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WHITE PAPER

Debunking Digital Imaging Myths

The Fallacy of Sharpness in Determining Digital Radiographic Image Quality.

INTRODUCTION

At Carestream NDT we want to share not only our technological developments and product portfolio, but also the knowledge and practical experience that our staff obtains by working shoulder-to-shoulder with customers like you. We aim to share this knowledge and experience in a straightforward fashion so that our readers may find practical applications in their everyday activities.

This series is directed but not limited to NDE professionals in the following industries: Oil & Gas, Nuclear, Construction, Foundry and Castings, Energy Generation, Aerospace, Transportation, Automotive, Military and Defense, Agriculture, Art Restoration & Museum Artifacts, and NDE Services Companies.

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Introduction - where is this image quality fallacy?

Sharpness is an important factor in digital radiography, contributing to the detection of discontinuities. However, the overall image quality is dependent upon the brightness, sharpness, and overall noise level in the image. Radiography can be used to detect internal discontinuities such as holes, inclusions, shrinkage, and cracks.

Typically, discontinuities are intentional or unintentional interruptions in the physical structure or configuration of a material or component, in simpler words they are missing material in a part with a specific material type and thickness. When an image is displayed for interpretation, what ultimately matters is whether the relevant features are sufficiently visualized. Image quality metrics provide a description of the detection capability; nevertheless, it is important to understand that medical radiology and industrial radiography use different terms to describe image quality, however both terminologies illustrate the same phenomenon. A discussion of image quality terms applicable to industrial radiography such as detective quantum efficiency (DQE), modulation transfer function (MTF), noise power spectrum (NPS), basic spatial resolution (SRb), signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR) and equivalent penetrameter sensitivity (EPS) are presented here.

A fallacy, in simple terms, is a false appearance, and pertaining to image quality in digital radiography, people often mistake improved image quality as the ability to resolve smaller details in a radiograph. They believe that if more detail can be seen, then the probability of detection (POD) of discontinuities will improve. This is true sometimes; however, other times, more discontinuities are visualized with decreased image sharpness. How can this be possible?

Let's have our Image Quality terms right.

As we have explained before, the physicist Stephen Hawking, while he was in the process of publishing his first book devoted to a general audience, was advised that any equation included in his text would diminish the number of potential readers in half. He took the risk to include just one equation (E=mc2, Einstein's mass–energy equivalence equation) because this equivalence notion was fundamental to explain the content included in the scope of its book. We will, similarly, take some risk with the potential readers of this article, and will include just some equations that will be fundamental to explain several of the ideas discussed in this article.

ASTM E1316 Standard Terminology for Nondestructive Examinations defines a radiograph as "any retrievable image produced by penetrating radiation passing through a material being examined. This may be hard copy, film, or a digital image", in other terms a shadow image is formed as radiation passes through an object to a detector. The degree of absorbed radiation is dependent upon the material type and thickness of the part. Radiography can be used to detect internal discontinuities such as porosity, metallic or non-metallic inclusions, shrinkage, and cracks.

Figure 1 presents a schematic for the fundamental physics and the geometric principles of forming a shadow image radiograph in a suitable recording media. The dark areas on the recording media or detector represent the shape of the less radiographically opaque discontinuity.

X-rays and gamma rays, as constituents of the electromagnetic spectrum, follow the same physics and geometric principles as light when forming shadows. We can understand how shadows are created with these types of radiation by using the same principles related to light. However, it's important to remember that the comparison between light and radiation isn't exact because objects can be more or less transparent to x-rays and gamma rays. Also, scattering effects are more challenging in radiography compared to optics. Still, the basic geometric rules for creating shadows are the same for both light and penetrating radiation.

If we ideally portray the radiation source used to produce a radiograph as a single geometric point, as is shown in Figure 1-A two interesting relevant things happen: 1) The shadow on the detector "C" cast by the object "O" will have a sharply defined border and 2) The shadow produced will have some degree of enlargement that is dependent of how close or far the object is from the detector and how close or far the radiation source is from the object.

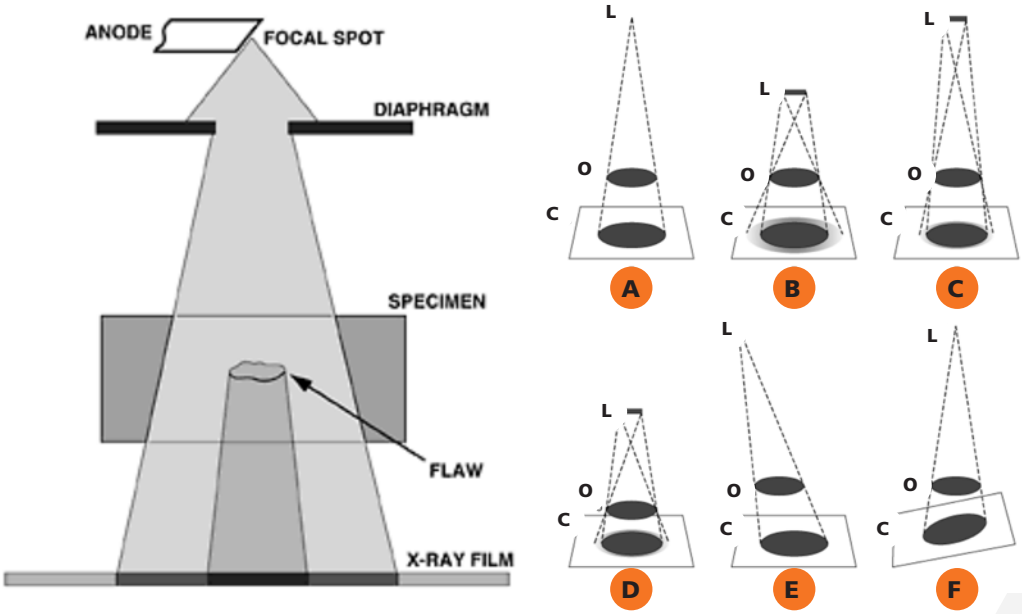

Figure 1: Illustrating the general geometric principles of shadow formation., Adapted from Radiography in Modern Industry [2]

If we move away from the idea of considering the radiation source a single geometric point and consider the actual physical dimensions of the radiation source, as is shown in Figures 1-B and 1-C we will see that every single point of the radiation source cast its own shadow of the object on the detector creating, through their superposition a zone of penumbra or geometric unsharpness is created in the border of the test object. Figures 1-B and 1-C also demonstrate the effect of the focal spot size and source-to-detector distance on the formation of the penumbra. The larger the penumbra, the greater the degree of unsharpness, and therefore more distortion will be seen in the radiograph. With all of the emphasis placed on unsharpness, some radiographers may believe that improved spatial resolution is the only way to produce better radiographs.

The form on the shadow of the object may resemble the form of the object if the detector is placed perpendicularly to the line that forms the radiation source with the detector as is shown in Figures 1-D but the form on the shadow of the object may be distorted if the detector is placed obliquely to the line that forms the radiation source with the detector shown in Figures 1-E and 1-F. Also, the spatial relations between objects may be distorted. In Figure 2 the shadow produced by two circular objects can be decided either as two clearly defined and separated circles (See Figure 2-A) or as two intersecting circles that constitute a single image (See Figure 2-B).

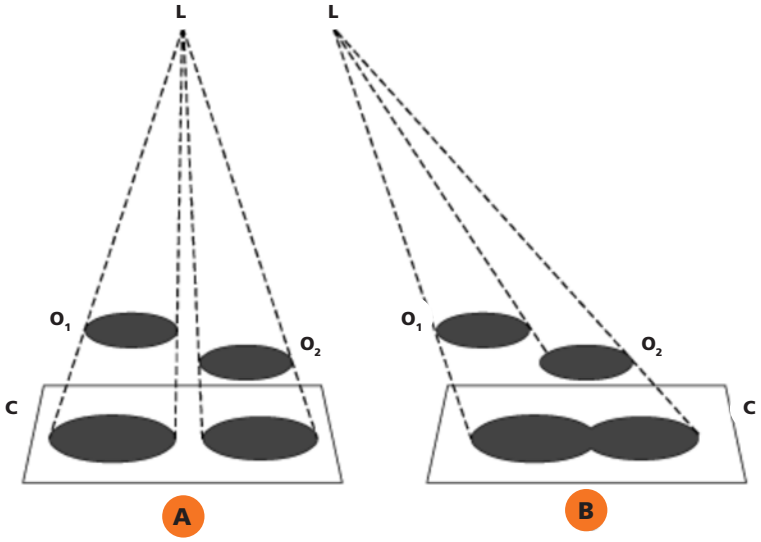

Figure 2: Illustrating the distortion of spatial relations on shadow formation, Adapted from Radiography in Modern Industry [2]

ASTM E1316 Standard Terminology for Nondestructive Examinations defines geometric unsharpness (Ug) as "the penumbral shadow in a radiological image which is dependent upon (1) the radiation source dimensions, (2) the source to object distance, and (3) object to detector distance";

The mathematical formula that binds together those three elements is:

$$U_g = Ft/d_o$$

In this equation:

U_g is the value of geometric unsharpness,

F is the maximum projected dimension of radiation source,

t is the distance from source side of specimen to film, and

d_o is the source-object distance.

Note: Please notice that all variables in the formula are distances and therefore the value of U_g is also a distance.

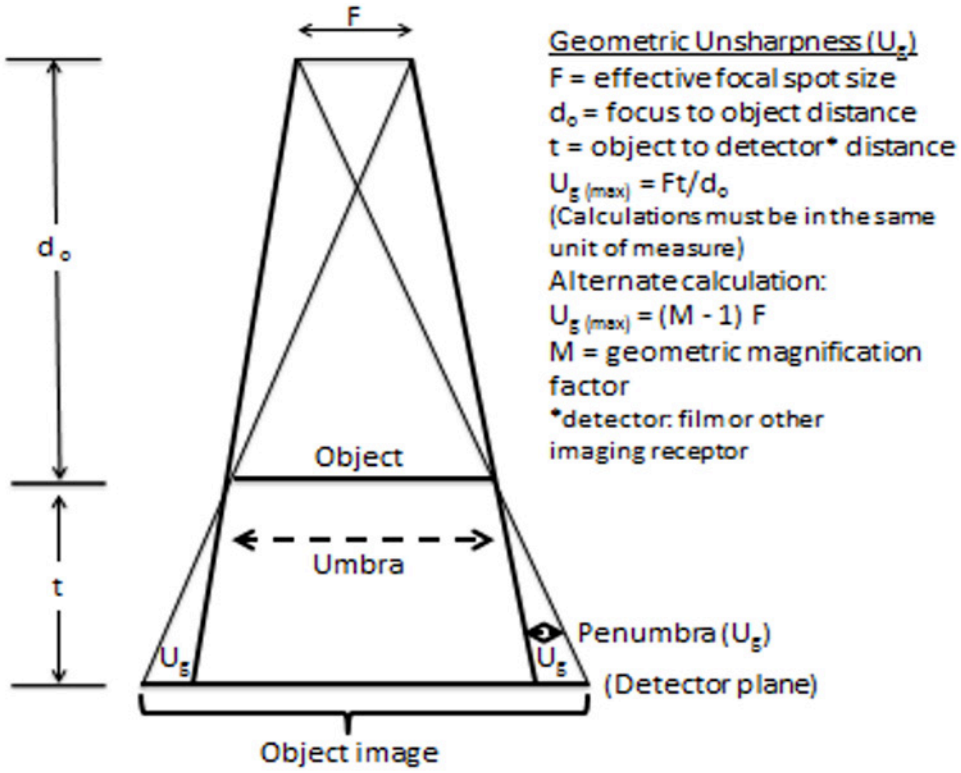

Figure 3: Schematic of geometric unsharpness,
Adapted from Radiography in Modern Industry [2]

Radiographers are often trained to focus on techniques to reduce the unsharpness in an image. Figure 3 demonstrates the effect on geometric unsharpness of the three factors outlined in its definition. From the formula construction, it should be now evident that geometric unsharpness improves as the focal spot size is reduced, the source-to-detector distance is increased, and the object-to-detector distance is decreased.

ASTM E1316 Standard Terminology for Nondestructive Examinations defines normalized image unsharpness (Uim) as "the blurring of test object features in a radiographic image (primarily due to detector properties), with the object measured adjacent to the detector plane without geometric magnification.";

The **maximum** normalized image unsharpness may be calculated with the following formula:

$$U_{IM} = \frac{1}{v}\sqrt[3]{U_g{}^3 + \left(2 \cdot SR_b{}^{det}\right)^3}$$

In this equation:

U_{IM} is the value of the maximum normalized image unsharpness,

U_g is the value of geometric unsharpness,

$SR_b{}^{det}$ is the basic spatial resolution measured at the detector, and

v is the geometric magnification, which in turn may may be calculated with the following formula:

$$v = \frac{SOD + ODD}{SOD}$$

Where:

SOD is the source-to-object distance, and

ODD is the object-to-detector distance

Table 1(a) provides the maximum normalized image unsharpness as a function of material thickness as defined by ASTM E2698 while Table 1(b) provides the tolerances for geometric unsharpness as defined by ASME BPVC Section V Article 2 (The maximum allowable unsharpness is determined by using the unsharpness equation above):

Material Thickness		UIM	
inches	mm	inches	mm
≤ 0.5	≤ 12.7	0.010	0.254
> 0.5 and ≤ 1.0	>12.7 and ≤ 25.4	0.015	0.381
>1.0 and ≤ 2.0	> 25.4 and ≤ 50.8	0.020	0.508
>2.0 and ≤ 4.0	> 50.8 and ≤ 101.6	0.030	0.762
>4.0	> 101.6	0.040	1.016

Table 1(a): Maximum normalized image unsharpness, adapted from ASTM E2698 [3]

Material Thickness		Ug Maximum	
inches	mm	inches	mm
Under 2	Under 50	0.020	0.51
2 through 3	50 through 75	0.030	0.76
Over 3 through 4	Over 75 through 100	0.040	1.02
Greater than 4	Greater than 100	0.070	1.78

Table 1(b): Maximum geometric unsharpness, adapted from ASME BPVC Section V Article 2 [4]

Transcending the focus on unsharpness

Whether a discontinuity has sufficient contrast to be visualized is what really matters when it comes to the inspection of parts for industrial radiography. The degree of imaged contrast of a discontinuity is dependent upon many factors, and it is typically described as radiographic contrast sensitivity. The contrast sensitivity is a measure of the ability of an evaluator to distinguish between signal levels in relation to the noise within a radiographic image, which can be used to estimate a minimum detectable material thickness difference or change in attenuation.

DISCUSSION-The contrast sensitivity is computed as the inverse of the minimum contrast-to-noise ratio needed to distinguish image features. The subject contrast is governed by the range of radiation intensities transmitted through the specimen. Subject contrast decreases as the penetrating power increases because more wavelengths penetrate the subject in both the thick and thin sections, thus reducing the overall difference in exposure between the areas with and without a discontinuity. Radiographic contrast is governed by both, subject contrast and detector contrast.

The detection capability of an imaging system determines the probability of detection (POD) of a discontinuity. In 1946, Albert Rose proposed the concept of equivalent (detective) quantum efficiency, or DQE, to describe the performance of imaging systems. DQE was first introduced to the medical radiology community by Shaw. He demonstrated that the image quality of imaging systems could be expressed by the number of X-ray quanta required to produce a specific signal-to-noise ratio (SNR). Detective quantum efficiency (DQE) provides a quantitative way to measure the detection capability of an imaging system for given exposure parameters and is a measure of image quality as a function of spatial frequency. Spatial frequency is a characteristic of any structure that is periodic across positions in space. The spatial frequency is a measure of how often sinusoidal components of the structure repeat per unit of distance (as determined by the Fourier transform). The SI unit of spatial frequency is cycles per meter (m). In image-processing applications, spatial frequency is often expressed in units of cycles per millimeter (mm) or equivalently line pairs per mm.

Mathematically, DQE is defined by the following equation:

$$DQE(f) = \frac{q \cdot g^2 \cdot T^2(f)}{NNPS(f)}$$

In this equation:

DQE(f) denotes that the detective quantum efficiency is a function of spatial frequency,

q is the density of incident quanta per unit area at the detector (flux),

g is the system gain, that is related with the amplification of the received signal

T is the Modulation Transfer Function (MTF)1, and

NNPS is the normalized noise power spectrum.

[1]MTF is a way to measure the achievable detail that a system can obtain. The MTF describes the contrast of an image as a function of spatial frequency. MTF is calculated by measuring the edge response of a tungsten phantom with a very sharp angle. A line profile is drawn in the radiograph across the sharp angle, resulting in an edge spread function (ESF). Taking the derivative of the ESF results in a rate of change across the angled edge, which is known as the line spread function (LSF). An oversampled LSF has a Fourier transform applied to it to yield the contrast modulation as a function of spatial frequency, as the Fourier transform decomposes the LSF into the frequency domain.

In medical radiology, MTF is a way to measure the achievable detail that a system can obtain. The MTF describes the contrast of an image as a function of spatial frequency. It is calculated by measuring the edge response of a copper phantom with a very sharp angled edge. A line profile is drawn in the radiograph across the sharp edge, resulting in an edge spread function (ESF). Taking the derivative of the ESF results in the rate of change across the angled edge, which known as a line spread function (LSF). An oversampled LSF has a Fourier transform applied to it to yield the contrast modulation as a function of spatial frequency, as the Fourier transform decomposes the LSF into the frequency domain.

The other component of the DQE calculation is the noise power spectrum (NPS), plotted as a function of spatial frequency. NPS is defined mathematically in terms of the Fourier transform of noise images. The images are normalized by subtracting out the mean signal, resulting in an estimation of statistical variability as a function of spatial frequency in the image.

DQE, MTF, and NPS require complex mathematical calculations to represent image quality; therefore, they are not used to describe the image quality of industrial radiography systems. Industrial radiography utilizes simplified calculations of image quality parameters that relate to the more complex calculations utilized for medical radiology.

Basic spatial resolution (SRb) is a measure of the amount of detail that can be seen in an image with a duplex wire gauge placed directly on the detector. The duplex wire gauge consists of several elements. Each element has two wires with a specific diameter and spacing between them. In an image, a line profile is drawn perpendicular to the elements. The element is said to be resolved if the intensity difference is greater than 20% of the wires against their background. The first unresolved element is considered to be the resolution of the image. Table 2 describes the corresponding resolution of each element in both micrometers (µm) and line pairs per millimeter (lp/mm). The resolution is one half of the unsharpness value.

Element	Unsharpness (mm)	SRb		lp/mm
		(mm)	(µm)	
17	0.040	0.020	20	25.00
16	0.050	0.025	25	20.0
15	0.064	0.032	32	15.63
14	0.080	0.040	40	12.50
13	0.100	0.050	50	10.00
12	0.130	0.063	63	7.94
11	0.160	0.080	80	6.25
10	0.200	0.100	100	5.00
9	0.260	0.130	130	3.85
8	0.320	0.160	160	3.13
7	0.400	0.200	200	2.50
6	0.500	0.250	250	2.00
5	0.640	0.320	320	1.56
4	0.800	0.400	400	1.25
3	1.000	0.500	500	1.00
2	1.260	0.630	630	0.79
1	1.600	0.800	800	0.63

Table 2: Duplex wire gauge resolution values, adapted from ASTM E2698 [3]

SNR is another very important image quality metric in industrial radiography. It can be plotted as a function of dose to assess the image quality level. SNR can be calculated in two different ways. The first method uses a rectangular region of interest (ROI) of at least 4000 pixel values and is defined as follows:

$$SNR = \frac{N}{\sigma}$$

In this equation:

SNR is the signal-to-noise ratio,

N is the mean pixel intensity of the ROI, and

σ is the standard deviation of the pixel intensities in the ROI

For improved accuracy, the second method uses a rectangular ROI of at least 8000 pixel values and is normalized for the maximum SRb. It also utilizes the median instead of the mean value in the numerator. It is defined as follows:

$$SNR = \frac{median\ pixel\ value}{\sigma}$$

$$SNR_N = SNR \cdot \frac{88.6_{um}}{iSRb_{\max}}$$

In these equations:

SNR is the signal-to-noise ratio,

σ is the standard deviation of the pixel intensities in the ROI,

SNR_N is the resolution normalized SNR, and

$iSRb_{max}$ is the maximum interpolated basic spatial resolution.

Note: The value of 88.6 µm is for normalization between rectangular ROIs and circular apertures that were used for film system granularity calculations iSRbmax is the interpolated maximum value of the basic spatial resolution, which is found at 20%.

Detectability of discontinuities is improved as contrast-to-noise ratio (CNR) is increased. Increased relative specific contrast (µeff) and reduced noise are the key enablers to detect a discontinuity in a radiograph. There is a point at which the discontinuity can be visualized; this is referred to as the perception threshold.

There are two different calculation methods for CNR. In both instances, an ROI is first drawn inside the 4T hole of an image of a penetrameter, and the same ROI is drawn in a region adjacent to the penetrameter hole. The two possible calculations that can be used are as follows.

$$DICOM\ CNR = \frac{PV1 - PV2}{\sqrt{\frac{s1^2 + s2^2}{2}}}$$

$$ASTM\ CNR = \frac{PV1 - PV2}{s2}$$

In these equations:

CNR is the contrast-to-noise ratio,

PV1 is the mean pixel intensity of the interior hole,

PV2 is the mean pixel intensity of the exterior region,

s1 is the standard deviation of the interior hole, and

s2 is the standard deviation of the exterior region

Note: The DICOM calculation utilizes a weighted average pooled standard deviation, whereas the ASTM calculation uses the standard deviation of the exterior hole only.

A third formula to calculate contrast-to-noise ratio is as follows:

$$CNR = \frac{PVI_{4T} - APVO_{4T}}{SD_{POOLED}}$$

In this equation:

CNR is the contrast-to-noise ratio,

PVI_{4T} is the pixel value inside the 4T hole,

$APVO_{4T}$ is the average of the two regions of interest outside the 4T hole, and

SD_{POOLED} is the pooled standard deviation of the two regions of interest outside the 4T

Another common industrial radiography image quality metric that is often referenced is equivalent penetrameter sensitivity (EPS).

ASTM E1316 Standard Terminology for Nondestructive Examinations defines equivalent penetrameter sensitivity as follows: "that thickness of penetrameter, expressed as a percentage of the section thickness radiographed, in which a 2T hole would be visible under the same radiographic conditions.".

EPS gives a measure of contrast sensitivity as a function of dose, providing an estimate of detectability based upon qualitative visual observations. Four plaques, each with different thickness and holes with different diameters, are exposed against a thick absorber. Three plaques with three rows of 30 holes and one plaque with four rows of 30 holes are exposed, and the observer must see 15 out of the 30 holes in any given row for that row to be resolved. Each assigned row corresponds to calculated contrast sensitivity. Dose series are performed with EPS plaques to establish a minimum qualified pixel value for specific radiographic and imaging system parameters.

Some radiographers, trained extensively in unsharpness for their radiographic technique, assume incorrectly that improvements in image quality must relate to better spatial resolution. In reality, the image quality is both a function of the SNR and the SRb. Improvements in image quality can be achieved by increasing the quanta per unit area via increased dose and by controlling the scatter, which reduces the noise levels. The idea of sharpness as the only important factor determining image quality is a fallacy, as detectability of discontinuities in an image is also dependent on the flux and the noise. This describes the DQE equation, which provides a measure of the detection capability. In industrial radiography, both SNR and SRb determine the image quality, which can also be described in terms of CNR and EPS. The DQE equation used in medical radiology can be represented in industrial radiography as the SNR times the SRb. Just because an image or imaging system has more sharpness, it does not mean that the image or imaging system has better image quality. Both SNR and SRb need to be maximized to deliver better detection capability, and often, SRb and SNR are inversely proportional to one another, meaning as one improves, the other gets worse.

An illustration of image quality related to detectability is accomplished via the compensation principle. This is: To detect a discontinuity, one must achieve an acceptable CNR for a given material thickness difference. A radiographer can compensate for insufficient sharpness with increased SNR, which is typically done by increasing the dose level. Improved SNR will compensate for insufficient SRb to maintain the overall image quality. Likewise, improvements in sharpness will improve detectability only if the SNR is maintained.

Brian White, Research Scientist and Level III Radiographer at Carestream NDT, explains the practical implications of the notions discussed in the present white paper in the following terms [8]: “In industrial radiography, the probability of detection of discontinuities can improve when more detail is seen in the image. This is true sometimes; however, at other times, more discontinuities are visualized with decreased image sharpness because of improvements to the SNR, which improves the DQE image quality. Therefore, just because an imaging system has better SRb, it does not mean that it produces images with better image quality. Both the SNR and SRb must be maximized, thus improving the visualization of discontinuities.”

Actionable approach - Guidelines to improve image quality

- Remember that in digital radiography imaging processes using DDA is of essence to compensate for insufficient sharpness with increased SNR, which is typically done by increasing the dose level.
- The geometric unsharpness (Ug) equation provides a means for determining geometric unsharpness values. The amount or degree of unsharpness should be minimized when establishing the radiographic technique. Achieving this may include reducing focal spot size, increasing source-to-detector distance and reducing object-to-detector distance.
- In order to minimize image distortion, the direction of the central beam of radiation should be perpendicular to the surface of the film whenever possible. Otherwise, the object image will be distorted if the film is not aligned perpendicular to the central beam. Different parts of the object image may be distorted in different amounts depending on the extent of the film to central beam offset.
- Document successful radiographic techniques in terms of image quality for components and assemblies that are often inspected and use them, together with sound radiographic imaging principles as a fundamental information resource to develop new techniques for components where there are no previous experience.

For readers interested in exploring how digital radiography (DR) can be integrated into your processes:

https://www.carestream.com/en/us/nondestructive-testing-ndt-solutions

For readers interested in exploring supplementary white papers on practical application and innovation on imaging processes:

https://www.carestream.com/en/us/nondestructive-testing-ndt-solutions/ndt-white-papers

Here are some supplementary information resources from Carestream NDT's products and services portfolio:

Products

- HPX-DR 3543 PE Non-Glass, Large Format Detector
- HPX-DR 2530 PH High-Resolution, Compact Detector
- HPX-DR 2530 PC High-Speed, Compact Detector
- HPX-DR 4336 GH High-Resolution, Large Format Detector
- HPX-DR 2329 GK, High-Resolution, Compact Detector
- INDUSTREX Digital Viewing Software
- Advanced Industrial Radiographic Training Academy
- NDT Archive Solution
- Virtual NDT Showcase
- Resource Center

Services - Training and Supplementary Resources:

- Digital Detector Array Radiography - 40 Hour Online Course
- Digital Imaging - 40 Hour Classroom Training

Resources from ASNT

- Nondestructive Testing Handbook, fourth edition: Volume 3, Radiographic Testing:

https://www.asnt.org/Store/ProductDetail?productKey=83ea27b3-d68f-483d-9354-e447ef2b3915

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