

Upgrading and Application of Neutron Absorption Performance Testing Equipment for Boron-Aluminum Alloys

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Abstract

Abstract: The neutron absorption material testing equipment for boron-aluminum alloys used in nuclear power plant spent fuel pool racks, originally developed by the China Institute of Atomic Energy, has been upgraded and improved through the development of an integrated data acquisition system, transmission system, and control-recording-analysis system. The equipment is applicable to multi-point measurements of samples of different sizes, featuring continuous, rapid, and full-area detection, with both fixed-point and mobile detection modes. Testing has been completed on $20\text{cm} \times 30\text{cm}$ suspended samples, $373\text{cm} \times 19.5\text{cm}$ long plates, $6\text{cm} \times 6\text{cm}$ square samples, and $\Phi 5\text{cm} \times 0.3\text{cm}$ circular samples, with analysis of the test results conducted. This boron-aluminum alloy material neutron absorption performance testing equipment establishes a foundation for non-destructive testing research on domestic boron-containing neutron absorption materials and provides strong assurance for criticality safety monitoring of nuclear power plant spent fuel pools.

Full Text

Upgrade and Application Research of Neutron Absorption Performance Testing Equipment for Boron-Aluminum Alloy Materials

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Abstract

The neutron absorption performance testing equipment for boron-aluminum alloy materials in spent fuel pool grids of nuclear power plants, developed by the China Institute of Atomic Energy, has been upgraded and improved with the development of an integrated data acquisition system, transmission system, and control-record-analysis system. This testing equipment enables multi-point measurements for samples of various sizes and features continuous, rapid, and full-area detection capabilities in both fixed-point and mobile detection modes. Testing has been completed for hanging samples (20 cm × 30 cm), long plates (373 cm × 19.5 cm), square samples (6 cm × 6 cm), and circular samples (Φ 5 cm × 0.3 cm), with analysis of the results performed. This neutron absorption performance testing equipment for boron-aluminum alloy materials establishes the foundation for non-destructive testing research on domestically produced boron-containing neutron absorption materials and provides robust support for criticality safety monitoring of spent fuel pools in nuclear power plants.

Keywords: boron-aluminum alloy; neutron absorbing material; non-destructive testing

The Science and Technology on Nuclear Data Laboratory of the China Institute of Atomic Energy has developed a neutron absorption performance testing device for B_4C -Al materials based on the principle of neutron transmission measurement [1-4]. The core components of this device are the neutron detector measurement system and neutron source, complemented by a neutron moderation system. During the upgrade and improvement process, an integrated data acquisition system, transmission system, and control-record-analysis system were developed to enable continuous, rapid, and full-area detection. The design of the testing equipment must address several critical issues, including selection and layout of the neutron source, choice of neutron detectors, and improvement of neutron source utilization efficiency [5-11]. To inspect entire grid materials for spent fuel pools, the testing equipment was further improved. To prevent long plates from deviating from their travel path during detection, the length of the detection panel frame was extended, and width-limiting devices were fabricated. To study changes in neutron absorption properties of neutron-absorbing materials after reactor irradiation, square samples (60 mm × 60 mm × 3 mm) and circular samples (Φ 50 mm × 3 mm) were measured before and after irradiation, and changes in their ^{10}B areal density were compared. Due to the small sample size, only one detector in the lithium glass array could be used for measurement. To ensure alignment between the sample and detector, a template matching the standard plate dimensions was specially fabricated by cutting square and circular holes of appropriate sizes into existing B_4C -Al plates, into which the samples were embedded for measurement.

The structure of the testing device is shown in [Figure 1: see original paper].

2.1 Data Acquisition System

A counting circuit was developed to process signals from neutrons emitted by the source, moderated by the moderator, absorbed by B_4C -Al samples, and detected by neutron detectors. The detected neutrons form pulse signals that pass through a preamplifier and main amplifier, undergo signal discrimination and A/D conversion, and are then transmitted to the data acquisition terminal for further processing to obtain boron content information.

The electronic circuitry consists of an integrated circuit board, as shown in [Figure 2: see original paper]. Each board can simultaneously process signals from three detectors, with four boards handling signals from 12 channels total. Each channel provides signal amplification, shaping, and threshold discrimination functions, while the high-voltage module can supply high voltage to 10 detectors simultaneously. This integrated electronic system avoids the disadvantages of traditional plug-in modules, such as large space requirements and high cost. The industrial computer communicates with the data acquisition system via an RS485 bus, and the terminal industrial computer software performs counting analysis and displays the data in graphical form.

2.2 Transmission System

The transmission device comprises a transmission platform, motor, lead screw, front and rear limit switches, and control system. The transmission platform features fixed crossbars for boron-aluminum plate samples, with both ends of the crossbars connected to lead screws on either side of the equipment. The motor drives the lead screw rotation, which moves the boron-aluminum plate across the detection platform. The motor control system connects to the control terminal, allowing motor speed and operating conditions to be set via software.

The speed control function of the transmission system primarily uses a frequency converter to vary the voltage frequency supplied to the motor, thereby controlling motor speed and belt transmission speed. During measurement, the main control program sets the sample movement speed, which corresponds to a specific frequency output from the converter. The converter then transforms 50 Hz AC power into AC power at the set frequency to drive the motor, which in turn drives the belt to move the sample through the measurement system at the specified speed. When the sample reaches the measurement terminal, it triggers the limit switch, which sends a signal to the main control system. The main control system then commands the frequency converter to stop, halting sample movement. Subsequently, the main control system commands the sample to return to its original position at a preset speed, enabling measurement of the next sample.

2.3 Control, Record, and Analysis System

The functions of the industrial computer terminal include: setting motor operating parameters to control the speed and segmented measurement conditions of the electric transmission device; real-time data acquisition and processing by the data acquisition system, enabling direct monitoring of neutron counts and transmission rates; and software-based setting and monitoring of the voltage applied to each detector via the high-voltage module.

The terminal control system of the testing equipment implements remote visualization control, with main functional modules including motor control system, data acquisition system, and high-voltage control module, as shown in [Figure 3: see original paper].

During measurement, the “Real-time Measurement Data” column allows selection of detectors based on actual effective usage, as shown in the measurement status display interface [Figure 4: see original paper]. Measurement data records the neutron transmission values and count rates for each detector channel during segmented measurements.

Communication between the terminal industrial computer and control modules is established through a PCI interface data card in the industrial computer chassis, with the data cable split into two strands connecting to the motor control system chassis and the detection system control chassis. The detection system comprises 10 lithium glass detectors, each with two connection ports: a signal line interface (S) and a high-voltage line interface (HV), totaling 10 high-voltage lines and 10 signal lines connected to the detection system control chassis. The terminal control system is shown in [Figure 5: see original paper], with three chassis arranged from top to bottom in the cabinet: the motor control chassis at the top, the detection system control chassis in the middle, and the industrial computer at the bottom.

To monitor sample movement inside the equipment in real time, prevent emergencies such as sample jamming during detection, protect the motor, and enable more precise positioning of small samples during equipment debugging, a camera was installed inside the shielding cover of the testing equipment. The camera connects to another monitoring industrial computer, with [Figure 6: see original paper] showing a real-time monitoring image of a sample during measurement.

3.1 Measurement of Entire B_4C -Al Plates

Users provided six B_4C -Al samples measuring 373 cm long, 19.5 cm wide, and 0.35 cm thick, as shown in [Figure 7: see original paper]. Standard plates were first used to create a calibration curve, and the measured neutron transmission rates were interpolated on this curve to determine ^{10}B areal density. Due to the excessive length of the samples, extension brackets made of stainless steel and organic glass were fabricated, with an electric roller installed at the bracket head that rotates with the motor. The roller drives the B_4C -Al plate movement

through connected tape, with the structure shown in [Figure 8: see original paper]. Previous experiments used fixed-point measurement, but this experiment employed mobile measurement to measure as many points as possible on the sample. The sample travel speed was 1.3 mm/s, with measurements taken at 187 data points. To maintain consistent sample travel direction, clips were installed on both sides of the sample at the top of the extension bracket to fix the plate position. Since the width of the entire B_4C -Al plate was smaller than previously measured hanging samples [2], the exit window for moderated neutrons was appropriately modified to reduce edge effects during measurement. The positions of plates inside the testing equipment were also fixed with boron-containing polyethylene on both sides, reducing the neutron exit window width to match the plate width while shielding thermal neutrons entering the detector from the side, thereby minimizing edge effects.

3.1.1 Standard Plate Measurement Results

The ^{10}B areal density and neutron transmission experimental data for standard plates used to create the calibration curve are shown in . The standard plates were B_4C -Al samples provided by the Institute of Metal Research, Chinese Academy of Sciences, with three boron carbide contents (21%, 26%, 31%) and multiple thicknesses (2 mm, 3 mm, 4 mm, 5 mm). To match the width of the test plates, they were cut into 32 cm \times 19.5 cm pieces for measurement. Since the width of the 10-neutron-detector array exceeded 19.5 cm, only the middle five detectors could effectively detect signals. Therefore, data from the middle five detectors (ch3-ch7) were used for measurement and analysis, with 10 data points measured at equal intervals for each standard plate. Because the B_4C -Al plate travel speed was relatively slow, detectors might be partially blocked by the plate at the beginning of measurement, making the initial neutron transmission data inaccurate. To improve accuracy, the neutron transmission data for both standard and test plates were averaged after removing the first few measurement points.

The fitted curve for standard plate measurement data is shown in [Figure 9: see original paper], with a goodness-of-fit reaching $R^2 = 0.9998$. The series formula represents the data fitting function.

3.1.2 Test Plate Measurement Results

Users did not provide detailed information such as ^{10}B content for the six test plates, making direct calculation of ^{10}B areal density impossible. The measured neutron transmission data were interpolated on the standard curve to obtain ^{10}B areal density, with results shown in . [Figure 10: see original paper] displays the neutron transmission data for 187 points as shown on the detection terminal. The smooth curve and uniform counting across the five detector channels indicate uniform boron content in the plates.

3.1.3 Uncertainty and Sensitivity Analysis

(1) Statistical Error Analysis

shows the total counting statistical errors for each detector channel (Ch3 to Ch7) during measurement of each test plate. The total error for the entire plate represents the statistical error from the sum of counts across all channels. The average counting error per point represents the counting error for each measurement point. For the entire plate, total counts reached 6×10^6 , with statistical errors below 0.04%. Each detector measured approximately 1.2×10^6 total counts, with statistical errors around 0.088%. For each measurement point, total counts were approximately 7,200, with average statistical errors around 1.18%. The background count without samples was 3.9×10^4 , with a statistical error of 0.5%. From these values, the relative standard error of transmission rate at each measurement point can be estimated at approximately 1.28%.

(2) Fitting Error Analysis

shows the fitting errors for the standard plate calibration curve. The relative residual values of ^{10}B areal density for standard plates of different boron carbide contents relative to the fitted standard curve can be controlled within 1.2%. Combined with statistical errors, the total uncertainty can be controlled within 2.5%.

The fitted curve shows that when ^{10}B areal density changes by 1%, the neutron transmission rate changes between 0.19% and 0.56%, with higher measurement sensitivity in regions of lower ^{10}B areal density.

3.2 Measurement of Irradiated Small Samples

3.2.1 Background

In the AP1000 nuclear power system, B_4C -Al composite materials are used as grid materials in spent fuel storage pools. To monitor the effectiveness of neutron-absorbing materials, multiple surveillance samples of neutron-absorbing material are typically placed in the spent fuel pool. Periodic testing of these samples' neutron absorption capability, boron uniformity, and long-term reliability ensures the effectiveness and safety of neutron-absorbing materials during use. Surveillance samples are taken from the same batch of material used to manufacture the grids, consisting of B_4C -Al material. Surveillance samples are arranged vertically within the storage grid, and the accumulated neutron fluence for each sample originates from the spent fuel assembly in whose storage grid it is placed.

To study ^{10}B consumption in surveillance samples within spent fuel pools, square samples of the same material were placed in the thermal column of the 49-2 swimming pool reactor at the China Institute of Atomic Energy for irradiation. The thermal neutron flux density in the thermal column is on the order of $10^{11} \text{ n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$, with an irradiation time of 5 hours. The irradiated samples included four types with nominal boron carbide contents of 20%, 25%, 31%, and 35%.

with six samples of each content, measuring 60 mm × 60 mm × 3 mm.

Thermal column irradiation produces relatively little ^{10}B consumption. To produce more significant ^{10}B consumption, materials were also irradiated in the H8 channel of the reactor core using circular samples with boron carbide contents of 20%, 25%, 31%, 35%, and 40%, with three samples of each content, measuring $\Phi 50$ mm × 3 mm. The neutron flux density in the H8 channel is larger, with a thermal neutron flux density of $2.6588 \times 10^{13} \text{ n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ in the central active region and an irradiation time of 9 days.

3.2.2 Measurement Scheme

Both pre-irradiation and post-irradiation samples were measured comparatively, including 24 square samples and 15 circular samples. Because the sample sizes were too small for direct measurement using the transmission device, a template matching the standard plate dimensions was specially fabricated to embed the small samples for measurement. Additionally, since only one detector could be used, the template position needed to be calculated in advance to ensure alignment with the detector.

The template was created by cutting square and circular holes matching the sample dimensions into existing B_4C -Al plates, into which the samples were embedded for measurement. To achieve better statistics and reduce errors, discrete component measurement was employed. Fixed-point measurement was used, with the square sample first reaching the detector measurement area under the transmission device's guidance, manually paused for measurement, then restarted to move the circular sample into the detection area. The specific hole positions in the B_4C -Al template required multiple tests for calibration.

As shown in [Figure 11: see original paper], the template serves two main purposes: first, to position the sample precisely in alignment with the designated detector; second, to shield scattered neutrons from the surroundings, ensuring measurement conditions similar to those for standard samples. The embedded samples are transported into the testing equipment by conveyor belt, with square samples measured using Detector No. 5 and circular samples measured using Detectors No. 4 and No. 6.

3.2.3 Measurement Results

The measured transmission rates of the test samples were substituted into the standard curve fitting formula to calculate their ^{10}B areal density. [Figure 12: see original paper] shows the ^{10}B areal density values of samples calculated through standard curve interpolation before reactor irradiation. The red points represent data from test plates, with calculated areal density results shown in .

The experiment measured neutron transmission rates for 39 test plates before and after irradiation. As shown in [Figure 12: see original paper], the ^{10}B areal

density distribution for samples with 40% boron carbide content is relatively dispersed, while the other series show more concentrated distributions.

Test plates were measured in two batches: pre-irradiation and post-irradiation. Square samples were irradiated in the thermal column of the 49-2 swimming pool reactor with relatively low thermal neutron flux density and short irradiation time. Circular samples were irradiated in the H8 channel of the reactor core with higher thermal neutron flux density and longer irradiation time. Results show that post-irradiation ^{10}B areal density is generally lower than pre-irradiation values. For square samples with shorter irradiation time, the areal density change ranges from 0.45% to 3.6%. For circular samples with longer irradiation time, the areal density change ranges from 9.46% to 17.42%.

3.2.4 Uncertainty Analysis

(1) Statistical Error Analysis

Statistical errors for detector counts during pre-irradiation and post-irradiation measurements were analyzed, with results shown in . The statistical error for total counts with samples is approximately 0.11%, while the background count without samples is 1.1×10^8 , with a statistical error of 0.03%. From these values, the relative standard error of transmission rate can be estimated at approximately 0.11%.

(2) Fitting Error Analysis

The standard curve used for small sample measurement is the fitted curve shown in [Figure 9: see original paper], with calculated relative residual values controllable within 1.2%.

(3) Systematic Error Analysis

1. **Error from Measurement Position:** Due to position variations as samples enter and exit the detector's sensitive region, systematic errors from position changes are within 0.7% based on statistical results from single sample measurements. Combined with statistical and fitting errors, total uncertainty can be controlled within 2%.

2. **Error from γ Background in Activated Circular Samples:** Circular samples irradiated for longer periods in the H8 channel became activated and exhibited strong γ radioactivity. After removal from the reactor, circular samples were stored for one week before measurement. Sample 20-R-1 had a γ background count rate of $6,257 \text{ s}^{-1}$, with 561 s^{-1} from the radiation source itself. Due to the high γ background count rate, samples were stored for 22 days before measurement, at which point the γ background count rate was $3,355 \text{ s}^{-1}$. The γ background from the sample itself caused neutron peak drift and increased count rates above the discrimination threshold. In [Figure 13: see original paper], the hollow spectrum (green line) shows the measurement spectrum before irradiation, while the solid spectrum shows the measurement spectrum after irradiation. Due to neutron peak position drift, correction of count rates above the discrimination

threshold was required. The original discrimination threshold was set at the starting position of the green region in [Figure 13: see original paper]. The increased counts in this region after irradiation needed correction. Analysis of the increased γ background counts from the discrimination threshold to the overlap point of the pre- and post-irradiation spectra (channels 1010-1099) revealed that post-irradiation counts increased by 16,975 compared to pre-irradiation, contributing 1.96% to the count rate. This effect has been corrected in the measurement results.

After subtracting the clearly increased γ background component within the neutron peak, the remaining increase is primarily due to γ peak pileup, estimated to account for 0.5% of the neutron peak count rate. This effect has also been corrected in the measurement results.

4 Conclusion

The B_4C -Al material neutron absorption performance testing device developed by the China Institute of Atomic Energy can be applied to detect neutron absorption performance of boron-aluminum composite materials used in spent fuel storage grids. Research results demonstrate that this testing equipment can be used for inspection of entire neutron absorption materials and hanging samples from spent fuel pool grids, as well as for measurement of small samples. The testing equipment provides credible results and exhibits excellent practical value and application prospects.

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