

# Establishing and Monitoring the Quality of Computed Radiography Imaging for Ceramic Body Armor Personal Protective Equipment

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**Abstract.** Ceramic body armor is designed to protect against high-velocity projectiles by leveraging the unique properties of ceramic materials. Therefore, they have been widely employed for lightweight armor protection. However, ceramic body armor personal protective equipment (PPE) plate and inserts can develop defects from several sources: (i) manufacturing, (ii) mishandling, and (iii) projectile impacts during operations. The ballistic performance of armor plate degrades due to the presence of damage and the required protection cannot be guaranteed. Due to their high manufacturing and raw material costs, the end user expects ceramic armor to have a prolonged service life while maintaining their integrity and performance. In order to promptly and nondestructively assess the operational readiness of ceramic protective plate, nondestructive evaluation (NDE) techniques are necessary. A successful body armor inspection guarantees that the PPE maintains its original characteristics.

Radiographic NDE can visualize and quantify damage or anomalies, thereby verifying the integrity of the armor plate. Computed radiography (CR) uses a reusable phosphor imaging plate instead of film and chemicals, making it easier to take faster pictures, analyze them better, store them digitally, while also lowering costs. This comprehensive experimental study of over several thousand plates proved that high-resolution CR effectively reveals typical damage in PPE armor plate. This paper establishes and validates a CR-based PPE inspection procedure, meant to monitor the quality of the CR imaging process, and the control mechanisms that ensure consistent optimal picture quality, high repeatability, and minimal false positives.

## 1. INTRODUCTION

Body armor PPE, commonly used in bulletproof vests, employs composite materials combining distinct constituents to achieve superior protective performance. Typically, a ceramic strike face fractures incoming projectiles, dispersing impact energy, while a polymer backing, such as aramid or polyethylene fibers, absorbs residual energy and retains fragments. Examples include Kevlar® vests, which may incorporate ceramic inserts for enhanced ballistic resistance.

Ceramic plates and inserts may develop defects during manufacturing or incur damage from mishandling, wear, or operational impacts. While ceramics are favored in armor systems for their low density, high hardness, and compressive strength, their brittleness and poor tensile properties make them prone to cracking, compromising ballistic performance [1]. Given the high cost of manufacturing and raw materials, ceramic armor is expected to have a long and effective service life. However, there is currently no standardized method or reliable mechanism for determining their lifespan, which can vary greatly. Maintaining the structural integrity of armor throughout its service life requires regular inspections. Non-destructive evaluation (NDE) techniques are essential for quickly and effectively assessing the combat readiness of ceramic plate. Properly conducted body armor inspections ensure that the armor worn by personnel remains effective.

Ultrasonic testing and radiographic imaging are key nondestructive methods for inspecting armor plates. However, the complex structure and multiple interfaces of composite materials hinder ultrasonic testing. In contrast, radiography, including film and computed radiography (CR), effectively detects internal defects. CR, which uses reusable phosphor imaging plates, offers faster acquisition, enhanced image analysis, digital storage, and greater efficiency, reducing reliance on traditional film-based methods.

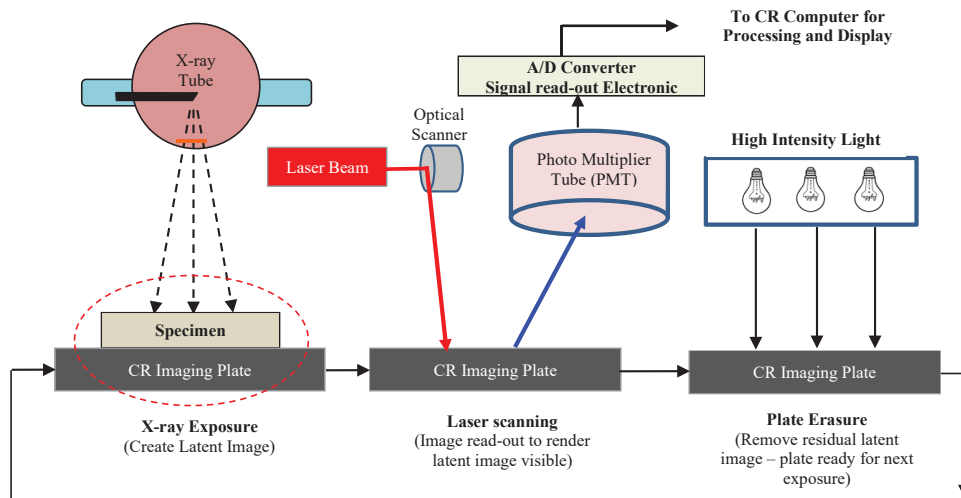
## 2. COMPUTED RADIOGRAPHY

Industrial radiography, a well-established NDE technique for volumetric analysis, has been widely used in industrial and medical imaging since the discovery of X-rays in 1895 [2-3]. Conventional radiography utilizes penetrating electromagnetic radiation to evaluate the internal structure of solid objects. Common detection media include

photographic films (for film radiography), phosphor plate (for computed radiography), fluorescent screens (fluoroscopy), and solid-state flat panel detectors (digital radiography) [4].

Computed Radiography (CR), introduced in 1980, became a leading eco-friendly digital method for producing radiographic images, following practices similar to traditional film radiography [5-6]. Unlike film radiography, CR uses a reusable photostimulable phosphor imaging plate (IP) with a coated detector layer composed of photostimulated crystals containing halogenides such as bromide, chlorine, or iodine. As illustrated in Figure 1, the imaging plate, loaded into a cassette and positioned beneath the test object (e.g., armor plate), is first exposed to radiation, such as X-rays or gamma rays, depending on the application. While undergoing radiation exposure, a portion of the radiation photon is absorbed by the test object, while the remaining transmitted photon passes through and is captured by the IP plate. The transmitted radiation photon energy excites the electrons in the phosphor material and causes some of them to move to a higher metastable energy state (i.e., electrons trapped in a high energy state) in the crystal lattice layer of the phosphor plate, which in turn creates an invisible latent image that stores the information from the X-ray exposure. The phosphor traps energy proportional to the incoming radiation intensity.

To retrieve the latent image, the exposed imaging plate undergoes scanning by a laser reading device, which uses a helium-neon laser to scan in a raster pattern. The red laser provides sufficient energy to stimulate the trapped electrons from prior exposure, causing them to return to a low-energy state and emit blue light (a process known as photostimulated luminescence, or PSL) which is proportional to the stored latent image. This blue light is captured by a light guide and directed to a photomultiplier tube (PMT). The PMT amplifies the collected light signal, samples it spatially, and converts it into a digital signal through analog-to-digital conversion, resulting in a digital image displayed on a monitor for evaluation. After laser scanning, the phosphor screen is exposed to a high-intensity white light beam to erase any residual latent image (reset), preparing it for reuse. The digitization process typically takes one to five minutes, depending on the image size and resolution. The resulting digital image can be processed, analyzed, stored electronically, and archived with ease, offering the advantage of being easily copied, edited, and shared [4].



**Figure 1.** Computed Radiography Principles Based on a Storage Phosphor Plate

## 2.1 Characteristic Parameters of CR Imaging

Computed radiographic (CR) imaging is governed by a set of critical characteristic parameters that determine image quality, efficiency, and the reliability of defect detection. With the advent of digital radiography technologies such as CR, radiographic images are captured and stored in a digital format, enabling the application of advanced image processing techniques and computational algorithms. These advancements have led to a significant transition from the qualitative and subjective assessment of imaging performance, typical of traditional film radiography, to an objective, separate quantitative evaluation based on critical characteristic metrics such as signal-to-noise ratio (SNR), basic spatial resolution (BSR), contrast-to-noise Ratio (CNR), dynamic range, and others [7].

During the traditional film radiography era “radiographic sensitivity” (often called “sensitivity”) is a global and subjective image quality term used that to describe the overall ability of a radiographic imaging procedure when processes were purely analog and lacked digital acquisition, image processing, filtering, and computational evaluation capabilities. As a result, the separate quantitative measurement of individual characteristic parameters (BSR, SNR, CNR etc.) was not possible. Therefore, it can be stated as

SNR, BSR, CNR, Dynamic Range (digital radiography CR, DR)  $\equiv$  sensitivity (film radiography)

Additional influencing factors include the characteristics of the inspected object (such as material and thickness), geometric aspects (including X-ray focal spot size, source-to-object distance, properties of the radiation source, and exposure sensitivity or speed class), the type of CR imaging plate (standard vs. high-resolution), and defect orientation relative to the X-ray beam. Exposure conditions (such as kilovoltage or kV, milliampere or mA settings, and exposure time), as well as the defect’s size, shape, position, and absorption coefficient, the specific settings of the CR system, and the visual perception of the operator, also play roles in determining CR image quality [8]. All of these parameters collectively affect the clarity, accuracy, and reliability of radiographic evaluations, particularly in industrial applications where precision is critical. While each of these parameters contributes to image quality in distinct ways, they are interrelated, and their quantitative interactions are complex. No single universal equation exists that links these factors across all CR systems, as their relationships depend on specific system characteristics, acquisition parameters, and inspection conditions. A thorough understanding and optimization of these parameters are essential to ensure accurate, repeatable results and to maintain quality assurance in computed radiography.

### **2.1.1 Contrast Sensitivity**

Contrast sensitivity, also known as contrast resolution or simply contrast, refers to the capability of a CR imaging system to identify subtle differences in thickness or density of a specimen due to anomalies, which are represented by changes in pixel or gray values between adjacent areas in the radiographic image [9]. Optimizing the contrast sensitivity enhances defect visibility, ensuring subtle imperfections can be detected effectively. In CR contrast sensitivity is usually expressed or evaluated by contrast-to-noise ratio (CNR), which defines how well two areas (interest vs. background) can be distinguished from each other in the presence of noise.

CNR is commonly evaluated using the ASTM E1647 standard 4-recessed-step gauge, a standardized tool comprising multiple steps of varying depth to assess the system’s ability to detect subtle low-contrast details (1%, 2%, 3% and 4% thickness change) [10]. The contrast sensitivity in CR is primarily influenced by factors such as signal-to-noise ratio (SNR) and basic spatial resolution (BSR). Engineering codes and film/CR process control guidelines often mandate achieving at least 2% contrast sensitivity.

### **2.1.2 Spatial Resolution**

Basic spatial resolution (BSR, also known as sharpness or resolution or detail) refers to the capability to differentiate between closely spaced small objects in a digital image or to distinctly identify abrupt changes within an object [11]. The spatial resolution is a critical characteristic for evaluating the efficacy of computed radiography systems in detecting crack-like discontinuities and measuring imaging performance levels. Spatial resolution is typically measured using dedicated gauges known as the duplex wire gauge or the line pair gauge. There is no industry standard guidance or universally defined minimum requirement for spatial resolution; however, higher spatial resolution (represented as a smaller value) is generally preferred because it allows for better visualization of fine details in the image, reduces blurring and yields sharper edges. Spatial resolution tends to be more of a qualitative goal: the smaller the details the system can resolve, the better.

Optimizing spatial resolution is important for detecting crack-like subtle indication. During PPE armor plate inspections, crack indications on radiographs appear as localized intensity variations, represented by pixel value changes, resulting from cracks within the test object. Owing to the characteristics of the radiographic technique, these crack indications typically exhibit low contrast and sharpness and are superimposed on a non-uniform and noisy background.

### 2.1.3 Signal-to-Noise Ratio (SNR)

Noise is unwanted random variations in the image signal intensity (variations in gray values or pixel values) that do not correspond to actual differences in the X-ray attenuation of the specimen or object. Quantum noise (photon noise), electronic noise, scatter noise, and image processing noise are types of inherent noise in CR system that may be present during CR imaging. CR systems convert X-ray signals into digital images, and during this process, noise can degrade image quality. Any irrelevant signal that disrupts the detection or processing of the desired defect signal is considered noise, which significantly impacts the overall image quality. Noise is typically described using the signal-to-noise ratio (SNR), which serves as an indicator of image quality; the higher the SNR, the less distracting the background noise. SNR reflects the signal intensity in relation to the CR system's inherent noise.

No specific hardware tool is used for SNR measurement. In the output radiographic image, SNR is determined mathematically by analyzing pixel intensity values, comparing signal strength in a region of interest to the standard deviation of background noise. No universally accepted minimum signal-to-noise ratio (SNR) requirement has been established across all industries or regulatory authorities. However, guidelines are often provided to minimize the impact of noise. In general, a higher SNR results in better image clarity, as a stronger signal relative to noise enhances the visibility of defect and improves inspection accuracy.

### 2.1.4 Bit Depth and Dynamic Range

Bit depth refers to the number of bits used to represent the gray levels (shades of gray) in each pixel of a digital image. The term "bit depth" is primarily associated with hardware devices (not software) such as computers, display monitors, and CR system, representing the maximum range of pixel values that a computer or other hardware can store. Displaying images at full bit depth is unnecessary, as it slows processing. Instead, system software adjusts brightness levels based on the imaging machine's application. If a monitor's pixels have an 8-bit depth ( $2^8$  or 256 pixel values), while the human eye discerns only about 5 bits ( $2^5$  or 32 perceivable brightness levels), the imaging equipment's bit depth exceeds human capacity, so images often appear identical to analog ones. Thus, bit depth generally describes the capabilities of the hardware equipment being used to capture process and display an image.

However, the dynamic range (a subset of bit depth) of an imaging system represents the range of X-ray exposure levels or the range of pixel values, brightness, or gray levels made available by the combined hardware and software of an imaging system to build up a final image on the display monitor. A broad dynamic range system improves overall image quality, allowing for detailed visualization of components with varying material densities/thicknesses from very low-density to high-density area in a single exposure. In film-based radiography systems, this window is narrow; whereas CR systems have a much wider dynamic range, allowing more flexibility in exposure and reducing the need for repeat images. Images can suffer from overexposure or underexposure that falls outside the dynamic range, thus affecting imaging performance (Figure 2).

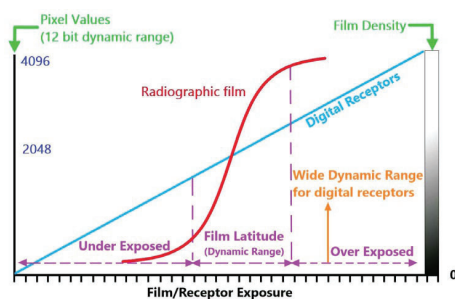


Figure 2: Dynamic Range: Film vs Digital System [12]

The dynamic range of a CR system is influenced by multiple factors, which are summarized in Table 1. These interdependencies emphasize the need for precise calibration, consistent hardware performance, and controlled environmental conditions to maintain the accuracy and reliability of the CR imaging results.

Table 1: Key Parameters Influencing Dynamic Range

Influencing Factors	Effect on Dynamic Range
Imaging Plate Type/Properties and Sensitivity	Higher sensitivity plates detect lower exposures; plate storage capacity affects saturation point (upper limit of dynamic range).
Laser Scanning System (Resolution and Stability)	High laser resolution and stable scanning improve the system's ability to capture small exposure differences; poor resolution or instability reduces the ability to distinguish subtle differences, especially at low exposures.
Photomultiplier Tube (PMT)	PMT consistency and sensitivity impact the accurate detection of emitted light during scanning, influencing dynamic range fidelity.
Analog-to-Digital Converter (ADC) Bit Depth	Higher bit depth (e.g., 12-bit or 16-bit) allows finer distinction between intensity levels, expanding the usable dynamic range.
Exposure Technique	Incorrect exposure settings (too high or too low) result in saturation or loss of data below detection threshold, narrowing the effective dynamic range.
Scatter Radiation	Increases noise, lowers signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR), effectively reducing usable dynamic range.
Image Processing Algorithm	Does not alter the physical dynamic range but affects perceived and diagnostically useful dynamic range through contrast enhancement, noise reduction, and windowing.
Quality of Radiation (kV)	Higher kV lowers contrast and narrows dynamic range; lower kV increases contrast and broadens dynamic range, requiring greater system capacity to accommodate intensity variations.
X-ray Focal Spot Size	Smaller focal spots improve image detail and contrast but may limit dynamic range; larger focal spots reduce detail but broaden dynamic range by accommodating wider intensity variations.
Change in Hardware, System components or Calibration	Modifications to X-ray tube characteristics, such as focal spot size or radiation quality, can influence the system's ability to manage varying intensity levels
Environmental conditions	temperature and humidity can indirectly influence system performance

In CR, a step wedge of varying thickness is often used to evaluate the dynamic range of an imaging system by counting the number of steps (exposure levels) that are visible, which provides an estimate of the usable dynamic range. There is no strict minimum dynamic range requirement, but a wider dynamic range is preferred as it enhances image detail and contrast across varying exposure levels.

### 2.1.5 Radiographic Sensitivity

The term *radiographic sensitivity*, originating from the traditional film-based approach, continues to be used in the context of digital radiography to describe a system's imaging performance or its capability to detect small or low-contrast features. In practice, it is often expressed as the ability to resolve a specified percentage of thickness variation within the specimen; however, it does not directly correspond to the actual defect size. Instead, it functions as an indirect indicator of the overall performance of the radiographic system, reflecting both process parameters and the system's ability to detect defect or thickness variations within the specimen. Lower percentage values indicate higher sensitivity.

The image quality indicator (IQI) is a well-established method for assessing image quality (specifically for measuring sensitivity), originally developed for film-based radiography but still widely utilized in digital radiography systems. Many industry standards (e.g., ISO 17636-2, ASME BPVC Section V) continue to require the use of IQIs, which serve as standardized gauges placed on or near the test specimen to measure and maintain radiographic sensitivity, thereby ensuring consistent and reliable image evaluation. The three primary types of IQIs (illustrated in Figure 3) commonly employed are: (i) wire type, predominantly used in Europe; (ii) step hole type, commonly utilized in France; and (iii) plaque hole type, frequently referred to as penetrameters in the United States.

The wire-type IQI consists of a set of thin, parallel wires (typically 16) of varying diameters, usually made

of the same material as the test object or a material with similar attenuation properties. Sensitivity is directly indicated by the smallest visible wire diameter or corresponding wire number. The French step-hole IQI consists of a single flat plaque with several steps (commonly 4, 5, or 6) of increasing thickness, without any holes. Sensitivity is measured based on the smallest thickness difference (step height) that can be detected on the radiograph.

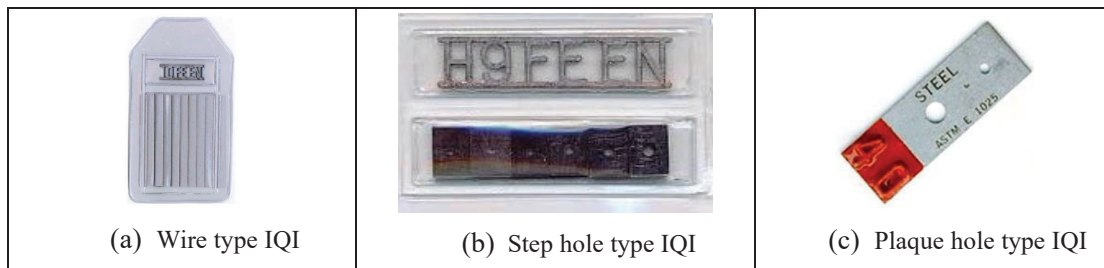
However, only for the plaque hole type IQI (Figure 3C), the term Equivalent Penetrameter Sensitivity (EPS) is used instead of the general term “sensitivity” (as applied to wire or step hole IQIs), and the EPS value is defined in ASTM E1025-11 as follows:

$$EPS (\%) = \frac{100}{t_{material}} \sqrt{\frac{T_{IQI} d_{hole}}{2}} \quad (1)$$

Where: EPS - Equivalent Penetrameter Sensitivity  
 $t_{material}$  - Thickness of penetrated material  
 $T_{IQI}$  - Thickness of IQI  
 $d_{hole}$  - Diameter of IQI hole

These IQIs consist of multiple plaques of uniform thickness, each containing three holes of known diameters drilled perpendicularly through the material. The diameters of these holes correspond to one, two, and four times the plaque thickness (T), and are designated as 1T, 2T, and 4T holes, respectively. The EPS directly relates to the percentage of thickness change represented by the visibility of the holes in the plaque radiograph (e.g., 2-2T corresponds to 2% sensitivity). A sensitivity level of 2-2T, indicating 2% of the material thickness with a hole diameter equal to twice the plaque thickness (2T), is considered the threshold of detectability on the radiograph [13]. The detectability of these holes on the resulting radiograph is influenced by several factors, including hole diameter, plaque thickness, image contrast, and signal-to-noise ratio. Plaque-type penetrameters provide a binary assessment (pass/fail) to verify whether the achieved sensitivity meets the specified acceptance criteria (e.g., 1-2T or 2-2T); however, they do not yield a precise quantitative measurement of the system’s sensitivity.

For computed radiographic imaging of armor plates, the plaque hole type IQI (Figure 3C) was employed, which enables radiographers to detect fine variations in image quality as radiographic parameters are optimized. Defect in armor plates such as clusters of porosity, chipped ceramic dimples, extra ceramic material fragments, micro-cracks, micro-tears, voids, or missing dimples, depend on the CR system's sufficient contrast sensitivity. In compliance with established engineering codes and film/CR process control guidelines, a minimum contrast sensitivity of 2% (i.e., visibility of the 2-2T hole) is required in radiographic imaging, which is also specified in the procedure as the target for imaging armor plates [14]. A 2% sensitivity refers to the imaging system's ability to distinguish at least 2% in material thickness or density, serving as a key measure of its capability to resolve subtle variations in material properties or low-contrast features, such as minor density variations or small defects, which is essential for accurate assessment in complex materials.

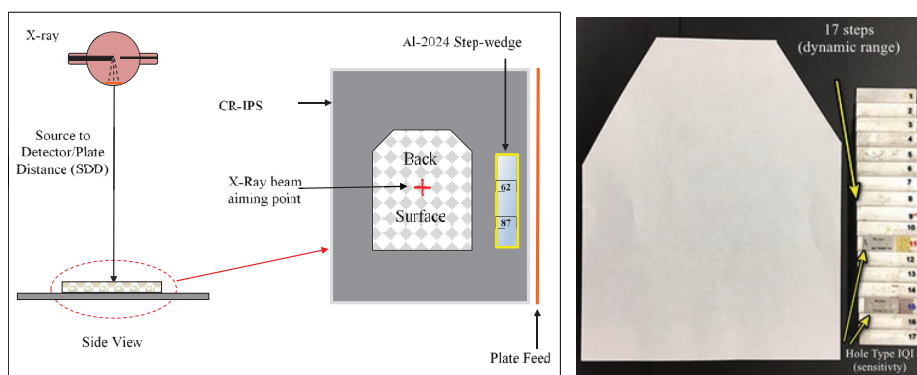


**Figure 3:** Three Conventional Types of Image Quality Indicators (IQIs) [15-16]

### 3. IMAGING PROCEDURE OF ARMOR PLATE AND QUALITY MONITORING

The schematic of the experimental setup for computed radiographic inspection of armor plate is illustrated in Figure 4. The armor chest plate is positioned on the CR standard resolution phosphor imaging plate with the strike face facing downward. The chest plate is aligned with the phosphor imaging plate, ensuring that its long axis runs parallel to the long axis of the imaging plate. The ceramic plates inspected in this study measure approximately 254 mm (10 inches) by 304.8 mm (12 inches), consisting of a hard ceramic dimpled front face and a backing layer made of high-

performance polymer composite. The body armor chest plate is considered sensitive material in terms of their fabrication and intellectual property; therefore, preventing disclosure of additional information.



**Figure 4:** Experimental Setup for Armor Plate Inspection

The procedure for armor plate inspection was initially developed using an X-ray tube paired with a computed radiography (CR) system. During the initial setup, no specific image quality indicator was employed. Nevertheless, after optimizing inspection parameters such as kilovoltage (kV), milliamperage (mA), source-to-object distance, and other critical variables, the system produced satisfactory CR images. These optimized images effectively revealed typical defect in the armor plate, demonstrating the setup's initial effectiveness.

However, complications arose when the X-ray tube and CR system were later replaced with new equipment. Although the same inspection parameters, including kV, mA, and exposure settings, were retained, the resulting images showed inconsistencies. The system's reliability was compromised as the new setup frequently generated inaccurate results, such as over-saturation at the edges of the armor plate, and occasional false-positive findings.

Investigations revealed that hardware changes altered the dynamic range of the imaging system, despite identical inspection parameters being maintained, which resulted in over-exposure of the ceramic material at the edge of the chest plate. This finding highlights the sensitivity of CR systems to hardware variations and underscores the necessity of maintaining repeatability and calibration to ensure consistent image quality. This case underscores the necessity of implementing a robust protocol to account for hardware variations and highlights the potential utility of incorporating image quality indicators (IQIs) to ensure consistency and accuracy in inspection results.

### 3.1 Revised Procedure with IQI and Step Wedge

To address inconsistencies in imaging results, both the imaging procedure and the setup were carefully revised. As part of the updated procedure, and to ensure both optimal image quality and repeatability, a seventeen-step Al 2024 (aluminum alloy 2024) step wedge was placed adjacent to the specimen on the imaging plate to assess the system's dynamic range (as shown in Figure 4). Accurate exposure settings were validated by ensuring that all steps on the Al-2024 step wedge (steps 3 through 17), except for the two thinnest steps, were clearly visible and readily distinguishable in the radiographic image. Additionally, approximate target gray-scale values for each step were specified and had to be achieved by varying the exposure settings in order to maintain consistency and precision in the imaging process. Similarly, the target gray scale value range for both the central and edge portions of the armor plate was also defined. X-ray parameters, including voltage, current, and exposure duration, were systematically adjusted to achieve target grayscale values at both the central dimples and the plate edges while preventing overexposure that could potentially produce false positives. The thickness of the ceramic material may vary slightly, potentially causing gray-scale values to deviate marginally from the specified range. In such instances, verification of the Al step wedge gray-scale values to ensure alignment with the specified range, as well as evaluation of the chest plate, is required.

Furthermore, two ASTM E1025-specified penetrameters were strategically positioned on two distinct steps of the wedge. These penetrameters serve as image quality indicators (IQIs), which were instrumental in verifying that the resulting CR image achieves the required sensitivity of 2% [Equation 1]. By integrating the step wedge (for

dynamic range assessment) and ASTM IQIs (for sensitivity verification), the procedure provides a standardized and robust approach for maintaining high-quality radiographic results.

In CR, grayscale values are represented as digital numbers (DN), or pixel intensity values, corresponding to the detected X-ray attenuation at each pixel. The CR system operates with a 16-bit processor, producing DN values ranging from 0 to 65,535 ( $2^{16}$  levels). Exposure parameters were carefully calibrated to achieve a dynamic range spanning from 10% (DN 6,553) to 90% (DN 58,981) of the system's maximum pixel intensity. This range minimizes the effects of low-end noise and high-end saturation, ensuring sufficient contrast and detail for reliable image interpretation.

The aluminum step wedge provides a controlled range of X-ray attenuation through its graduated thickness steps. Dynamic range is evaluated by identifying the lowest thickness step where the signal exceeds the noise floor (the lower limit) and the highest step before signal saturation (the upper limit). A characteristic response curve can be plotted with step thickness or logarithmic exposure on the x-axis and pixel value (DN) on the y-axis. The linear portion of this curve defines the usable dynamic range, where pixel values increase proportionally with exposure. The total dynamic range is determined by the span between the minimum detectable signal and the saturation point, reflecting the system's capability to capture varying levels of X-ray attenuation.

This also reflects the system's ability to distinguish minimal variations in attenuation due to small differences in material thickness, thereby assessing contrast resolution. It ensures that exposure parameters (kV, mA, exposure time) are optimized for the specific material and imaging setup. Additionally, the step wedge plays a critical role in periodic quality assurance by monitoring hardware or inspection parameter changes, detecting any decline in imaging performance, and maintaining consistent accuracy and reliability.

The incorporation of image quality indicators (IQIs) ensured that the acquired images met specific quality standards by providing a consistent reference for contrast sensitivity and defect detectability. The combined use of the step wedge and IQIs standardized the inspection process, enabling reliable results despite minor variations in hardware or operational parameters. This methodological refinement enhanced both the accuracy and repeatability of the computed radiography system, substantially reducing false positive indications and increasing confidence in defect detection. A comprehensive inspection of several thousand armor plates was conducted, with each inspection requiring less than five minutes. Interpretation of the images was performed by certified personnel specialized in radiographic nondestructive testing.

#### **4. INSPECTION RESULT**

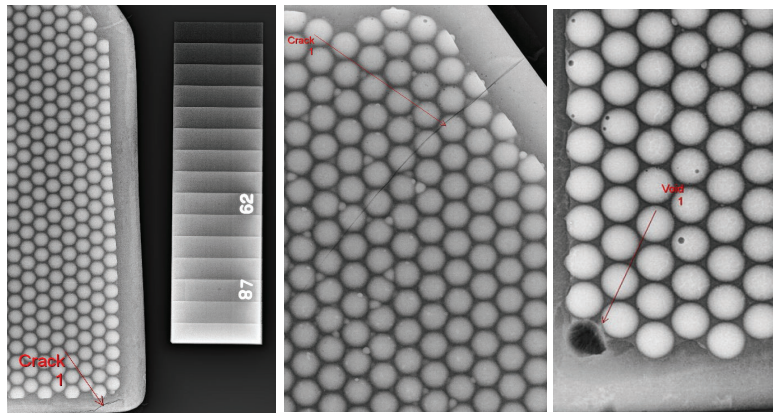
The CR inspection primarily aimed to identify and evaluate defect such as cracks and voids that could adversely affect ballistic performance of ceramic PPE. Cracks of varying lengths could appear anywhere on the plate, whereas voids were typically located along the flat outer edges, often resulting from wear-related chipping or breakage. During the inspection, anomalies or discontinuities associated with the manufacturing process such as clusters of porosity, chipped ceramic dimples, fragments of additional ceramic material, micro-cracks, or micro-tears were also observed. These manufacturing-related defect did not constitute grounds for rejection, as the primary objective was to detect and assess service-induced defect. Acceptance or rejection of the plate was determined according to pass/fail criteria established from prior ballistic performance testing. Specifically, cracks (excluding craters or micro-cracks), missing dimples in the central region of the chest plate, and defect exceeding 10 millimeters along the edges were classified as reasons for rejection due to their detrimental effects on the overall structural integrity of the plate.

Cracks and voids resulting from service conditions constituted the primary defect that led to the rejection of plates. The crack profiles displayed a wide range of sizes, extending from a few millimeters to the full length or width of the armor plate. These cracks exhibited characteristics similar to conventional linear defect typically observed in both brittle and ductile materials. Potential causes for the formation of these cracks included pressure exerted during the pressure-casting stage of manufacturing, the release of localized stresses within the material, or external mechanical forces such as impacts caused by dropping or striking the plate.

Certain objects detected at the dimples were identified as unwanted inclusions, such as ceramic chips, which were likely introduced during packaging from adjacent layers. Edge void defects were primarily attributed to chipping

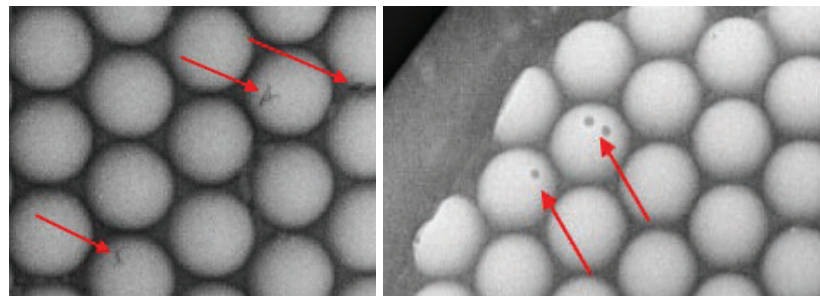
along the ceramic edges, occurring either during handling or manufacturing processes. Localized discontinuities in ceramic thickness were attributed to deviations in the molding and casting processes, which resulted in the incorporation of multiple small fragments of excess ceramic material.

The observed defects, regardless of whether their origin was manufacturing or service-related, encompassed porosity, micro-tears or micro-cracks, missing dimples at the edges, trimmed dimples along the edges, small voids with diameters less than 10 mm situated along the edges, unwanted ceramic particles dispersed between dimples, and substantial thinning voids at the edges. These defects were discernible in the radiographic images. During the evaluation process, all indications, whether deemed acceptable or constituting grounds for rejection, were systematically annotated within the CR images using specialized software tools. A selection of representative X-ray images depicting various defect types is provided in Figure 5 to Figure 7 and in Table 2.



(a) Small Crack at Edge (b) Through-Plate Crack (c) Void at Edge

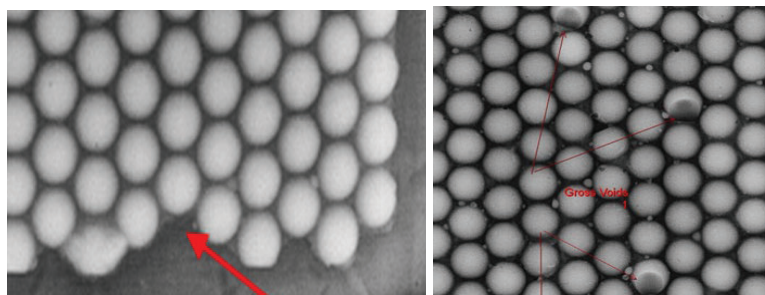
**Figure 5:** Crack and Void Defect (with Step-Wedge Gauge)



(a) Miro-tears /Micro crack

(b) Porosity

**Figure 6:** Manufacturing Defect



**Figure 7:** Manufacturing Process Defects (missing dimple at the edge in left image)

Table 2: Defects Detected in Radiographic Images of Ceramic Armor Plates

Cracks: Varying length, presence anywhere in plate Few millimeters to the through length or width of the ceramic plates	Figure 5a,b
Void at Edge	Figure 5c
Micro-tears / Micro crack	Figure 6a
Porosity	Figure 6b
Missing dimple at edge	Figure 7a
Gross Voids	Figure 7b

## 5. CONCLUSION

Over several thousand PPE armor plate were inspected, with damage types categorized for acceptance or rejection. Cracks and void-like discontinuities, as per inspection criteria, were the main reasons for rejection. Using standard-resolution CR imaging plate, the system was able to identify non-critical manufacturing and service-induced defects such as porosity, micro-tears, micro-cracks, edge-related dimple defects, small edge voids (<10 mm in diameter), dispersed ceramic particles, and significant edge thinning voids. The CR inspection procedure, integrated with a comprehensive quality monitoring setup, demonstrated the capability of CR to facilitate efficient, high-throughput nondestructive evaluations. It demonstrated resilience against the considerable variations in the design, size, and condition of armor inserts and their coverings. It successfully detected various types of defects and provided clear, digital image records of inspected plate for verification purposes.

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