



Original Article

Feasibility study on Cherenkov radiation-based crack detection for reactor vessel monitoring in sodium-cooled fast reactors

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ARTICLE INFO

Keywords:

Cherenkov radiation
Crack detection
Sodium-cooled fast reactor
Optical fiber sensor
Reactor vessel monitoring
Nondestructive examination

ABSTRACT

Structural health monitoring of reactor vessels in sodium-cooled fast reactors (SFRs) is challenging due to high temperatures, intense gamma fields, and the optical opacity of liquid sodium. This study proposes a crack detection methodology utilizing Cherenkov radiation generated within optical fiber sensors deployed in the annular space between the reactor vessel and guard vessel. The detection principle exploits spatial variation in gamma-ray transmission through the vessel wall, where structural defects produce localized enhancements in Cherenkov photon yield due to reduced material attenuation. Experimental validation was performed using a ⁶⁰Co source at approximately 1 kGy/h with lead crack phantoms containing precision slits of 2–10 mm widths. A sensor array of high-OH silica fibers coupled to silicon photomultipliers resolved slit widths of 3–10 mm above the 3 σ detection criterion (SNR ≥ 3.0), while the 2 mm slit produced a visually discernible peak (SNR = 1.84) approaching the formal minimum detectable limit of 2.355 mm. A preliminary width calibration yielded $R^2 = 0.9987$, and stable optical transmission was confirmed up to 450 °C. This passive approach, requiring no external source and offering intrinsic electromagnetic immunity, represents a promising alternative for in-service inspection of SFR structural components.

1. Introduction

Sodium-cooled fast reactors (SFRs) are among the most promising Generation IV nuclear technologies, offering advantages in fuel utilization, actinide transmutation, and inherent safety [1,2]. Several nations, including France, Russia, China, Japan, and the Republic of Korea, have actively pursued SFR development programs [3]. However, the harsh operating environment presents formidable challenges for structural integrity monitoring and in-service inspection (ISI). Pool-type SFRs operate with sodium temperatures of 390–545 °C, and reactor vessel (RV) walls are exposed to gamma dose rates of approximately 1 kGy/h throughout their operational lifetime [4,5]. Cracks initiated by thermal fatigue, creep, or stress corrosion cracking (SCC) may propagate undetected and lead to sodium leakage or structural failure [6], making effective ISI essential.

Although conventional nondestructive examination (NDE) techniques—such as ultrasonic testing (UT), eddy current testing (ECT), and visual inspection—have been successfully applied in light water reactor

(LWR) environments, their implementation in SFRs faces significant limitations. UT requires specialized high-temperature transducers with degraded performance above 300 °C, while ECT suffers from temperature-dependent conductivity variations [7,8]. Most critically, the opacity of liquid sodium precludes visual inspection during operation [9]. These limitations necessitate alternative inspection methodologies tailored to SFR conditions [10,11].

In this context, the annular space between the RV and the guard vessel (GV), known as the RV/GV annulus, presents a particularly attractive location for deploying monitoring systems [12]. This region provides access to the outer surface of the RV without direct contact with liquid sodium. Thermal analysis of pool-type SFR designs indicates that the annulus temperature, governed primarily by thermal radiation from the RV wall and natural convection of the inert cover gas, can exceed 400 °C [13,14]. While still elevated, this thermal environment is significantly more benign than that of the primary sodium and offers a viable window for deploying appropriately designed sensor systems.

To leverage this accessible region, we explore Cherenkov radiation as

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<https://doi.org/10.1016/j.net.2026.104378>

Received 14 February 2026; Received in revised form 16 April 2026; Accepted 21 April 2026

Available online 29 April 2026

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a detection mechanism. Cherenkov radiation is emitted when charged particles traverse a dielectric medium at velocities exceeding the local phase velocity of light. Compton electrons generated by the 1.369 and 2.754 MeV gamma rays from activated sodium (^{24}Na) readily exceed the Cherenkov threshold in silica fibers [15,16]. While Cherenkov radiation has been utilized for spent fuel monitoring and medical dosimetry, its application for structural health monitoring in reactor environments remains underexplored [17,18]. Optical fibers as the detection medium are well suited to this application owing to their compact form factors compatible with restricted annular clearances, resilience in high-radiation environments, and the ability to transmit signals over extended distances, thereby isolating sensitive readout electronics from the harsh environment [19].

In this study, we demonstrate the feasibility of utilizing Cherenkov radiation generated in an optical fiber sensor deployed in the RV/GV annulus for crack detection in SFR RV walls, and focus on three key investigations: experimental verification of the detection principle using gamma-ray excitation, development of signal processing algorithms for crack characterization, and evaluation of optical fiber thermal stability for RV/GV annulus deployment.

2. Materials and methods

2.1. Principle of Cherenkov radiation-based detection

The proposed methodology utilizes the ambient gamma radiation field inherent to the SFR environment as a probe source. Gamma rays from the core and activated sodium penetrate the reactor vessel wall, and the transmission probability is governed by the material thickness along the ray path as described by the Beer-Lambert law:

$$I = I_0 e^{-\mu x} \quad (1)$$

where I is the transmitted intensity, I_0 is the incident intensity, μ is the linear attenuation coefficient, and x is the material thickness [20]. Consequently, regions containing structural defects, such as cracks, exhibit reduced shielding thickness, resulting in a localized enhancement of gamma transmission compared to intact regions.

This enhanced gamma flux is detected using a fiber-optic sensor positioned in the RV/GV annulus. The incident gamma rays interact with the silica core of the optical fiber primarily through Compton scattering. In low-atomic-number materials like silica (effective atomic number $Z_{\text{eff}} \approx 10$), Compton scattering is the dominant interaction mechanism for gamma rays in the MeV energy range [21]. This interaction produces energetic recoil electrons with kinetic energies that can reach several MeV.

Cherenkov radiation is generated when these secondary electrons traverse the dielectric medium (silica) at a velocity v exceeding the phase velocity of light in that medium (c/n) [22]. This condition is expressed as $\beta > 1/n$, where $\beta (=v/c)$ is the relativistic velocity parameter and n is the refractive index of the medium. For silica fibers ($n \approx 1.5$), the threshold kinetic energy for electrons to initiate this process is approximately 200 keV. The emitted spectrum follows the Frank-Tamm formula, yielding a continuous blue-ultraviolet distribution with intensity proportional to $1/\lambda^2$ [23]. The Cherenkov photon yield scales linearly with the incident gamma intensity [24], and the resulting spatial intensity variations along the fiber are analyzed to locate and size cracks. The sensor targets the RV/GV annulus, where temperatures are estimated to exceed 400 °C at the hot-pool elevation, based on the primary sodium temperature of 500–545 °C and heat transfer across the vessel wall [13,14]; the system was therefore designed for reliable operation up to 450 °C.

2.2. Experimental Setup for crack width evaluation

Prior to combined thermal-radiation testing, room-temperature

irradiation experiments were first conducted to isolate and validate the fundamental detection principle under controlled conditions, with thermal effects evaluated independently in Section 3.3. Gamma irradiation experiments were conducted at the ^{60}Co irradiation facility at the Korea Atomic Energy Research Institute (KAERI). The ^{60}Co source emits gamma rays with energies of 1.173 MeV and 1.332 MeV, selected to approximate the dominant high-energy gamma radiation field produced by activated sodium (^{24}Na) in an SFR primary loop [15]. The irradiation facility employs six ^{60}Co sources arranged symmetrically at 60° intervals around the central irradiation axis, producing a dose rate of approximately 1 kGy/h at the fiber position. This multi-source geometry creates a spatially overlapping radiation field at the phantom surface, which contributes to the geometric broadening of the detected Cherenkov signal profile. It should be noted that the ^{60}Co gamma energies (1.173 and 1.332 MeV) are lower than those of ^{24}Na (1.369 and 2.754 MeV) present in an operating SFR. The implications of this multi-source geometry and spectral discrepancy for signal broadening and Cherenkov photon yield are discussed in Section 3.2.

The experimental assembly, as shown in Fig. 1, was configured to replicate the high-contrast radiation environment of a reactor vessel crack. Instead of actual vessel steel, 50 mm thick lead bricks were employed as crack phantoms to maximize gamma-ray attenuation and enhance the signal-to-background contrast. Crack defects were simulated by inserting acrylic (PMMA) spacers of precise thickness between the lead bricks, establishing four rectangular slits with widths of 2, 3, 5, and 10 mm and a uniform length of 200 mm, and vertical slit walls. The fiber-optic sensor probe comprised 14 high-OH pure silica fibers (Optran® UV, CeramOptec; core diameter 1000 μm ; active sensing length 0.25 m) arranged in a linear array parallel to the slit [25]. The high-OH composition minimizes radiation-induced attenuation (RIA), while the polyimide coating provides thermal stability for the SFR environment [26,27]. To confine the measurement to the target zone, all fiber sections excluding the 0.25 m active sensing length were shielded using a combination of 20 mm thick lead plates and 50 mm thick lead bricks to prevent extraneous signal generation.

To acquire the spatial intensity profile, the sensor assembly was mounted on a motorized linear actuator and scanned horizontally across the slit phantom at a constant speed of 0.66 mm/s, traversing from the shielded region through the crack opening to the opposite shielded region.

To enable remote monitoring, the sensing fibers were coupled to 35 m plastic optical fiber (POF; GH4001, Mitsubishi Chemical) transmission lines. This extended optical path, routed through the shielding labyrinth, allowed the detection system to be housed in the control room, isolated from the high-radiation field. The transmitted optical signals were converted to electrical signals by silicon photomultipliers (SiPM; S14161-6050AS-04, Hamamatsu Photonics) mounted on a custom-designed printed circuit board (PCB). The SiPM outputs were recorded by a data acquisition (DAQ) system (DT5202, CAEN) at 1-s intervals. Both the irradiation room and the control room were maintained at a constant temperature of 23 °C using an air conditioning system.

The fiber sensor was positioned at a specific distance from the source to achieve a dose rate of approximately 1 kGy/h. This value was chosen to match the typical radiation intensity at the reactor vessel shell adjacent to the coolant level in an operating SFR ($\sim 10^3$ Gy/h). This region corresponds to the environment within the RV/GV annulus where the sensor would be deployed for in-service inspection [5]. The cumulative absorbed dose was determined using alanine dosimeters (Aerial).

2.3. Signal processing and data analysis

The raw scanning data acquired from the DAQ system typically contain high-frequency statistical noise inherent to photon counting, mechanical vibrations induced by actuator movement, and low-frequency baseline drifts caused by non-uniformities in the

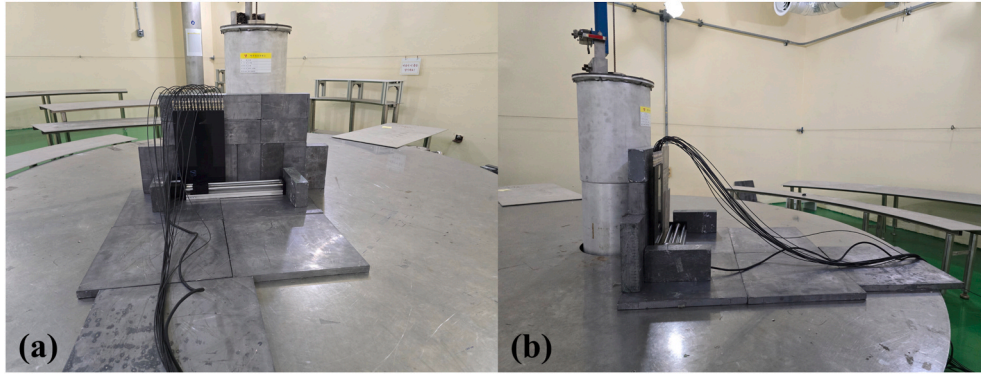


Fig. 1. Experimental configuration for crack width evaluation: (a) front view, (b) side view.

background gamma field. To extract reliable crack signatures and quantify their characteristics, a multi-stage signal processing algorithm was developed using MATLAB, as shown in Fig. 2.

First, a Savitzky-Golay (S-G) filter was applied to the raw data for noise reduction. The S-G filter performs a local polynomial regression, effectively smoothing the data while preserving peak morphology [28].

Second, to isolate the crack-induced signal from the background radiation, a baseline estimation and subtraction process was performed for signal extraction. The background level was estimated using a moving average filter with a wide window size of 120 points, which was subsequently subtracted from the S-G filtered signal. This process ensures that the crack signal appears as a distinct positive peak relative to a zero-centered baseline.

Finally, Gaussian fitting was applied to extract peak amplitude and full width at half maximum (FWHM), with the latter serving as the primary metric for crack width calibration.

3. Results and discussion

3.1. Signal processing and reconstruction performance

The efficacy of the multi-stage signal processing algorithm (described in Section 2.3) was evaluated by analyzing the stepwise transformation of the scanning data. Fig. 3 illustrates the progression from raw data to the final crack signature represented as 1D spatial profiles.

S-G filtering suppressed stochastic noise while preserving peak morphology, and subsequent baseline subtraction isolated the crack-induced Cherenkov signal as a distinct positive peak. The Gaussian fit (Fig. 3(c)) shows close agreement with the processed profile. The spatial distribution of the reconstructed signal is further visualized as a 2D intensity heatmap in Fig. 4.

The processed 1D profile was also rendered as an intensity heatmap (Fig. 4). The upper panel shows residual noise in the subtracted data, while the lower panel presents the Gaussian-reconstructed field with red

dashed lines indicating the FWHM boundaries of the extracted crack width.

3.2. Quantitative crack detection and width calibration

The core performance of the proposed method was evaluated using scanning measurements for four distinct slit widths (2, 3, 5, and 10 mm). Fig. 5 summarizes the Gaussian-fitted spatial profiles, the peak amplitude characteristics, and the width calibration results.

Fig. 5(a) presents the Gaussian fitting results of the spatial intensity profiles. As the sensor traversed the crack region, sharp intensity peaks were observed for all tested slit widths, with the 2 mm slit yielding a peak that, while visually discernible, fell below the formal 3σ detection threshold ($\text{SNR} = 1.84$).

The relationship between the peak amplitude and the actual slit width is shown in Fig. 5(b). The amplitude exhibits a strong linear increase with slit width. Notably, the absolute magnitude of the amplitude error increases as the slit width increases. This trend is primarily driven by Poisson counting statistics, where the absolute statistical noise (σ) scales with the square root of the photon count (N) [29]. Consequently, wider slits yielding higher photon counts exhibit larger absolute fluctuations compared to narrower slits.

For precise sizing, the correlation between the measured FWHM and the actual slit width was analyzed, as shown in Fig. 6. Contrary to the amplitude results, the FWHM uncertainty increased as the slit width decreased, attributable to the reduced SNR at lower peak amplitudes and the increasing dominance of geometric broadening effects as the crack width approaches the spatial resolution limit.

The measured FWHM values were systematically larger than the actual slit widths. This broadening arises from the standoff distance between the sensor array and the lead phantom, which introduces geometric beam divergence and Compton-scattered photon contributions. In particular, the six ^{60}Co sources arranged at 60° intervals (Section 2.2) create a spatially overlapping radiation field, which further increases the effective source extent and contributes to the composite

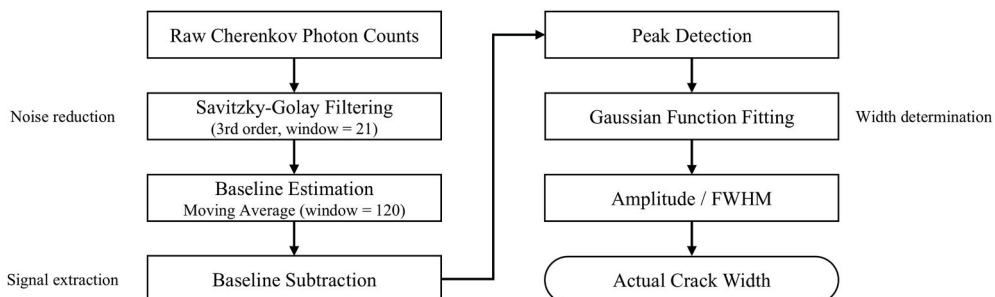


Fig. 2. Flowchart of the multi-stage signal processing algorithm developed for quantitative crack width evaluation.

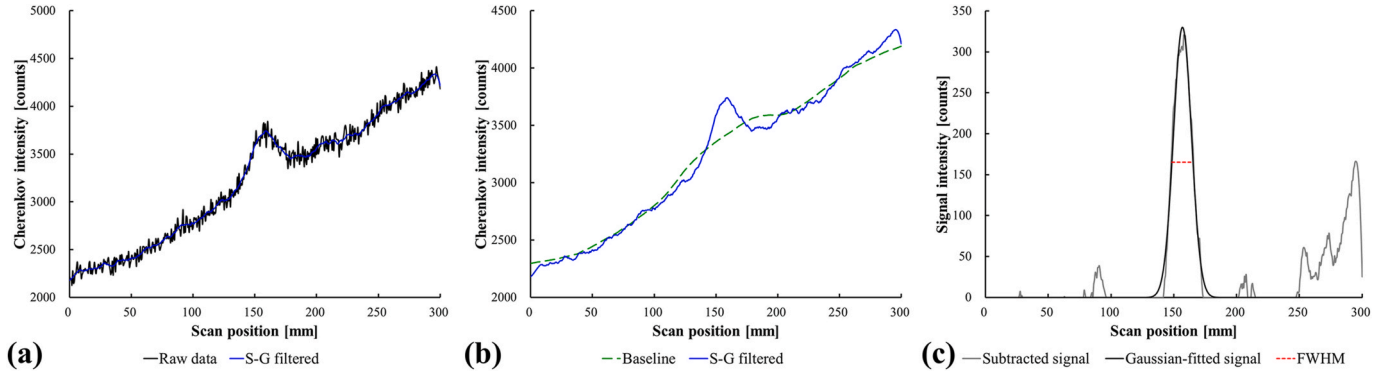


Fig. 3. Step-by-step results of the signal processing algorithm. (a) Raw Cherenkov photon counts (black) and S-G filtered signal (blue), showing noise suppression while preserving peak morphology. (b) S-G filtered signal with estimated moving average baseline (green dashed). (c) Baseline-subtracted signal (gray) isolating the crack-induced Cherenkov peak, with Gaussian fit (black) showing close agreement with the processed profile and red dashed lines indicating the FWHM boundaries.

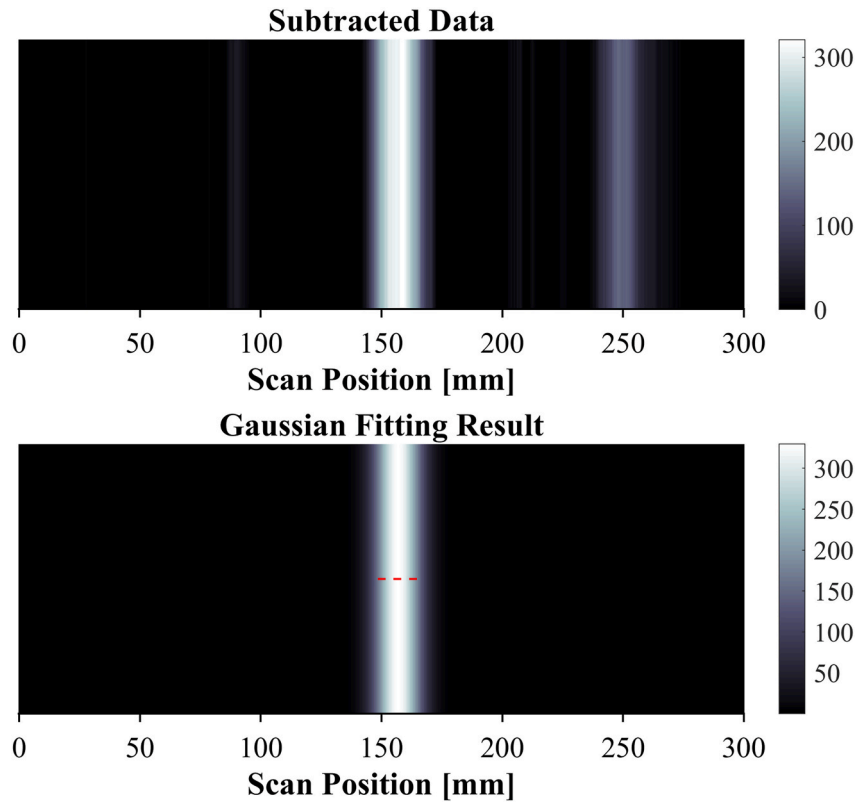


Fig. 4. Visualization of the signal reconstruction. Red dashed lines in the lower panel indicate the FWHM boundaries of the extracted crack width.

point-spread function of the measurement geometry. As a result, even a zero-width crack would produce a non-zero measured FWHM of approximately $|\beta_0|/\beta_1 = 27.437/1.986 \approx 13.81 \text{ mm}$, which corresponds to the composite point-spread function of the present multi-source measurement geometry. The negative intercept (β_0) in Eq. (2) therefore does not imply a physically negative crack width, but rather quantifies this system-level geometric broadening offset. Despite these factors, a strong linear correlation was established:

$$W_{\text{actual}} = (1.986 \pm 0.216) \times W_{\text{measured}} - (27.437 \pm 3.541) \quad (R^2 = 0.9987) \quad (2)$$

where W_{actual} is the physical crack width and W_{measured} is the FWHM obtained from the Gaussian fitting. The resulting coefficient of determination ($R^2 = 0.9987$) indicates a strong linear trend within the tested range. It should be noted that this calibration was derived from only four

data points ($n = 4$, $df = 2$), which limits the statistical precision of the fitted parameters. The 95% confidence intervals, computed using t-distribution with $df = 2$ ($t_{0.025,2} = 4.303$) and a residual standard deviation of $s = 0.156 \text{ mm}$, are: slope $\beta_1 = 1.986$ (95% CI: [1.770, 2.202]) and intercept $\beta_0 = -27.437 \text{ mm}$ (95% CI: [-30.978, -23.896]). The relatively wide interval for the intercept reflects the limited degrees of freedom and the extrapolative nature of the geometric broadening offset. The confidence and prediction interval bands are shown in Fig. 6.

It is also important to consider the spectral discrepancy between the ^{60}Co source employed in this study and the ^{24}Na gamma radiation field encountered in an operating SFR. The maximum kinetic energy of Compton recoil electrons, T_{max} , scales with the incident photon energy according to $T_{\text{max}} = 2E_\gamma^2/(m_e c^2 + 2E_\gamma)$, yielding $T_{\text{max}} \approx 1.118 \text{ MeV}$ for the 1.332 MeV line of ^{60}Co , compared to $T_{\text{max}} \approx 2.520 \text{ MeV}$ for the 2.754 MeV line of ^{24}Na . Since the Cherenkov yield per unit path length

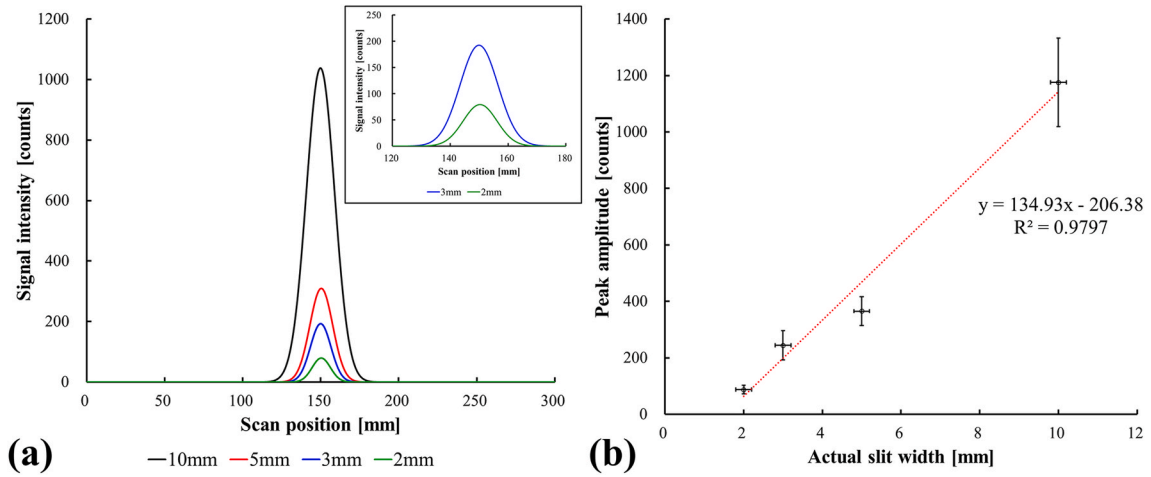


Fig. 5. Experimental results for quantitative crack evaluation: (a) measured signal intensity profiles as a function of scan position for various slit widths (2, 3, 5, and 10 mm), where the inset provides an enlarged view of the 2 mm and 3 mm profiles to facilitate assessment of individual peak shapes, and (b) linear correlation between the actual slit width and the corresponding peak signal amplitude. In (b), horizontal error bars represent spacer fabrication tolerance and vertical error bars indicate inter-fiber standard error across 14 sensing fibers.

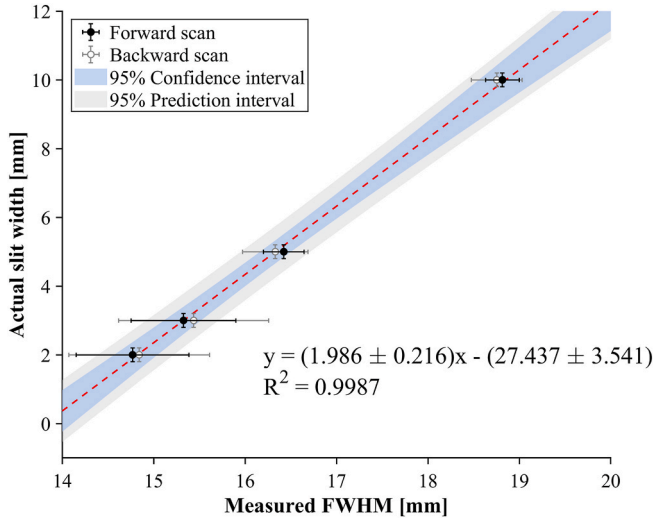


Fig. 6. Linear regression between measured FWHM and actual slit width. The x-axis origin (14 mm) accounts for the inherent geometric broadening offset (≈ 13.8 mm) due to the standoff distance and multi-source configuration. Filled circles represent forward scan measurements and open circles represent backward scan measurements. Vertical error bars represent spacer fabrication tolerance and horizontal error bars indicate the inter-fiber standard error of FWHM across 14 sensing fibers.

scales as $(1 - 1/\beta^2 n^2)$, the higher-energy ^{24}Na recoil electrons exhibit a greater Cherenkov emission rate and a longer electron range, further increasing the total photon yield per interaction. Combined with the lower attenuation of higher-energy gamma rays in stainless steel, the actual SFR environment is expected to produce a higher absolute Cherenkov signal. The present ^{60}Co results can therefore be regarded as a conservative estimate of the detection capability.

To evaluate scan-to-scan reproducibility, bidirectional scanning measurements were performed for all four slit widths by reversing the actuator traversal direction. This approach captures not only photon-counting statistics but also mechanical backlash and actuator hysteresis, providing a more stringent repeatability assessment than simple repeated unidirectional scans. The mean absolute FWHM difference between forward and backward scans was 0.084 mm, with all differences falling within the combined standard error of the two

measurements. A paired t -test yielded $t = -0.148$ ($df = 3$, $p \gg 0.05$), confirming the absence of statistically significant directional bias. Independent regression analyses on the forward and backward datasets yielded calibration coefficients within each other's 95% confidence intervals ($\beta_{1,\text{bwd}} = 2.068$, $R^2 = 0.9993$; within forward 95% CI [1.770, 2.202]), confirming that the calibration relationship is independent of scan direction. These results indicate that measurement reproducibility is governed primarily by photon-counting statistics rather than mechanical positioning errors.

To formally characterize the detection capability, the minimum detectable limit (MDL) was estimated from the measured noise floor using the 3σ detection criterion ($\text{SNR} \geq 3.0$, corresponding to a false-alarm probability of 0.27%). The noise floor $\sigma = 47.72$ counts was obtained from a fully shielded reference scan processed through the identical signal processing pipeline (SG filtering and MA baseline subtraction, window = 120 points), yielding a sub-Poisson ratio of $\sigma/\sqrt{N_{\text{bg}}} = 0.722$. This sub-Poisson ratio (< 1.0) reflects the noise-suppressing effect of temporal integration during SiPM gate accumulation, wherein photon-counting fluctuations are averaged over the gate period T , reducing the relative variance below the single-sample shot-noise limit. The SNR values for the four tested slit widths were: 24.64 (10 mm), 7.66 (5 mm), 5.12 (3 mm), and 1.84 (2 mm). The 3 mm through 10 mm slits satisfy the 3σ criterion, while the 2 mm slit does not. Linear interpolation yields a formal MDL of 2.355 mm under the present experimental conditions, indicating that the 2 mm slit represents the practical lower bound of the tested range rather than a formally confirmed detection.

To quantify the effect of the material and spectral differences described above, MCNP radiation transport simulations were performed comparing gamma-ray flux profiles through lead and Type 316 stainless-steel phantom geometries. The simulation source term was modeled using the two discrete emission lines of ^{60}Co at 1.173 MeV and 1.332 MeV with equal intensity weighting, consistent with the actual laboratory irradiation configuration. For analytical reference, linear attenuation coefficients at a representative energy of ~ 1.5 MeV—which brackets the two ^{60}Co emission lines and approximates their mean—are cited as $\mu_{\text{Pb}} = 0.593 \text{ cm}^{-1}$ and $\mu_{\text{SS}} = 0.391 \text{ cm}^{-1}$; flux and contrast values reported herein are derived from the full energy-dependent MCNP transport calculation. The baseline transmission flux is approximately a factor of 5.0 higher in stainless steel ($\mu_{\text{SS}} = 0.391 \text{ cm}^{-1}$) than in lead ($\mu_{\text{Pb}} = 0.593 \text{ cm}^{-1}$ at 1.5 MeV) [30,31]. This ratio exceeds the narrow-beam exponential estimate (~ 2.7) owing to the substantially lower photon build-up factor of lead relative to stainless steel, which causes secondary

Compton-scattered photons to be preferentially re-absorbed in the high-Z lead medium. This flux difference increases the Poisson noise floor by a factor of $\sqrt{5} \approx 2.2$. The relative crack-signal contrast ($\Delta I/I_0$) decreases from 6.48% to 2.88% for 2 mm slits and from 26.23% to 8.65% for 5 mm slits when transitioning from lead to stainless steel. The resulting SNR ratio (stainless steel/lead) is 0.99 for 2 mm and 0.73 for 5 mm slits, confirming that detection performance under realistic vessel conditions remains within the same order of magnitude as the present lead phantom results. Full Monte Carlo validation incorporating the actual SFR ^{24}Na gamma spectrum and SFR vessel geometry is designated as a priority task in future work.

3.3. Thermal stability and applicability to SFR environments

While the crack detection performance was validated at room temperature, the practical deployment of the sensor system in an SFR requires resilience against high-temperature environments. To evaluate the thermal stability of the polyimide-coated optical fibers used in this study, a broadband transmission test was conducted across the temperature range of 200 to 650 °C. The same high-OH silica fiber (Optran® UV, CeramOptec) was heated inside a ceramic fiber heater, and a broadband UV/white LED source (FC5-LED, Prizmatix) was used to measure transmitted light intensity. At each target temperature, the specimen was stabilized for 5 min, followed by repeated measurements over 1 h.

Fig. 7 illustrates the normalized sensor response as a function of temperature. The sensor exhibited remarkable stability up to 450 °C, maintaining relative intensity above 98%. This robust performance is primarily attributed to the superior thermal resistance of the polyimide coating compared to conventional acrylate coatings, which typically degrade below 100 °C. Beyond 500 °C, a gradual decrease in signal intensity was observed, likely due to the onset of coating carbonization or silica thermal darkening. However, considering the practical deployment scenario—specifically within the annulus between the RV and the GV where temperatures can exceed 400 °C—the sensor retains sufficient optical transmission capability to function as a monitoring device.

Additionally, the high-OH silica core benefits from thermal annealing of radiation-induced color centers at elevated temperatures [32], which is expected to mitigate long-term radiation-induced attenuation (RIA) under SFR conditions.

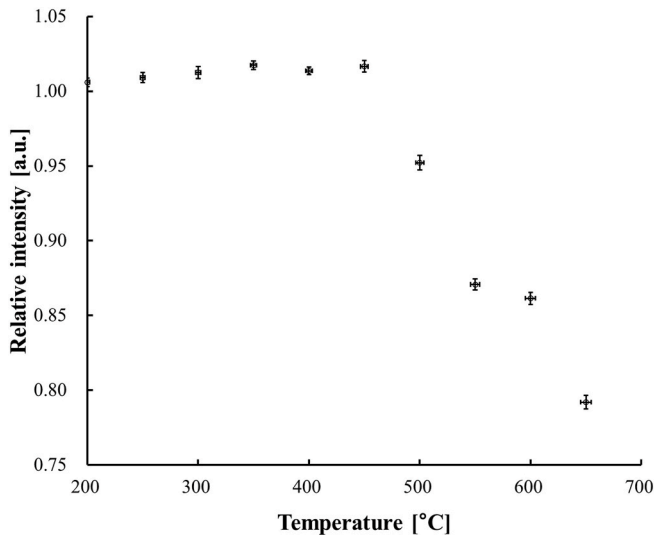


Fig. 7. Thermal stability of the polyimide-coated optical fiber sensor. Horizontal error bars represent Type K thermocouple measurement uncertainty; vertical error bars indicate standard deviation of transmitted intensity.

3.4. Discussion and practical implications

While the present results establish the fundamental detection principle, several limitations should be considered when assessing the applicability of the proposed method to in-service SFR environments.

First, the crack phantoms employed in this study were idealized as through-thickness rectangular slits with parallel walls and uniform widths. In practice, structural defects in reactor vessel walls manifest as far more complex geometries. Fatigue cracks typically initiate as surface-breaking semi-elliptical flaws and propagate with tortuous, branching morphologies. SCC defects often exhibit tight crack-tip openings on the order of tens of micrometers, with significant branching and intergranular propagation paths [6]. Such geometries would alter the gamma-ray transmission profile: tight cracks would produce weaker enhancement due to residual material bridging, while partially penetrating surface cracks would diminish the contrast mechanism. Future studies should employ electro-discharge machined (EDM) notches and fatigue-grown cracks in steel specimens to evaluate detection capability under realistic defect conditions.

Second, the thermal stability and radiation response of the optical fiber sensor were characterized independently in this study: the high-temperature transmission test (Section 3.3) was conducted without concurrent radiation exposure, while the crack detection experiments (Sections 3.1–3.2) were performed at ambient temperature. In an operating SFR, however, the fiber sensor would be simultaneously subjected to elevated temperatures (up to 400–450 °C) and sustained high-dose-rate gamma irradiation ($\sim 10^3$ Gy/h) over extended operational periods. Under such combined conditions, the interplay between RIA and thermal annealing becomes critical. Although thermal annealing above 300 °C significantly mitigates RIA in silica fibers [32], the equilibrium defect concentration depends on the balance between defect generation and annealing rates under simultaneous exposure. Additionally, prolonged high-temperature operation may degrade the polyimide coating through oxidative decomposition or carbonization. Accelerated aging tests under simultaneous thermal and radiation loading are therefore essential to validate long-term sensor reliability and establish maintenance intervals.

Concerning the signal integrity under these combined conditions, the Cherenkov emission spectrum, governed by the Frank-Tamm relation ($dN/d\lambda \propto 1/\lambda^2$), is concentrated in the UV-to-visible range. This spectrum overlaps with the principal RIA band of high-OH silica fibers—specifically the non-bridging oxygen hole center (NBOHC) absorption at approximately 620 nm. However, it has been demonstrated that the steady-state RIA in high-OH silica fibers within the visible light range decreases significantly with temperature, falling from approximately 0.30 dB/m at 100 °C to 0.026 dB/m at 400 °C, where near-complete elimination of NBOHC defects is achieved [32]. This temperature dependence is governed by the thermally activated annealing of NBOHC defects. At temperatures exceeding ~ 300 °C, sufficient thermal energy is supplied to the silica lattice to promote recombination of these paramagnetic defect sites, progressively restoring pre-irradiation transmission levels. At the target operating range of 400–450 °C, thermally driven defect elimination dominates over radiation-induced defect generation, establishing a dynamic equilibrium that yields a near-negligible steady-state RIA. While RIA generally scales with the dose rate, at elevated irradiation temperatures (>400 °C), the defect generation rate is progressively offset by accelerated thermal recombination [26]. Consequently, the net attenuation under SFR ambient fields ($\sim 10^3$ Gy/h) is expected to remain negligibly small relative to the crack-induced signal increment.

From a signal-processing perspective, any residual RIA drift is spatially uniform along the fiber and temporally quasi-static after system equilibration, rendering it distinguishable from crack-induced Cherenkov intensity anomalies. These anomalies manifest as spatially localized peaks (FWHM on the millimeter scale) that are effectively isolated through the baseline subtraction and Gaussian peak fitting

algorithms developed in this study. Complementary real-time correction for slow RIA evolution can be further achieved through reference-channel normalization using a radiation-exposed but mechanically shielded fiber segment installed in the same annular gap.

Regarding the physical deployment in an operating SFR, the sensor is envisioned as a scanning assembly situated within the RV/GV annulus. Due to the small sensing volume inherent to the thin optical fiber core, a fixed-point installation may offer limited spatial coverage for large-scale vessel monitoring. Therefore, a scanning approach is adopted, where the fiber-optic probe is integrated into an automated crawler or a motorized rail system specifically designed to traverse the inert gas environment of the annulus. This sensor assembly can be physically deployed by inserting it through dedicated penetration ports located at the top of the RV head, allowing access to the annular space without breaching the primary sodium boundary. This top-down insertion method leverages the compact form factor of optical fibers, enabling the sensor to overcome the spatial constraints of its environment while providing comprehensive coverage of the reactor vessel's outer surface with high spatial precision. In terms of spatial coverage, an inter-fiber channel spacing of approximately 50 mm is considered as a reference configuration, providing a balance between spatial resolution and the number of fiber channels required for full circumferential coverage of the reactor vessel outer surface. Based on the current actuator traversal speed of approximately 0.66 mm/s and a SiPM gate time of 1.0 s per sampling point over a 300 mm scan length, a single linear pass requires approximately 7.6 min. For the PGSFR reactor vessel (O.D. = 8754 mm, circumference ≈ 27.5 m) with this channel spacing, full circumferential coverage at a single axial elevation requires approximately 550 scan passes, corresponding to a total inspection time of approximately 70 h without parallel operation. With multi-channel parallel operation, this duration can be substantially reduced to a level compatible with scheduled refueling outage intervals.

Since silica optical fibers are inherently immune to electromagnetic interference (EMI) and exhibit low signal loss over long distances, the signal transmission lines can be efficiently routed from the high-radiation and high-temperature zones to remote readout electronics. This remote instrumentation strategy ensures that the sensitive SiPM-based DAQ system is located in a shielded, ambient-temperature environment far from the high-radiation zones. As a result, high signal-to-noise ratios are maintained even in the electrically noisy conditions of a nuclear power plant, and the radiation tolerance of the semiconductor components is effectively managed. While 35-m-long transmission lines were demonstrated in this study to verify remote signal integrity, the exceptionally low attenuation of optical fibers allows for even longer cable runs (e.g., up to 1 km) if necessary to reach remote auxiliary rooms in a full-scale SFR plant. This physical isolation effectively eliminates the risk of radiation-induced performance degradation in the DAQ system, ensuring long-term reliability throughout the reactor's operational lifetime.

As for the influence of scattered gamma radiation from surrounding reactor structures, such effects are expected to manifest as spatially diffuse, low-frequency variations in the background signal. The multi-stage signal processing algorithm developed in this study specifically addresses this by employing a moving average filter to estimate and subtract the non-uniform baseline. This ensures that the spatially localized Cherenkov anomalies induced by cracks remain clearly distinguishable from the quasi-static scattered radiation background.

Furthermore, multiply scattered gamma photons in a complex reactor geometry may contribute not only to the baseline level but also to a broadening of the spatial point-spread function (PSF) of the measurement system. In the present laboratory configuration, Compton-scattered photons originating from the six-source array already contribute to the geometric broadening quantified as the ~ 13.8 mm intrinsic PSF offset in the calibration relationship (Eq. (2)). In an actual SFR geometry, additional scattering from surrounding structural components—such as the guard vessel shell and thermal insulation

layers—may further increase the effective PSF width, thereby slightly increasing the measured FWHM for a given crack aperture. While this effect is not expected to preclude detection, it implies that the calibration coefficients derived from the present lead phantom geometry may require re-characterization under representative reactor boundary conditions. This re-calibration is explicitly identified as a component of the planned full-scale Monte Carlo validation campaign using the actual SFR ^{24}Na gamma spectrum and vessel geometry.

Third, the present calibration model relating measured signal FWHM to actual crack width is based on four slit widths ($n = 4$, $df = 2$), which limits the statistical precision of the fitted parameters (95% CI: slope $\beta_1 = 1.986$ [1.770, 2.202], intercept $\beta_0 = -27.437$ mm [−30.978, −23.896]). Acquisition of measurements at additional intermediate slit widths (e.g., 4, 6, and 8 mm) is planned in the next experimental study, which would increase df to 5 and reduce the confidence interval width by approximately 40%.

The MDL of 2.355 mm is specific to the present laboratory configuration and acquisition parameters. Since SNR scales as $\sqrt{T}$ with SiPM gate time T , increasing T from 1.0 s to 2.7 s would raise SNR (2 mm) to 3.02, enabling formal 3σ detection of 2 mm apertures without hardware modification. For a further reduction in MDL, T can be increased up to the limit imposed by the spatial sampling requirement ($\text{pts}/\text{FWHM} \geq 5$), beyond which the Gaussian peak fitting becomes unreliable. The self-consistent solution satisfying both constraints simultaneously yields a practical MDL of approximately 2.03 mm at $T = 4.5$ s: at this gate time, the required SNR threshold ($\text{SNR}(2.03 \text{ mm}) \times \sqrt{4.5} = 3.00$) and the spatial sampling condition ($\text{FWHM}_{\text{measured}}(2.03 \text{ mm})/(0.66 \times 4.5) \approx 5.0$) are jointly satisfied, representing a 13.8% improvement over the baseline MDL of 2.355 mm. Additionally, the higher-energy ^{24}Na gamma field in an operating SFR is expected to further reduce the MDL below the value demonstrated in the present laboratory study.

Furthermore, the MCNP simulations presented here used a ^{60}Co source and lead/stainless-steel phantom geometries as a first-order approximation. Dedicated simulations incorporating the full SFR geometry, the ^{24}Na gamma spectrum, and realistic crack morphologies are required to quantitatively predict detection performance under actual SFR operating conditions.

4. Conclusion

This study demonstrated the feasibility of Cherenkov radiation-based crack detection and quantitative width measurement in SFR vessel structures, targeting RV/GV annulus deployment without direct sodium contact.

The Cherenkov-based detection principle was experimentally validated using ^{60}Co gamma irradiation and lead crack phantoms, with slit widths of 3–10 mm successfully resolved as distinct peaks above the 3σ detection criterion, and the 2 mm slit yielding a visually discernible peak approaching the formal MDL of 2.355 mm. A multi-stage signal processing algorithm incorporating S-G filtering, baseline subtraction, and Gaussian fitting was developed to extract crack signatures from scanning measurements. A preliminary calibration relationship between measured FWHM and actual crack width was established from four data points ($R^2 = 0.9987$), enabling conversion of measured optical signatures to physical crack dimensions. High-temperature transmission measurements confirmed stable optical performance of the polyimide-coated high-OH silica fibers up to 450 °C, validating the sensor's suitability for long-term deployment in the RV/GV annulus environment where temperatures can exceed 400 °C.

These results establish the technical foundation for Cherenkov radiation-based structural health monitoring in SFR environments, offering significant advantages over conventional NDE techniques including passive operation, electromagnetic interference immunity, and compatibility with the thermal conditions of the annulus region. As discussed in Section 3.2, validation using representative stainless steel

vessel materials, supported by Monte Carlo simulations, constitutes a priority for future investigation. Additionally, optical fibers with different sensing lengths will be utilized to perform scanning measurements. By cross-calibrating the Cherenkov intensities measured from each fiber and analyzing signal variations due to differences in sensor tip length, imaging of cracks with various geometries will be targeted. Furthermore, reducing the optical fiber core diameter below the current 1000 μm is identified as a pathway to decrease the effective point-spread function of the measurement geometry, potentially extending crack detection capability toward sub-millimeter apertures.

CRedit authorship contribution statement

Seunghyeon Kim: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sangjun Lee:** Software, Formal analysis. **Jae Hyung Park:** Software, Formal analysis. **Jinhong Kim:** Investigation, Formal analysis. **Seung Hyun Cho:** Writing – review & editing. **Chulhaeng Huh:** Writing – review & editing. **Bongsoo Lee:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Funding: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Trade, Industry and Energy (MOTIE) of Republic of Korea [grant number RS-2024-00398867].

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