclear fuel rods. This technique enables a range of tests to be conducted on fresh and spent fuel rods, including determining ^{235}U enrichment, distinguishing the distribution of natUO_2 and PuO_2 clusters within mixed oxide fuels, detecting defects in nuclear fuel rods, and examining hydrogen accumulation in the cladding. In the future, we aim to automate the INR process, making both primary and secondary exposures more efficient and reducing overall operation time. In addition, we strive to reduce the nonlinear influence of the detection process by improving the consistency of image detection conditions from different angles to enhance CT resolution and effectively improve detection efficiency. We will conduct NDT on nuclear fuel rods of various reactor types to provide important testing technology. By providing accurate and reliable INCT technology, we aim to support the sustainable growth and development of the nuclear industry while prioritizing the safety and well-being of both the public and the environment.

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