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Standard Guide for
Digital Detector Array Radiology[1]

This standard is issued under the fixed designation E2736; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This standard is a user guide, which is intended to serve as a tutorial for selection and use of various digital detector array systems nominally composed of the detector array and an imaging system to perform digital radiography. This guide also serves as an in-detail reference for the following standards: Practices E2597, E2698, and E2737.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E94 Guide for Radiographic Examination
E155 Reference Radiographs for Inspection of Aluminum and Magnesium Castings
E192 Reference Radiographs of Investment Steel Castings for Aerospace Applications
E747 Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology
E1000 Guide for Radioscopy
E1025 Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiology
E1316 Terminology for Nondestructive Examinations
E1320 Reference Radiographs for Titanium Castings
E1742 Practice for Radiographic Examination
E1815 Test Method for Classification of Film Systems for Industrial Radiography
E1817 Practice for Controlling Quality of Radiological Examination by Using Representative Quality Indicators (RQIs)
E2002 Practice for Determining Total Image Unsharpness in Radiology
E2422 Digital Reference Images for Inspection of Aluminum Castings
E2445 Practice for Performance Evaluation and Long-Term Stability of Computed Radiography Systems
E2446 Practice for Classification of Computed Radiology Systems
E2597 Practice for Manufacturing Characterization of Digital Detector Arrays
E2660 Digital Reference Images for Investment Steel Castings for Aerospace Applications
E2669 Digital Reference Images for Titanium Castings
E2698 Practice for Radiological Examination Using Digital Detector Arrays
E2737 Practice for Digital Detector Array Performance Evaluation and Long-Term Stability

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *digital detector array (DDA) system*—an electronic device that converts ionizing or penetrating radiation into a discrete array of analog signals which are subsequently digitized and transferred to a computer for display as a digital image corresponding to the radiation energy pattern imparted upon the input region of the device. The conversion of the ionizing or penetrating radiation into an electronic signal may transpire by first converting the ionizing or penetrating radiation into visible light through the use of a scintillating material. These devices can range in speed from many minutes per image to many images per second, up to and in excess of real-time radioscopy rates (usually 30 frames per seconds).

3.1.2 *signal-to-noise ratio (SNR)*—quotient of mean value of the intensity (signal) and standard deviation of the intensity (noise). The SNR depends on the radiation dose and the DDA system properties.

3.1.3 *normalized signal-to-noise ratio (SNR_n)*—SNR normalized for basic spatial resolution (see Practice E2445).

3.1.4 *basic spatial resolution (SRb)*—basic spatial resolution indicates the smallest geometrical detail, which can be resolved using the DDA. It is similar to the effective pixel size.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.5 *efficiency*—dSNR$_n$ (see 3.1.6 of Practice E2597) divided by the square root of the dose (in mGy) and is used to measure the response of the detector at different beam energies and qualities.

3.1.6 *achievable contrast sensitivity (CSa)*—optimum contrast sensitivity (see Terminology E1316 for a definition of contrast sensitivity) obtainable using a standard phantom with an X-ray technique that has little contribution from scatter.

3.1.7 *specific material thickness range (SMTR)*—material thickness range within which a given image quality is achieved.

3.1.8 *contrast-to-noise ratio (CNR)*—quotient of the difference of the mean signal levels between two image areas and the standard deviation of the signal levels. The CNR depends on the radiation dose and the DDA system properties.

3.1.9 *lag*—residual signal in the DDA that occurs shortly after the exposure is completed.

3.1.10 *burn-in*—change in gain of the scintillator or photoconductor that persists well beyond the exposure.

3.1.11 *internal scatter radiation (ISR)*—scattered radiation within the detector (from scintillator, photodiodes, electronics, shielding, or other detector hardware).

3.1.12 *bad pixel*—a bad pixel is a pixel identified with a performance outside of the specification for a pixel of a DDA as defined in Practice E2597.

3.1.13 *grooved wedge*—a wedge with one groove, that is 5 % of the base material thickness and that is used for achievable contrast sensitivity measurement in Practice E2597.

3.1.14 *phantom*—a part or item being used to quantify DDA characterization metrics.

4. Significance and Use

4.1 This standard provides a guide for the other DDA standards (see Practices E2597, E2698, and E2737). It is not intended for use with computed radiography apparatus. Figure 1 describes how this standard is interrelated with the aforementioned standards.

4.2 This guide is intended to assist the user to understand the definitions and corresponding performance parameters used in related standards as stated in 4.1 in order to make an informed decision on how a given DDA can be used in the target application.

4.3 This guide is also intended to assist cognizant engineering officers, prime manufacturers, and the general service and manufacturing customer base that may rely on DDAs to provide advanced radiological results so that these parties may set their own acceptance criteria for use of these DDAs by suppliers and shops to verify that their parts and structures are of sound integrity to enter into service.

4.4 The manufacturer characterization standard for DDA (see Practice E2597) serves as a starting point for the end user to select a DDA for the specific application at hand. DDA manufacturers and system integrators will provide DDA performance data using standardized geometry, X-ray beam spectra, and phantoms as prescribed in Practice E2597. The end user will look at these performance results and compare DDA metrics from various manufacturers and will decide on a DDA that can meet the specification required for inspection by the end user. See Sections 5 and 8 for a discussion on the characterization tests and guidelines for selection of DDAs for specific applications.

4.5 Practice E2698 is designed to assist the end user to set up the DDA with minimum requirements for radiological examinations. This standard will also help the user to get the required SNR, to set up the required magnification, and provides guidance for viewing and storage of radiographs. Discussion is also added to help the user with marking and identification of parts during radiological examinations.

4.6 Practice E2737 is designed to help the end user with a set of tests so that the stability of the performance of the DDA can be confirmed. Additional guidance is provided in this document to support this standard.

4.7 Figure 1 provides a summary of the interconnectivity of these four DDA standards.

5. DDA Technology Description

5.1 *General Discussion:*

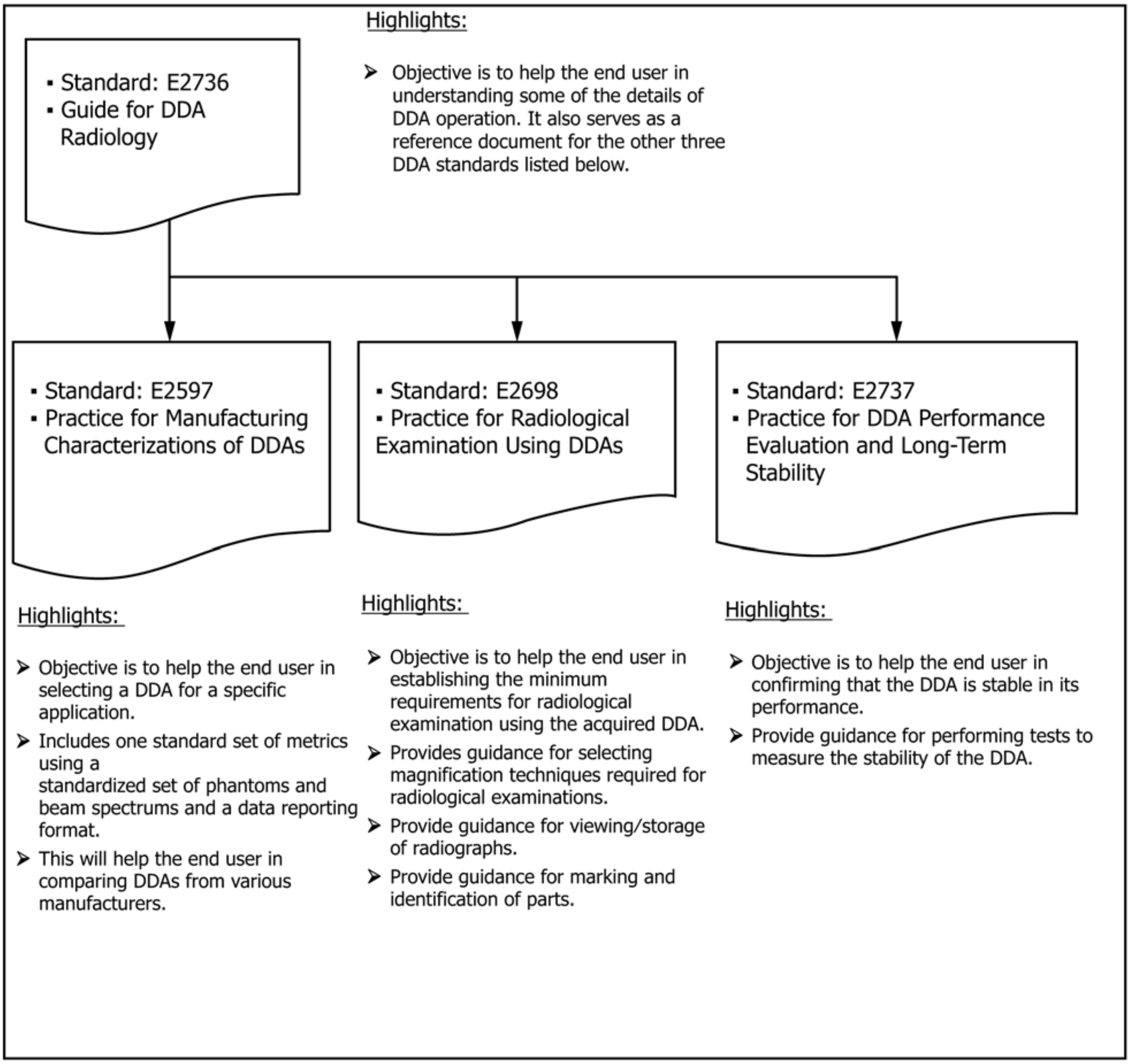
5.1.1 DDAs are seeing increased use in industries to enhance productivity and quality of nondestructive testing. DDAs are being used for in-service nondestructive testing, as a diagnostic tool in the manufacturing process, and for inline testing on production lines. DDAs are also being used as hand held, or scanned devices for pipeline inspections, in industrial computed tomography systems, and as part of large robotic scanning systems for imaging of large or complex structures. Because of the digital nature of the data, a variety of new applications and techniques have emerged recently, enabling quantitative inspection and automatic defect recognition.

5.1.2 DDAs can be used to detect various forms of electromagnetic radiation, or particles, including gamma rays, X-rays, neutrons, or other forms of penetrating radiation. This standard focuses on X-rays and gamma rays.

5.2 *DDA architecture:*

5.2.1 A common aspect of the different forms of this technology is the use of discrete sensors (position-sensitive) where, the data from each discrete location is read out into a file structure to form pixels of a digital image file. In all its simplicity, the device has an X-ray capture material as its primary means for detecting X-rays, which is then coupled to a solid-state pixelized structure, where such a structure is similar to the imaging chips used in visible-wavelength digital photography and videography devices. Figure 2 shows a block diagram of a typical digital X-ray imaging system.

5.2.2 An important difference between X-ray imaging and visible-light imaging is the size of the read-out device. The imagers found in cameras and for visible-light are typically on the order of 1 to 2 cm^2 in area. Since X-rays are not easily focused, as is the case for visible light, the imaging medium must be the size of the object. Hence, the challenge lies in meeting the requirement of a large uniform imaging area without loss of spatial information. This in turn requires high pixel densities of the read-out device over the object under



Highlights:

- Objective is to help the end user in understanding some of the details of DDA operation. It also serves as a reference document for the other three DDA standards listed below.

Highlights:

- Objective is to help the end user in selecting a DDA for a specific application.
- Includes one standard set of metrics using a standardized set of phantoms and beam spectrums and a data reporting format.
- This will help the end user in comparing DDAs from various manufacturers.

Highlights:

- Objective is to help the end user in establishing the minimum requirements for radiological examination using the acquired DDA.
- Provides guidance for selecting magnification techniques required for radiological examinations.
- Provide guidance for viewing/storage of radiographs.
- Provide guidance for marking and identification of parts.

Highlights:

- Objective is to help the end user in confirming that the DDA is stable in its performance.
- Provide guidance for performing tests to measure the stability of the DDA.

FIG. 1 Flow Diagram Representing the Connection Between the Four DDA Standards

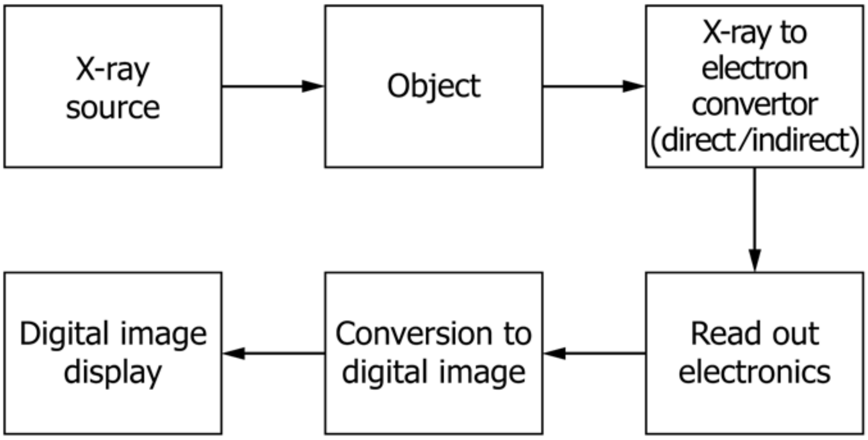


FIG. 2 Block Diagram of a Typical Digital X-Ray Imaging System

examination, as well a primary sensing medium that also retains the radiologic pattern in its structure. Therefore, each DDA consists of a primary X-ray or gamma ray capture medium followed by a pixelized read structure, with various means of transferring the above said captured pattern. For each of these elements, there are numerous options that can be selected in the creation of DDAs. For the primary X-ray conversion material, there are either luminescent materials such as scintillators or phosphors, and photoconductive materials also known as direct converter semiconductors.

5.2.3 For read-out structures, the technology consists of charge coupled detectors (CCDs), complementary metal oxide silicon (CMOS) based detectors, amorphous silicon thin film transistor diode read-out structures, and linear or area crystalline silicon pixel diode structures. Other materials and structures are also possible, but in the end, a pixelized pattern is captured and transferred to a computer for review.

5.2.4 Each primary conversion material can be coupled with the various read structures mentioned through a wide range of coupling media, devices, or circuitry. With all of these possible combinations, there are many different types of DDAs that have been produced. But all result in a digital X-ray or gamma ray image that can be used for different NDT applications.

5.2.5 Following the capture of the X-rays and conversion into an analog signal on the read-out device, this signal is typically amplified and digitized. There are numerous schemes for each of these steps, and the reader is referred to (**1**, **2**, **3**)[3] for further discussion on this topic.

5.3 *Digitization Methods:*

5.3.1 Digitization techniques typically convert the analog signal to discrete pixel values. For DDAs the digitization is typically, 8-bit (256 gray values), 12-bits (4096 gray values), 14-bits (16,384 gray levels) or 16-bits (65,536 values). The higher the bit depth, the more finely the signal is sampled.

5.3.2 The digitization does not necessarily define the gray level range of the DDA. The useful range of performance is defined by the ability of the read device to capture signal in a linear relation to the signal generated by the primary conversion device. A wide linear range warrants the use of a high bit depth digitizer. It should be noted that if digitization is not high enough to cover the information content from the read device, digitization noise might result. This can be manifested as a posterization effect, where discrete bands of gray levels are observed in the image.

5.3.3 Conversely, if digitization is selected that is significantly higher than the range of the read-out device then the added sampling may not necessarily improve performance. Secondly, if the digitization is completed well beyond the linear range of the read structure, these added gray levels would not be useable. For example, 16-bits of digitization do not necessarily indicate 65,536 levels of linear responsivity.

5.3.4 The useful range of a detector is frequently defined as the maximum usable level, without saturation in relation to the noise floor of the DDA, where again no useful differentiation can be extracted from the data. This is sometimes referred to as the detector dynamic range.

5.3.5 The dynamic range is different from the specific material thickness range (SMTR) as defined in this standard and Practice E2597. That range is a true practical range of the DDA at hand, a range significantly tighter than the DDA dynamic range.

5.3.6 The SMTR is one of the properties to consider in DDA selection, as it impacts the thickness range that can be interpreted in a single view. This is dependent on the characteristics of the read device and the digitization level. This test provides a means of determining an effective range without understanding the subtle nuances of the detector readout, and avoids erroneous parallels between bit depth and its relation to thickness range, and maximum possible signal from a device.

5.4 *Specific DDA components*—There are numerous options in each component of the imaging chain to produce a DDA. To understand the options and limitations of each category, and to best assess which technology to pursue for a given application, the underlying technology will be discussed beginning with the image capture medium. This is followed by the image read structure and then the image transfer device is discussed for the various configurations of the read-out devices. For a more detailed description of the architectures of these devices, the reader is referred to Ref. (**2**).

5.4.1 *X-ray Capture—Scintillators (phosphors)*—Scintillators are materials that convert X-ray or gamma ray photons into visible-light photons, which are then converted to a digital signal using technologies such as amorphous silicon (a-Si) arrays, CCDs or CMOS devices together with an analog-to-digital converter. This will facilitate real time acquisition of images without the need for offline processing. Since there are various stages of conversion involved in recording the digital image, it is very important to ensure that minimum information is lost during conversion in the scintillator. The properties desirable of ideal scintillators are listed below. These properties allow for high efficiency, stable and robust operation yielding ideal imaging performance:

(1) High stopping power for X-rays obtained by high atomic number and, or the use of high density materials without loss of spatial information due to scattering processes within the scintillator.

(2) High X-ray to light conversion efficiency

(3) Matched emission spectrum of the scintillator to the spectral sensitivity of the light collection device

(4) Low afterglow during and after termination of the X-ray illumination.

(5) Stable output during long or intense exposure to radiation.

(6) Temperature independence of light output.

(7) Stable mechanical and chemical properties.

5.4.1.1 The scintillator based on CsI:Tl (thallium doped cesium iodide) has shown considerable success as a scintillator because of the following reasons:

(1) Cesium iodide can be formed into needles (see Fig. 3) and coupled directly to a diode read structure or a fiber optic component to direct the light to the photodiodes without significant light loss or optical scatter. This is the most efficient

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[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

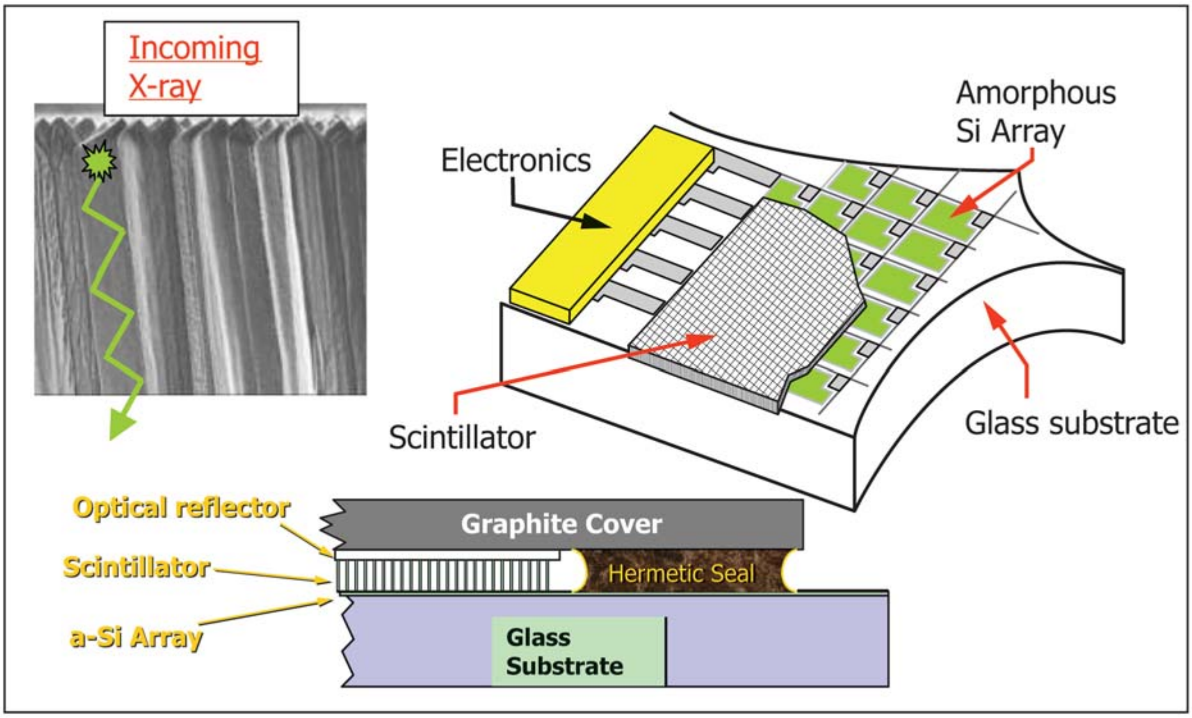


FIG. 3 Architecture of CsI:Tl needle structure demonstrating light guiding nature following x-ray conversion to light, and the amorphous silicon architecture illustrating direct contact of the scintillator with the diode thin film transistor readout matrix.

means for depositing light into photodiodes. All other scintillators lose light at the interface because of reduced optical coupling between the scintillator and the diode structure. CsI is very well matched in index of refraction to that of the entry layer of the amorphous silicon diode structure.The needle-like structure enables thick phosphor layers, which improves X-ray absorption without significant loss in spatial resolution.

(2) The cesium iodide has a high effective atomic number (Z) which also contributes to good X-ray absorption efficiency.

The drawback of CsI are:

(1) CsI:Tl has been prone to severe hysteresis effects, an effect that leads to an unstable signal under constant flow of X-rays, and this instability is non-linear with the dose rate used. This can cause residual images (ghost images) to be retained in the detector from prior scans. In some circumstances, recent preparations have significantly overcome this effect.

(2) CsI is hygroscopic and sensitive to moisture, and must be encapsulated to avoid loss in crystallinity.

(3) CsI:Tl has a primary decay time of 1 microsecond at 1/e (to ~37 % of peak signal), but has a long decay component into the millisecond range that is non-zero but well below 1 %. This needs to be taken into consideration where a very opaque object follows either an open air exposure or a very low opacity exposure, as the afterglow from the bright exposure may encroach on the signal level of the dim exposure.

5.4.1.2 Other scintillators (phosphors) such as polycrystalline Gd_2O_2S:Tb have been successfully used, but have limitations on how thick they can be made given that the powder architecture scatters the light produced from the deposited X-rays. Nevertheless, these are simple phosphors to purchase and implement, and like the CsI needles, can be optically coupled through a lens, or directly coupled to a read structure. For the latter, and as with CsI:Tl, this can be achieved via a fiber optic lens, an optical lens, or by direct coupling to the read-structure itself.

5.4.1.3 Certain scintillators such as Gd2O2S:Tb can be sintered to ceramic imaging plates with discrete cell boundaries yielding the same advantage of the CsI needle structures, but typically without the temporal drawbacks of the CsI:Tl chemistry. However, they are difficult to grow directly onto diode structures, typically require an optical couplant to improve transfer efficiency due to index mismatch, and typically are more expensive to produce and couple to large diode structures.

5.4.1.4 Certain glass scintillators based on terbium activation can be formed into fiber optic scintillating plates yielding the same advantage of the CsI needle structures. These plates tend to also have some temporal drawbacks, and are not as efficient in converting X-rays to light as any of the other scintillators already mentioned.

5.4.1.5 Other materials are under development, and the above sections are not intended to cover all possible options.

5.4.1.6 *Temporal Properties of scintillators*—When radiation impinges upon a scintillator, the atoms/molecules in the scintillator material absorb this radiation and get excited. They de-excite by emitting the energy in the form of visible light. The emitted energy is 'luminescence,' which falls broadly under two categories namely, fluorescence and phosphorescence. These manifest as a two-component exponential decay—fast (prompt) for fluorescence and slow (delayed) for phosphorescence. An ideal scintillator should essentially have only a fast decay component with a linear conversion, that is, light yield should be proportional to the deposited energy. Any phosphorescence might introduce residual latent artifacts into subsequent imagery and make interpretation difficult. Scintillator phosphorescence can lead to image lag or image burn-in as defined herein, where features from prior images contaminate new scenes.

5.4.2 *Semiconductors (Photoconductors)*—A photoconductive material converts X-rays to electron-hole pairs that then get separated by the internal bias of the device as defined by the material properties, such as the manufactured charge imbalance into the semiconductor material. As with scintillating materials, another electronic element is needed to capture the signal produced, such as an electrode structure with pixelization, possibly with additional added electron bias on one electrode to separate the electron-hole pairs. But unlike a scintillating material, there is a lower likelihood that the charges produced will have as much lateral spread as experienced optically in luminescent materials. Also since the photoconductive material converts the X-ray signal directly into electron-hole pairs, there is greater conversion efficiency than with the production of light, that first generates electron-hole pairs prior to producing the light. For X-ray applications, photoconductive materials such as amorphous selenium (a-Se), CdTe, and HgI2 have been used because of their high atomic numbers, and the ability to manufacture these materials into a monolithic structure. Other photoconductive materials are available, or may become available in the future. It should be noted that although light is not generated from these materials, lag and burn-in effects can occur due to subtle effects of sweeping the charge out of the semiconductor.

5.5 *Capture of the converted image:*

5.5.1 *Charge-coupled devices (CCDs)* are light imaging devices that are typically small in size, and have high pixel densities. They use a transparent poly-silicon gate structure for reading out the device, and because of their high pixel fill factor are very efficient in collecting the light produced from the phosphor material. Unlike amorphous silicon pixel structures, current limitations in crystal growth methods have restricted the fabrication of these devices into larger arrays. A larger field of view can be accomplished with CCDs through a lens or a fiber optic transfer device to view a phosphor or scintillator screen. The downside of the lens approach is that it has very poor light collection efficiency, while fiber optic image plates have significantly improved light collection efficiency, but are expensive and are not amenable to large fields of view. For small field of view applications, the directly coupled charge coupled device approach will provide high spatial resolution and high light collection efficiency.

5.5.2 *CMOS read structures* are based on Complementary Metal-Oxide Semiconductors, which is a dominant semiconductor circuit for microprocessors, memories and application specific integrated circuits (ASICs). CMOS technology, leveraging the multi-billion dollar semiconductor industry enables low cost production of pixelized devices. Like CCDs, they are formed with crystalline silicon, but the read structure is individually addressed. Unlike CCDs, where charge is actually transferred across active pixel regions, CMOS technology has individually addressed pixels. CMOS image sensors draw less power than CCDs. However, they are known to produce more electronic noise than CCDs. Like CCDs, they can couple to various scintillators either directly, or by lens or fiber optics.

5.5.3 *Amorphous silicon read structures*—Larger amorphous silicon based thin film transistor pixelized read structures have been made commercially available as large flat panel devices. Figure 3 provides a schematic of an amorphous silicon DDA architecture. Amorphous silicon, through large area silicon deposition and processing/etching techniques offers a solution to the size constraints of CCDs and CMOS devices. Since the phosphor or photoconductor layer is typically deposited or coupled directly onto the silicon, efficient optical or electron transfer is easily obtained. However, the readout circuitry in these devices requires a large pixel space to accommodate the thin film transistor (TFT) and data lines and scan (gate) lines required for operation, thus limiting how small a pixel this device can permit. The amorphous silicon read structure is composed of over a million pixels that include photodiodes. The diode has a sensitivity that peaks in the middle of the visible spectrum where a number of good phosphors emit. The electric charges generated within every pixel of the photodiode are read by the active matrix of TFTs in place. The TFT matrix, which is essentially a matrix of switches, is scanned progressively. At the end of each data-line is a charge- integrating amplifier, which converts the charge packet to a voltage, followed by a programmable gain stage and an Analog-to-Digital Converter (ADC), which converts the voltage to a digital number that is transferred serially to a computer, where the data is formed into an N × M (N = number of columns and M = number of rows) pixel image.

5.5.4 *Choice of Read Structure*—For small field of view applications, the directly coupled CCD or CMOS approach will provide high spatial resolution and high light collection efficiency. As mentioned, these devices have pixel pitch, as fine as 10 microns. For large field of view applications, the amorphous silicon approach offers excellent collection efficiency (no lenses), in a thin, compact, robust package. However, pixel pitch is typically on the order of 100 microns or larger, although smaller pixel pitch structures are likely to appear in the near future.

6. DDA Properties

6.1 An important prerequisite for a good digital X-ray detector system is the capability of the system to control the interplay of all its components (the entire imaging chain) and reflect the capability of the system in the final image. The technology of image capture, the representation of images as digital data, their processing, enhancing of data for a specific image display, and the nature of the display technology, form a significant part of this capability. From an image interpretation standpoint, the quality of images from the detector is an important metric for the choice of the detector and system specifications. This section introduces the image quality parameters/metrics that form the basis for selection, and monitoring performance as delineated in Practices E2597, E2698, and E2737.

6.2 The dominant contributions to a digital radiographic image, and hence the final image quality, come from two sources: (*a*) the inherent property of a detector and (*b*) the radiographic technique itself. Some of the inherent properties of the detector which influence the image quality are, (*1*) signal and noise performance for a given dose, (*2*) basic spatial resolution, (*3*) normalized signal-to-noise ratio—SNR-normalized for spatial resolution, (*4*) detection efficiency, (*5*) detector lag (residual images, ghosting), (*6*) internal scatter radiation and (*7*) bad pixels. The other metrics such as (*8*) achievable contrast sensitivity, and (*9*) specific material thickness range are dependent on both, the DDA used as well as the object under test. Another strong factor is the radiation quality of the X-ray beam used for imaging.

6.2.1 A standardized methodology has been established for evaluating the inherent detector properties of DDAs as listed in 6.2 and may be found in Practice E2597. This practice provides procedures for evaluating and recording DDA properties by manufacturers or providers so that a potential purchaser may compare devices under standardized conditions and techniques in order to make an informed decision on the purchase. The ASTM standard suggests that providers of DDAs offer a spider diagram that summarizes the performance of a detector using a numerical grading scheme listed in the standard that highlights the strengths or weaknesses of a DDA. The purchaser can easily review those diagrams and decide what is most important for the application at hand.

6.2.2 Subections 6.3 to 6.19 provide additional details into these important detector properties, and how these impact overall performance of an inspection. Section 9 provides additional guidance into the selection of a DDA based on a review of the performance metrics taken together.

6.3 *Image Quality from a DDA*—The SNR of the DDA, using a specific radiation quality, and the relative contrast sensed by the radiation beam in the object together constitute an element of the image quality that relates to the contrast sensitivity of the DDA. The higher the SNR, the better, or lower the contrast sensitivity. A high signal to noise ratio improves contrast sensitivity as noise levels are suppressed in relation to signal differences. The SNR of a DDA system can be increased significantly by capturing multiple images with identical settings and integrating in a computer (frame averaging). The ability of the imaging chain to maintain the spatial information that originally impinged onto the primary detection medium is another critical element of the resulting image quality. This is typically referred to as the basic spatial resolution, SRb.

6.4 *Signal and Noise*—The signal recorded by a DDA is the response of the DDA to a given radiation dose. The noise is the variation of the signal read using the DDA for the same amount of dose. Signal and noise characteristics of the DDA depend on the radiation quality and the DDA structure. Radiation quality which is defined as the beam spectrum used, is directly related to the efficiency of the DDA that is related to the quantum efficiency of the scintillator. The higher the quantum efficiency of the scintillator, the higher the SNR will be. The DDA structure here refers to the type of scintillator used, type of signal conversion chain employed, and the associated electronics design. In an optimized DDA system where the DDA follows Poisson statistics, the noise is proportional to the square root of the signal level captured and thus the higher the efficiency of capturing and converting the radiation to a visible, or electronic signal at the DDA, the higher the performance of the DDA. For example with higher signal levels, the noise is reduced, and lower contrast, subtle features may be discerned in an image.

6.5 The transmitted X-ray beam signal propagates through various energy conversion stages of an imaging system, as discussed in 5.2. In Fig. 4, N_0 quanta are incident on a specified area of the detector surface (stage 0). A fraction of these, given by the absorption efficiency (quantum efficiency) of the material, interact (stage 1). Here it is important that the absorption efficiency is high, or a larger X-ray dose would be needed to arrive at a desired signal level. The mean number N_1 of quanta interacting with the scintillator represents the primary quantum sink of the detector. If we assume N_1 represents a measure of the signal, then the variance σ^2 is linearly proportional to N_1. Hence, the signal-to-noise ratio (SNR) is defined as $\sqrt{N_1}$. SNR therefore increases as the square root of the number of quanta interacting with the detector. Regardless of the value of the X-ray quantum efficiency, the maximum signal-to-noise ratio of the system will occur at this point ($SNR = \sqrt{N_1}$). If the signal-to-noise ratio of the imaging system is essentially determined there, the system is said to be X-ray quantum limited in performance. For example, performance will only improve if more X-rays are captured. The phosphor layer typically creates a large gain factor at this point. Following this, any subsequent inefficiency in emitting the light and capturing it by the photodiode will result in losses and additional sources of noise. If the number of quanta falls below the primary quantum sink, then a secondary quantum sink will be formed and becomes an additional important noise source.

6.6 For most detection systems discussed here, where the phosphor is in direct contact with the diode as in the flat panel detectors, the limiting source of noise is the quantum efficiency of the X-ray conversion material. Additional discussions on SNR of digital detectors are found elsewhere (**3**).

6.7 For direct conversion systems, the photoconductor is in direct contact with the read device, and with efficient charge transfer through the photoconductor into the read device, the limiting source of noise is the quantum efficiency of the X-ray conversion material.

6.8 Since noise is related to the square root of the number of X-ray quanta absorbed, it is crucial for efficient detection systems to have a sufficient signal level to avoid quantum mottling. Quantum mottling here refers to the variation in the signal level due to quantum noise. Quantum mottling makes detection of smaller contrast features more difficult. In medical imaging, regulations allow a certain maximum dose to the patient and optimal signal levels may not be obtainable. In this scenario, it is critical to absorb as many X-ray photons as possible, and then to transfer that energy efficiently, and not introduce secondary quantum sinks. On the other hand, in nondestructive testing, it may be possible to increase signal levels by selecting any or all of the following: (*a*) a longer

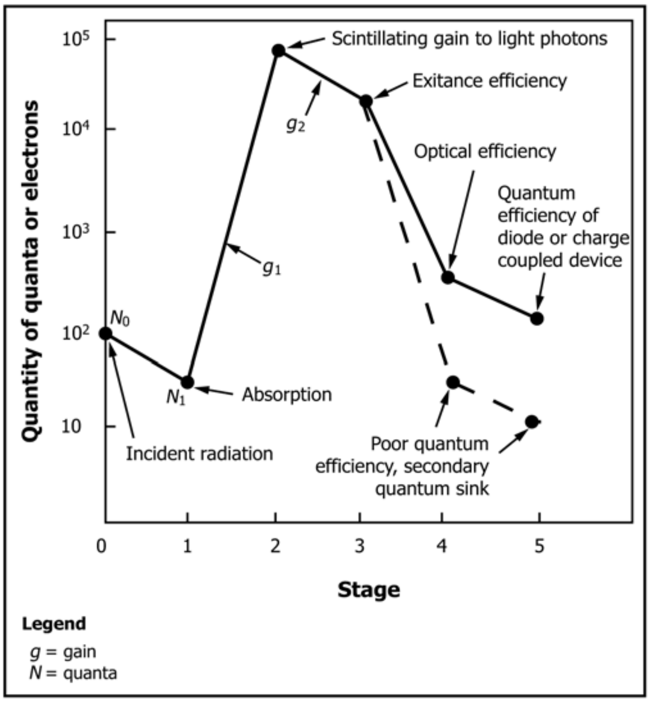


FIG. 4 Quantum Statistics of X-Ray Imager.

exposure time, (*b*) a combination of frames, either by integration or averaging, (*c*) a higher beam flux, (*d*) a higher radiation beam energy (assuming absorption is still high at those energies), (*e*) a closer working distance between source and detector, or (*f*) a different DDA with a more absorbing primary detection medium (phosphor or photoconductor). These techniques may provide improved image contrast due to higher SNR levels. Some of these techniques, however, may not meet other goals, such as throughput or allowable space needed for a specimen between the detectors and the X-ray tube. Certainly a thicker absorbing material (scintillator or photoconductor) may also impact the spatial resolution (see 6.12) possible from the DDA. Therefore, tradeoffs need to be made in selecting the appropriate DDA and technique to use for any given application.

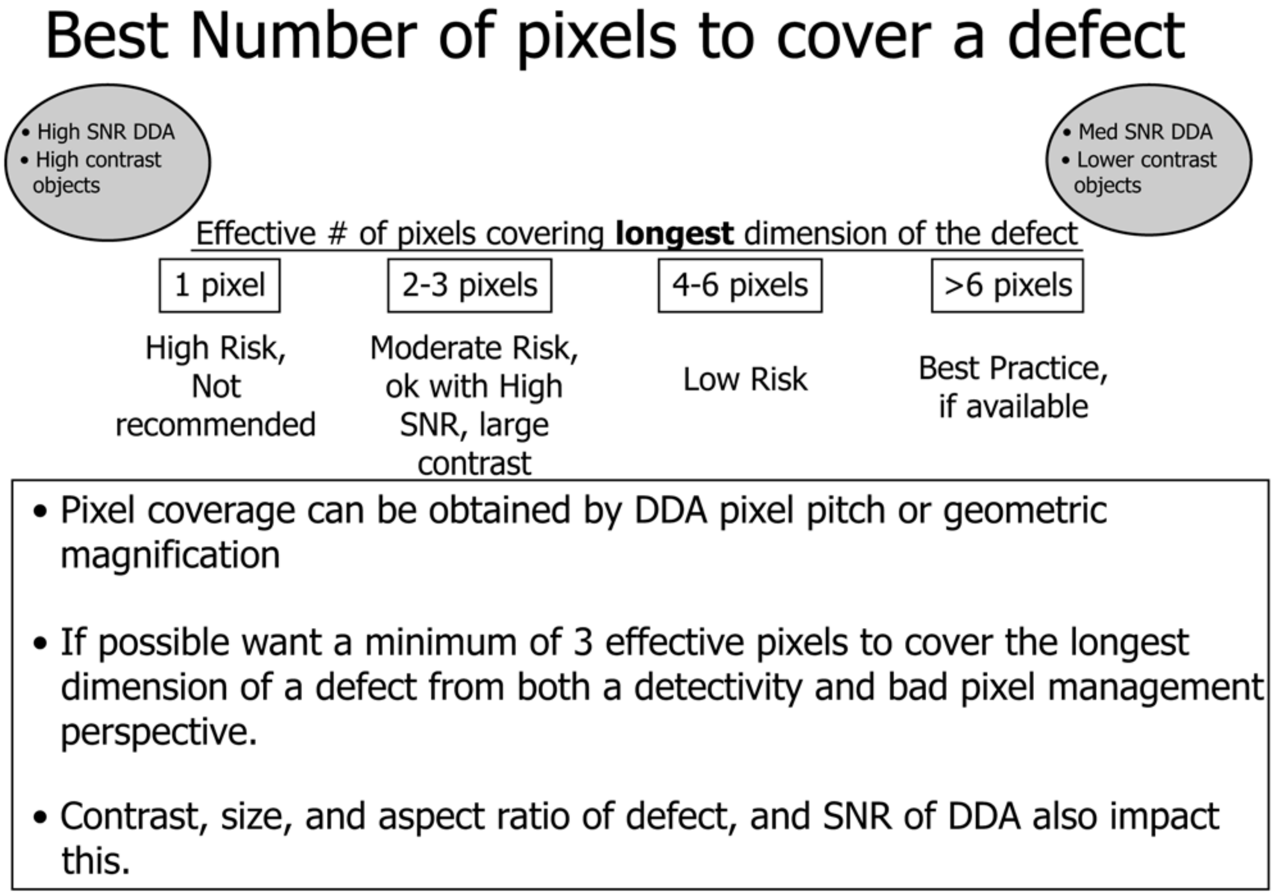
6.9 Outside of the quantum chain discussed above, additive noise from the device in the form of fixed patterns, or other noise sources, or from the digitization process, can degrade an image even from the most efficient image chain. For a full discussion on noise sources, see (**3**). Therefore the noise of the device, as well as the coupling scheme is important in selecting the DDA for the application at hand. Appropriate calibrations (see Section 7) to remove fixed patterns within the DDA will result in drastically improved noise performance.

6.10 In a DDA system the detectability of a feature is defined in terms of contrast-to-noise ratio (CNR). Contrast in a radiographic image is mainly driven by subject contrast (see Practice E2597). DDA contrast sensitivity as mentioned above is dependent on the SNR of the device, and this contrast acts as a threshold limit for detection of subject contrast. When the subject contrast is below the DDA contrast, not enough information will be available to create a signal level in the resulting image for visual perception. Hence, CNR is related to subject contrast and noise in the imaging system.

6.10.1 Subject contrast, here referred to relative subject contrast that depends on the material properties of the object being imaged and energy of radiation used. To resolve a small change in thickness of an object (low subject contrast) and to achieve a high CNR, a high SNR of the imaging system is required. Additionally, improved detection of subject contrast can be obtained by using an optimized X-ray energy beam spectrum that best separates features in the object.

6.11 *Spatial Resolution*—The spatial resolution of the detector determines the detectability of features in the image from a pixel sampling consideration. The selection of the spatial resolution of the DDA is also important in designing or selecting a detection system. From the aspect of image contrast and spatial resolution, it is desirable to have the largest pixel that will allow detection of the features of interest in the radiographic examination. For example, it is not necessary to select a 10-µm pixel pitch if the application is for the detection of large foreign objects in an engine nacelle. Similarly, aircraft fatigue crack probability of detection will be low with a pixel pitch of 200 µm or larger, unless low unsharpness magnification techniques are used. See Fig. 5 for a discussion on selection of a DDA based on the size of the anticipated smallest defect, subject contrast, SNR, and the DDA pixel size.

6.12 *Pixel Pitch*—The predominant factor that governs the spatial resolution of a detector is the pixel pitch. Pixel pitch represents the physical dimension of the pixels. Most DDAs have square type pixels. As the pixel pitch is reduced for increasing the resolution, the total number of pixels in the image increases for a constant field of view. The file sizes for typical images run from 2 to 8 megabytes or greater. Other



Best Number of pixels to cover a defect

- High SNR DDA
- High contrast objects

- Med SNR DDA
- Lower contrast objects

Effective # of pixels covering **longest** dimension of the defect

1 pixel	2-3 pixels	4-6 pixels	>6 pixels
High Risk, Not recommended	Moderate Risk, ok with High SNR, large contrast	Low Risk	Best Practice, if available

- Pixel coverage can be obtained by DDA pixel pitch or geometric magnification
- If possible want a minimum of 3 effective pixels to cover the longest dimension of a defect from both a detectivity and bad pixel management perspective.
- Contrast, size, and aspect ratio of defect, and SNR of DDA also impact this.

FIG. 5 Number of Effective Pixels to Cover a Defect Based on the Contrast of the Feature as Well as the SNR of the DDA. Single pixel coverage of the longest dimension of a defect is not recommended from the perspective of detection. It also may be confused for a bad pixel and missed.

factors that impact the spatial resolution of the image are (*1*) the geometric unsharpness of the inspection, (*2*) the thickness and properties of the scintillator or photoconductor material used to absorb X-rays, and (*3*) various sources of scatter that might degrade the modulation of features in an image. For a thick scintillator or photoconductive material, X-rays can scatter a greater distance depending on the X-ray energy employed and thus impact the spatial resolution. Optical spread can also occur in scintillation materials, especially thicker layers. In thick photoconductive materials, the bias levels to drive the carriers to the readout electrodes must also be high enough to avoid electron spreading that will degrade resolution. It is important to note, that the intrinsic spatial resolution of the DDA can never be higher than the pixel spacing. Magnification radiography is one means to compensate for the limitation in pixel pitch if the appropriate X-ray focal spot is available and can be used for the application at hand.

6.13 *Basic Spatial Resolution (SRb)*—The smallest geometrical detail, which can be resolved using the DDA. It is similar to the effective pixel size, and is typically expressed in µm. A means to measure the SRb is to use a duplex wire gage (see E2002), and measure the unsharpness, which in turn records the wire pair that can be seen in the image with 20 % contrast modulation. A contrast modulation of 20 % is usually assumed as a standard to determine if the the wire pair is visible. One half of the unsharpness value corresponds to the effective pixel size or the basic spatial resolution, as two pixels are typically required to resolve a wire (d) and its adjacent space (wire + space = 2d, the unsharpness). Figure 6 shows an example image of a duplex wire pair. The contrast modulation for the wire pair is the percentage dip in the signal. The SRb is calculated as the linear interpolation of the wire pair distances of the last wire pair with more than 20 % dip between the wires in the pair, and the first wire pair with less than 20 % dip between the wires (see Fig. 6). Where, D1 is the diameter of the smallest wire pair with >20 % resolution of the gap. D2 is the diameter of the largest wire pair with <20 % resolution of the gap. R1 and R2 is the modulation of the corresponding wire pair (dip %value) of D1 and D2 respectively.

6.14 *SNR and Pixel Size*—Among other factors, SNR is dependent on pixel area. A greater pixel area will typically result in higher SNR levels under identical exposure conditions. More specifically, assuming no other extraneous factors are dominant such as intra-scintillator or intra-photoconductor X-ray scatter that uniformly contaminates the signal without providing any spatial information, or a spatial frequency dependent fixed pattern noise, the SNR will increase by the square root of the pixel area if the X-ray conditions are held constant. A means to determine if these extraneous factors are present is to measure the SNR as a function of binning pixels.

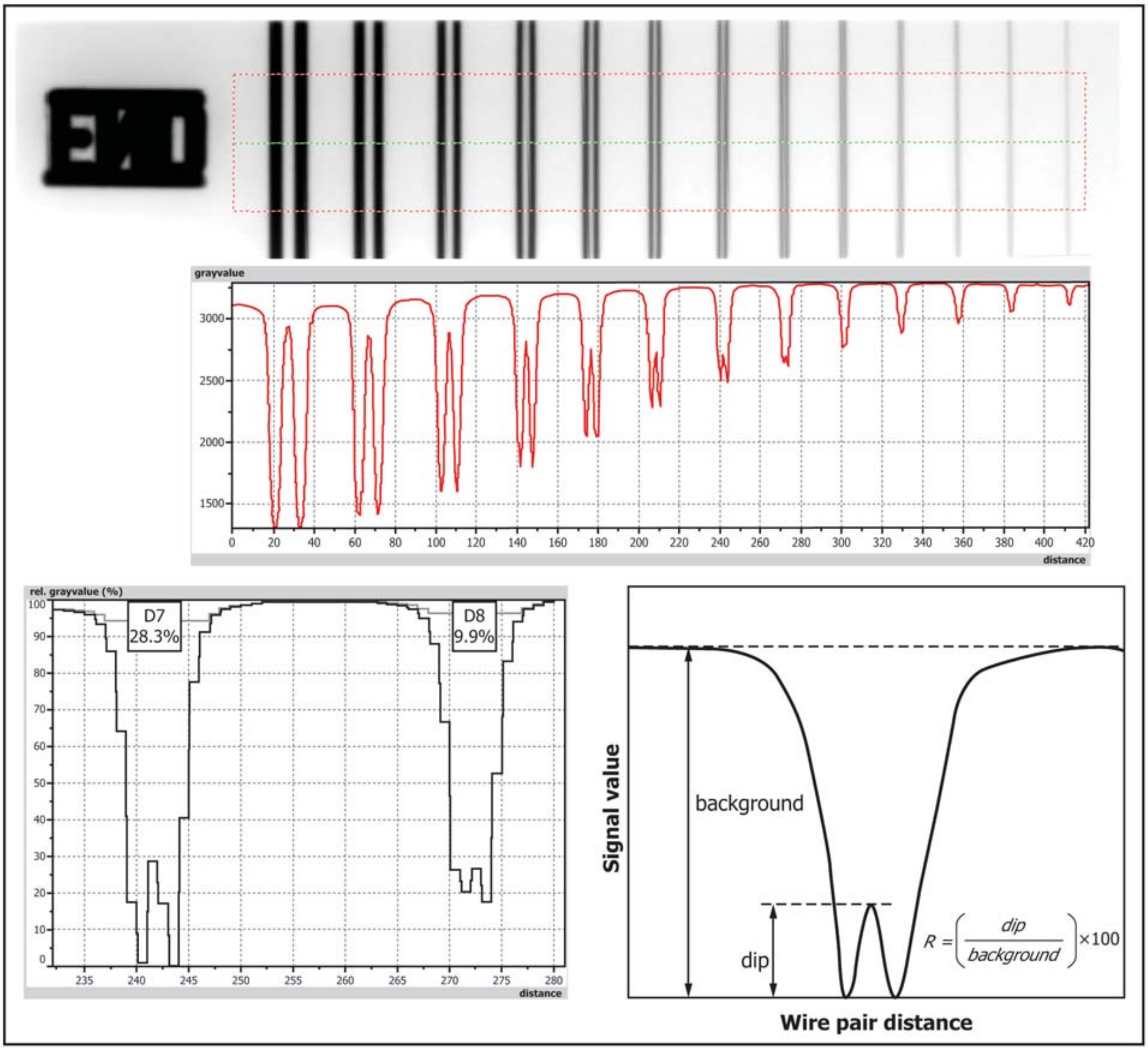


FIG. 6 Wire-pair Image Analysis for Calculation of Basic Spatial Resolution. Schematic of the measurement is shown at lower right.

If doubling the pixel size (quadruple the area) does not double the SNR (square root of the increased area), then some of these extraneous factors are present in the DDA.

6.15 *Normalized SNR*—To compare DDAs with different pixel architectures a first approximation can be made to normalize the SNR by the basic spatial resolution of the detector (SRb). Note: It is to be understood that this comparison might breakdown if the extraneous factors listed above are dominant (as the SNR and, or SRb values may be altered differently by those extraneous effects). For the normalization, 88.6 micron factor is used as the baseline value taken from the film normalization procedures in (see Test Method E1815). The circular aperture area for film densitometry is the same as the area of a digital square sampling box with 88.6 micron sides. Thus the DDA square pixel can be compared on a 1:1 basis to film. Hence the normalized SNR is computed as:

$$SNR_{norm} = SNR \times \left(\frac{88.6\,microns}{SRb}\right) \quad (1)$$

This same SNR_{norm} is also defined in the CR standards (see Practices E2445 and E2446), and is now in the DDA standards (Practices E2597 and E2698).

6.16 *Efficiency*—Efficiency of a DDA represents its speed to get to an SNR value. Typically this is expressed as a graph representing the dependency of SNR on incident dose to the DDA. A good measure of efficiency is the relationship between normalized SNR and the square root of dose incident on the DDA surface. This relationship should be linear. When the dose is set to 1 mGy, the normalized SNR at that point is the slope of the curve and represents an efficiency value for the beam quality employed. Figure 7 shows an example of efficiency of a DDA with various beam spectra. Each DDA has a peak efficiency, typically related to the thickness and absorptivity of the primary X-ray capture medium.

6.17 *Detector Lag*—Detector lag is a phenomenon where residual signal in the DDA is observed shortly after an exposure is completed and a "ghost" image is obtained. Lag in

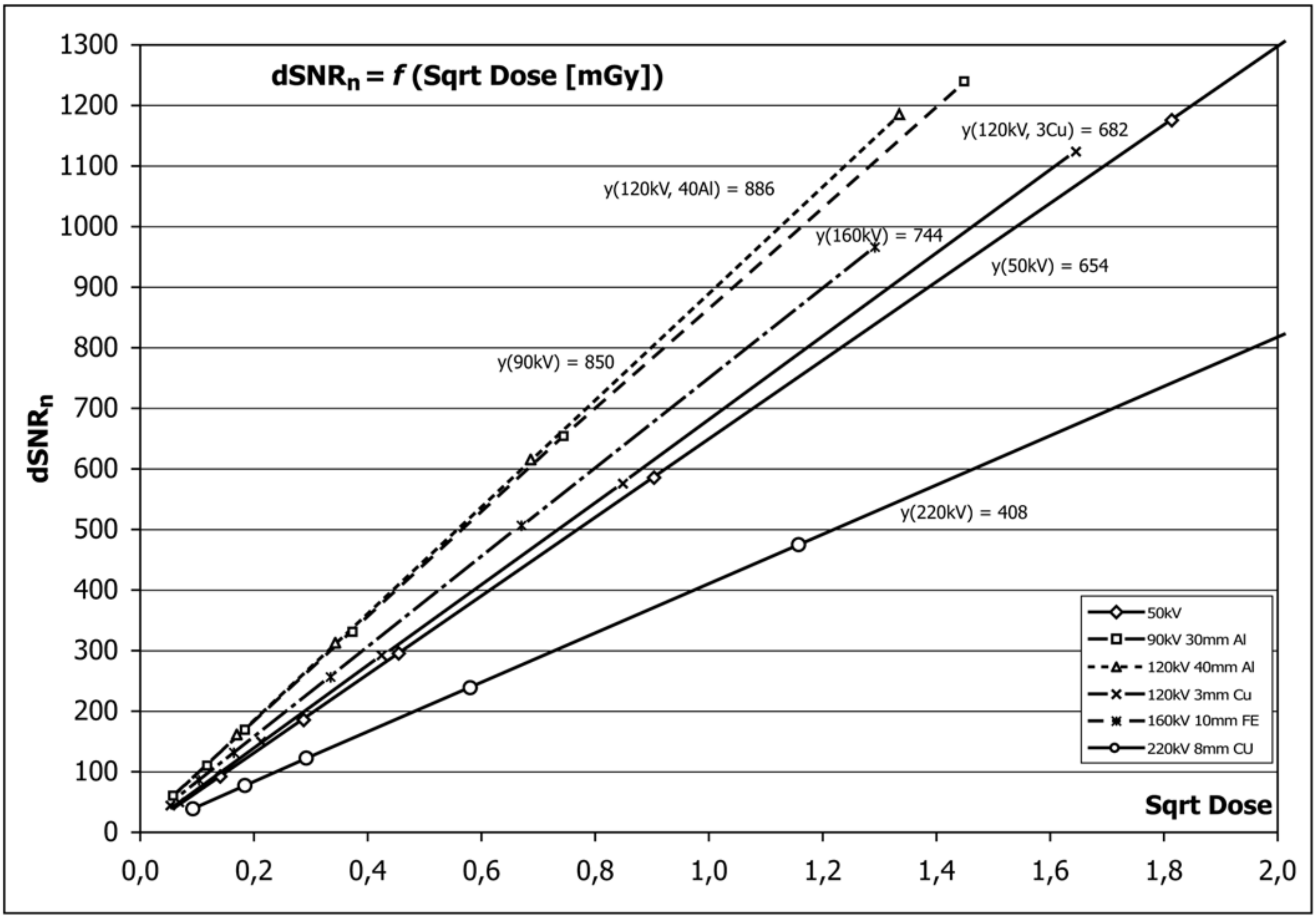


FIG. 7 Example Chart for Efficiency Test with Difference Images at Different Energy Levels

DDAs is an unwanted process and causes image artifacts on a frame-by-frame basis. Detector lag occurs either due to the hysteresis effect in the scintillator or due to the limited timescale involved in the electronic circuits. Detector lag is usually represented as a percent value of the signal retained after a certain time of exposure. To compare the lag of various DDAs, standard beam spectra have been defined and an initial exposure established in Practice E2597.

6.18 *Badpixel*—Any pixel of a DDA that has a performance outside the specification range is termed as a badpixel. Commercially available DDAs usually have bad pixels. A complete definition of the different types of bad pixels is found in the manufacturer qualification standard Practice E2597. Badpixels are also categorized as, isolated badpixels, cluster of badpixels or a line of badpixels. Clusters are further divided into relevant and irrelevant types (see Practice E2597). Clusters, which are not correctible, are those with a cluster kernel pixel, which are pixels that do not have five or more good neighborhood pixels. Note, for further discussion on bad pixels as well as a discussion for calibrating bad, see 7.2.

6.19 *Achievable contrast sensitivity (CSa) and Specific Material Thickness Range (SMTR)*—Optimum contrast sensitivity using a DDA that can be achieved using a phantom and with careful radiography procedures that reduces scattered radiation content in the image is referred to as achievable contrast sensitivity. This defines the best performance that can be expected of a DDA. Similarly the specific material thickness range defines the maximum latitude for a material that can be imaged with a fixed image quality under certain radiation beam quality. Both CSa and SMTR depend on the radiation dose and are functions of exposure time. Figure 8 shows an example plot for a DDA, for both CSa and SMTR. Typically a detector with a lower CSa is used for applications where the subject contrast between the defect and the body of the object is very small. For larger industrial components and with lot of variations in the object thickness a DDA with larger SMTR is preferred.

7. Calibration and Corrections

7.1 *Gain and Offset Correction:*

7.1.1 Images obtained from a DDA are referred to as raw images. This is the pixel response obtained as a result of the conversion of the X-ray energy to an electrical signal. These images require calibration (or correction) to create an ideal image. Calibration, which is an image correction procedure, forms an important step in image acquisition, since there are inherent pixel-to-pixel gain variations, and the presence of non-uniform background or offset signals. Additionally, if there are any non-linearities in the response of the DDA with respect

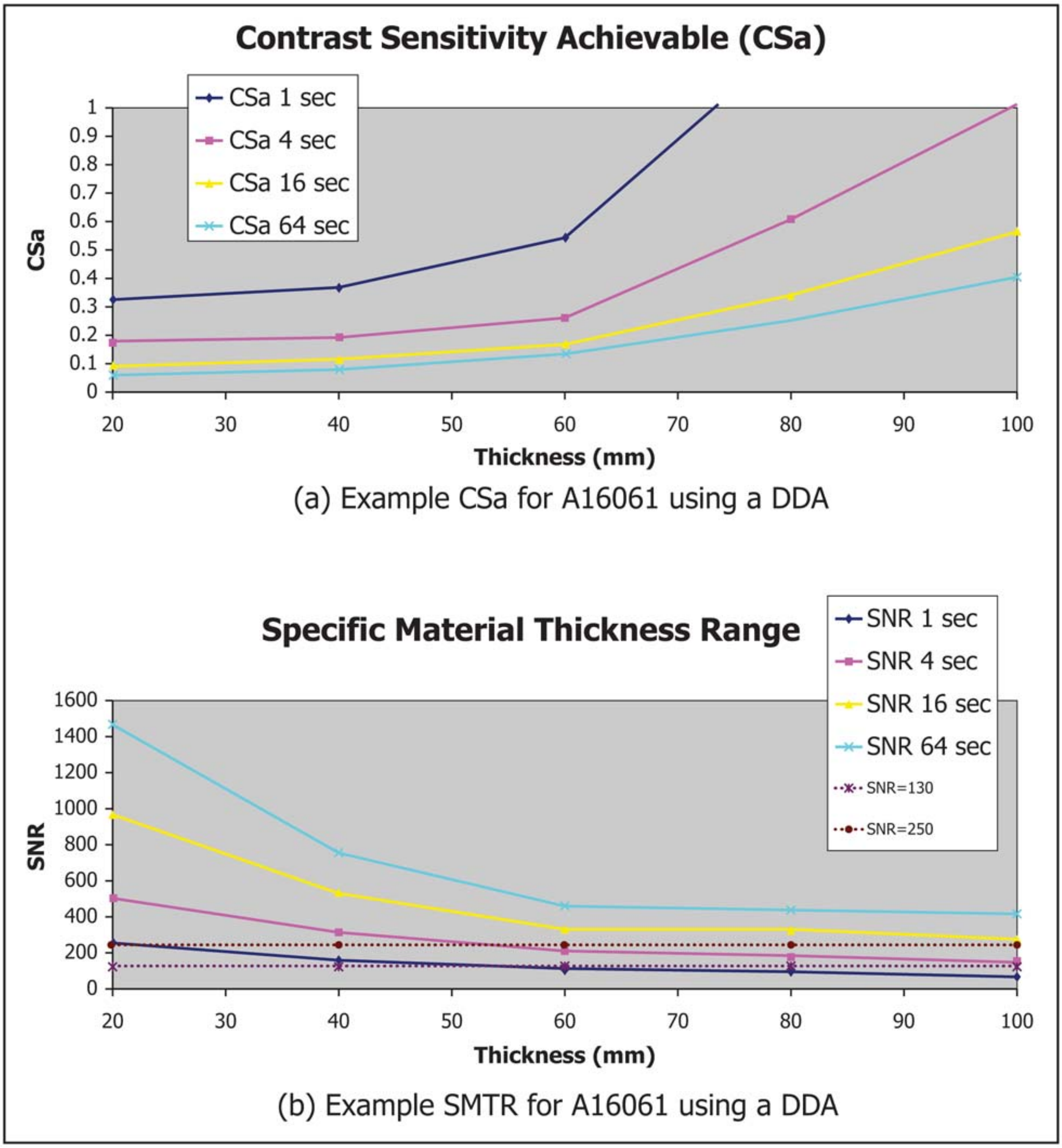


FIG. 8 Example Chart CSa and SMTR for a DDA Using Al6061.

to the X-ray dose, these need to be corrected. Lastly, unlike with film and CR systems, the non-uniformity of the X-ray beam may also be corrected to provide a lower noise image across the entire detector.

7.1.2 Different manufacturers recommend different calibrations to optimize the performance of the DDAs. These calibration procedures are usually designed to reduce the structural noise to a minimum possible value.

7.1.3 A very common implementation of a calibration is accomplished by taking an image with a radiation quality similar to that planned for production but without an object in the beam (an air image, also know as a gain image) and similarly taking an image in the absence of X-ray radiation (offset image, also known as a dark image). The offset image can be subtracted from both air image and the object image to create offset corrected images. Now, by simply performing an image division by the offset corrected air image of the offset corrected image of an object, a calibrated X-ray image of the object can be obtained. There can be more complicated gain corrections that the manufacturer can recommend to further reduce the structural noise from a DDA. Following gain and offset correction, detection sensitivity improves in relation to an image that does not have this correction. For the air image, it is critical that the image be free of transient latent images, have the correct intensity and also not contain an object of any sort (such as a fixture) in the beam. If any of these occur, then every subsequent corrected object image will contain artifacts and the correction will do more damage than good.

7.2 *Bad Pixel Calibration:*

7.2.1 Most DDAs have some bad pixels. Methods to identify bad pixels by the manufacturer are found in Practice E2597. Methods for identifying bad pixels at the user organization are found in E2698. Methods for managing the appearance of new bad pixels after the DDA is in service are found in E2737.

7.2.2 Single, and even some cluster bad pixels can have their pixel value restored (to approximate value) by interpolating that pixel value using the surrounding pixel values. A worst-case scenario is that where a true defect is overlaying a bad pixel, and its neighbors. Note, if a defect size is expected to be on the order of, or even smaller than a pixel, then that pixel pitch DDA shall not be used for that inspection unless geometric magnification techniques are used.

7.2.3 Since there is always some blur, on a pixel-by-pixel basis, any defect information in the bad pixel's area gets spilled over to neighboring pixels. This effectively makes a potential defect easier (larger) to see if a defect happens to be in that area. The use of interpolation on bad pixels does not impact the performance of neighboring good pixels; it simply restores an estimated pixel value for the bad pixel in question. Therefore the interpolation process will not hide a defect, but in fact, may accentuate a defect because it restores signal to that pixel that thereby restores that feature to a reasonable estimation of its true size.

7.2.4 Another scenario is that of a large, non-correctable cluster of bad pixels that might be the same size as the defect to be detected. Non-correctable pixels (Cluster Kernel Pixels, CKPs) are usually clustered pixels that do not have enough good neighboring pixels to fully restore information. Therefore, these clusters remain bad, and will likely remain either completely dark or completely white, depending on their nature during the service life of the DDA. This is a situation where a bad cluster might hide all or a part of a defect. The greater number of these in a DDA, the higher the risk of missing a defect due to an overlap of the cluster with a defect. The best way to manage this is for the user in coordination with the CEO, to select a DDA with a specified limited number of these bad clusters in the region of the detector that is used for interpretation. If there are a group of CKPs outside of the region where interpretation is done, then those CKPs might be acceptable in practice.

7.2.5 Alternatively, regarding CKPs, if the technique allows geometric magnification to reduce the effective size of these clusters so that they don't interfere with interpretation, this might allow the use of the DDA with CKPs. Performing this magnification compensation shall not alter other properties, such as geometric unsharpness that might deleteriously affect the inspection at hand.

7.2.6 In either scenario, it is important that the user be provided with a means to track the number and location of all bad pixels, including CKPs. This allows a ready reference to differentiate bad pixels from true defects.

7.2.7 The risk of false positives due to these uncorrectable clusters is usually low, as the user will have a record of where the bad pixels and CKPs are located. As stated above, the manufacturer of the DDA delivers a bad pixel map with every DDA, so it is easy to compare the map to the image to determine if the anomaly is a defect or a bad pixel or cluster. Lastly, if so arranged between the user and the manufacturer, the bad cluster can be marked as such, either by color, or otherwise. It should be noted, once an uncorrectable cluster is identified, that region and its surrounding two pixel-wide perimeter is not to be used for interpretation, unless magnification techniques are employed to effectively reduce the size of that cluster.

7.2.8 Single isolated pixels that are flagged as a bad pixel or even a cluster that is correctible, will not create false information in the radiograph after a bad pixel correction. As an example, Fig. 9 shows a simulated radiographic image of a 20-mm Fe plate, with several 0.2 mm (1 %) shims placed on it. There are holes in each of the shims of diameters 0.4, 0.8, 1.2, 1.6, 2.0, 2.2 and 2.4 mm. The pixel pitch used here is 0.2 mm. Bad pixels were randomly created using a computer program but with controlled numbers. Cluster formations were also allowed and embedded in the image. The radiograph was then modified using the randomly created bad pixel map and corrected using a bad pixel correction algorithm. Figure 9 also shows the modified image in a side-by-side fashion with the corrected image. As can be seen, the bad pixel corrected image looks very similar to the original image, and does not interfere with detection of the features in the image.

7.2.9 Since individual bad pixels and small correctable bad clusters do not impact interpretation, these pixels can be interpolated. Most manufacturers will provide this capability in the acquisition or analysis software, and it is by agreement between contracting parties, the CEO and user organization to use interpolation for the application at hand. As mentioned, most manufacturers will also provide a map of the bad pixels in a given DDA. The user organization can use this map as a reference to confirm that an anomaly is in fact a bad pixel. The same map can also be used to track the formation of new bad pixels, or the development of bad clusters, including uncorrectable clusters, (CKPs). If the organization chooses not to interpolate individual bad pixels and small clusters, this will not impact interpretation, as the DDA selected will have bad pixels that are much smaller than the defects that are to be identified if methods identified in Fig. 5 are employed.

7.2.10 Irrespective of whether interpolation is done, each bad-pixel is identified through the recommended tests in Practices E2597 and E2737, and flagged as a bad pixel that is recorded to a bad pixel map/image.

7.2.11 DDA manufacturers, with the aid of Practice E2597 are publishing bad pixel results for different models of DDAs. This is the average prevalence and range of the different types of bad pixels as listed in Practice E2597 for any given model. In most circumstances, an individual serial number from that model will fall within the range in prevalence of bad pixels (clusters and lines). An important aspect of managing bad pixels is to select the DDA considering these statistics, and in particular, the prevalence of CKPs. This is one of the factors

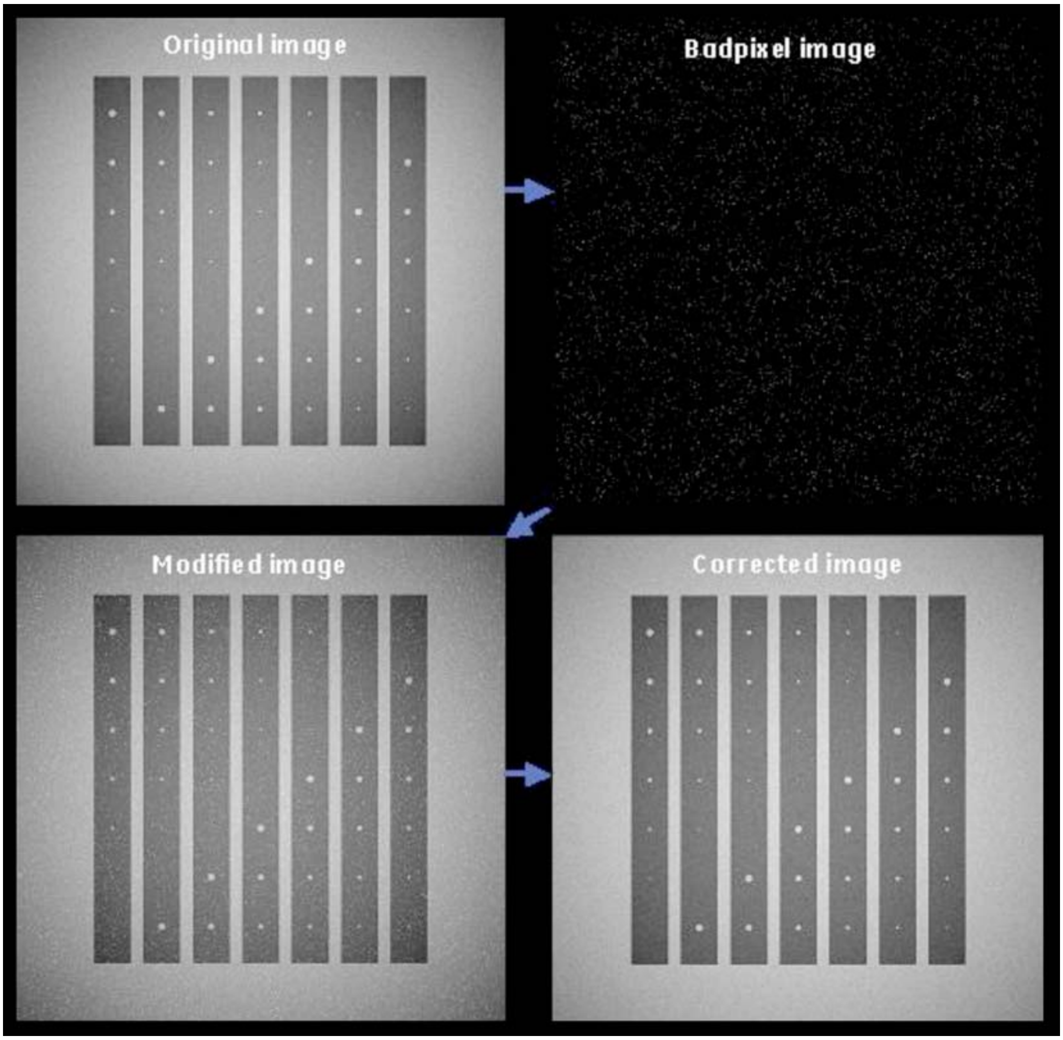


FIG. 9 An Example of Bad Pixel Corruption of Signal and Recovery Using a Correction. This example has 1 % of the DDA pixels as bad pixels.

among all of the detector properties that needs to be considered in the trade-off analysis of a DDA selection. So the selection of a make and model from a manufacturer must also include an evaluation of the bad pixel data of that model. As with selecting other properties, the CEO sets the defect requirements typically for the most stringent inspection. The technique developed by the user for a given size and shape of a defect leads to a desired spatial resolution and unsharpness that has a corresponding pixel pitch. The NDT engineer in the user organization must consider the aspect ratio of the defect. For example, is it a tight, small fatigue crack or small size porosity? Or is it an open crack, or some other larger feature such as corrosion? This then sets the bad pixel requirements in relation to the effective size of the defect for that aspect of the DDA selection. Figure 5 provides further discussion along these lines. A discussion on tradeoffs of DDA properties may be found in Section 9.

8. Radiation Damage

8.1 In digital imaging devices, there are numerous elements of the detector assembly that can be damaged by the ionizing radiation. Every component in the DDA can be damaged from X-rays or gamma rays. The term radiation damage is a general term that can refer to any range of damage to a component in the detection chain. The damage can lead to subtle changes in performance, all the way to failure. Most digital detectors are designed so that the electronic components behind the X-ray conversion material are either shielded from the X-rays (for example, by the conversion material itself or by fiber optic transfer components behind it), are sufficiently thin to absorb only a small portion of the X-rays that impinge on the component or the area behind the X-ray conversion field is free of electronic components. Otherwise the electronics will be damaged. The damage that occurs in the electronic circuitry can result in an increase in the electronic noise of the device, or structures in the image from local increased damage, and eventually lead to failure as the accumulated dose in the component increases. Each manufacturer uses proprietary circuitry and various forms of shielding elements to prevent these effects. Each system is different, so the reader is referred to a general text on radiation effects on silicon circuitry. To avoid radiation damage of the electronic components the complete detector should be shielded—outside the active area of the device. In some cases, if components are not shielded by the manufacturer, there may be further responsibility of the purchaser to provide additional shielding around the periphery of the device.

8.2 The X-ray conversion material, being the primary X-ray absorption component, is exposed to the highest levels of radiation within the imaging chain. Phosphors such as cesium iodide and photoconductive materials such as selenium have discontinuity centers within their band structures that will trap electron and hole carriers produced by the ionizing radiation. In many circumstances, thermally released carriers from these traps will yield a delayed luminescence or a delayed release of charge. This form of radiation damage known as afterglow or lag usually increases as a function of radiation dose until equilibrium occurs where the number of carriers being trapped equals the number being thermally released.

8.3 Another form of radiation damage to X-ray conversion materials that occurs is when the carriers are permanently trapped in deep centers within the band gap. This trapping is sometimes associated with a darkening of the conversion material and usually results in a rapid decrease in signal that can only be healed by thermal annealing of the material or by slow thermal release at room temperature. This form of damage results in a decrease of gain. In other materials, it is possible to observe a rapid signal gain increase as a function of increased radiation dose. Although the mechanism of gain decrease or increase is not widely understood, both gain changes can impart spatial artifacts into a current image created by the variation in radiation intensity across a prior specimen image. In most cases these gain changes are not long term or permanent. If the system is prone to these radiation induced gain changes, it is important to continually update gain and offset data, even if the actual examination is not changing, so that these artifacts can be reduced. If the problem becomes severe it might warrant a new or different phosphor, photoconductor or DDA.

8.4 Radiation damage shows different artifacts in the image. Amorphous silicon detectors tend to increase the offset value. In CMOS detectors the amount of bad pixel and bad lines is increasing. As discussed in Practice E2698, the CEO and using organization shall agree on the limits of radiation damage for the application at hand.

9. Guidelines for Selection of a DDA for Nondestructive Testing

9.1 A flowchart for selection of a DDA is shown in Fig. 10. Practice E2597 is a practice recommended for use by manufacturers and system integrators of a DDA system to provide DDA performance data in a common format using a set of guidelines as stated in the document. The intent of the document is to offer the end user a quantitative means to compare the intrinsic properties of DDAs from different vendors so that the DDA selection is best matched to the application. Subsequent testing including representative quality indicators and realistic test objects with defects similar to those to be found in practice, is then employed to confirm that the DDA is appropriate for the application at hand.

9.2 As mentioned in the DDA selection flowchart (see Fig. 10), the user needs to select the required specification for the

Step 1 Cognizant Engineering Officer (CEO), or End Customer, sometimes referred to as the “Prime” establishes detection requirements for the applications (parts or structures). This might be an extensive set of requirements from feature detection to reliability of the measurement.

Step 2. Using this guide and other resources, the DDA user organization interprets these requirements and devises a set of measurable metrics that the DDA must meet initially and throughout its service life. These metric can be the DDA parameters as described in E2597. The CEO and the user organization will also set limits and tolerances on these properties that will direct an out-of-service condition for the DDA.The CEO also establishes a schedule to check the performance of the DDA after it is entered into service.

Step 3. The DDA manufacturers, following E2597 publishes results obtained from the DDA models offered based on an average distribution of devices tested for each model.

Step 4. The DDA user organization then selects an appropriate DDA from a host of potential suppliers that best matches the CEO’s requirements. Consultation with the CEO might be warranted to confirm the selection. At this stage the purchaser might confirm with the manufacturer, with live testing, the appropriateness of the DDA to meet the need, using representative quality indicators under conditions close to what would be experienced in the factory or field environment.

Step 5. Once a DDA is selected, and purchase agreement is in place, the manufacturer will typically provide a data sheet that demonstrates that the delivered DDA falls within the manufacturer’s stated performance range for all properties listed, unless the user organization accepts a lesser value in one of the properties, as it is not critical to the success of the inspection.

Step 6. Upon receipt of the DDA, the user following techniques and methods in E2737 baselines the performance of the DDA that is then used to track long-term stability of the DDA throughout its service life. The same standard is used with the same techniques to track its performance.

Step 7. Once the DDA is brought into service, the user organization refers to E2698 to perform examinations relying on traditional ASTM IQIs to verify performance of the inspection, and with specific guidelines unique to DDA operation to assure high quality performance and display of the data. According to the pre-arranged schedule, the DDA’s performance is checked periodically using E2737 to assure it is within the pre-set ranges. Additionally, if at anytime, there are new artifacts that interfere with interpretation or there is an indication of reduced performance based on reduced IQI clarity, the DDA’s long term stability tests shall be performed. New calibrations and or bad pixel map shall be generated as required. If the device still falls out of the prescribed ranges, it shall be repaired, replaced or used for other applications where the artifacts or performance do not interfere with interpretation.

NOTE 1—CEO with already existing DDA may not go through steps 1-6 and can still follow step 7 for smooth operation of the DDA.

FIG. 10 Flow Chart for Selection and Operation of a DDA

inspection, some of these could be speed of inspection, flaw size specifications, range of thickness of the materials to be inspected etc. Once these parameters are established, the manufacturer reports generated using Practice E2597 will be handy to compare various detectors and select the one that will meet the need of the user.

9.3 The efficiency of the detector can be related directly to the efficiency test of the Practice E2597. A higher quality factor in the efficiency is desirable for fast operation. Practice E2597 recommends the efficiency test using Fe, Inconel 718 and Al-6061. So the user needs to select that standard that is close to the material that will be inspected using the DDA. The efficiency (normalized SNR, $dSNR_n$) represents the normalized SNR at 1 mGy of dose. Hence the user can compute the required time of exposure that is required with the X-ray source planned with the DDA to get a certain SNR. Ideally the relationship between the SNR_n and the square root of dose is linear and the reported efficiency is the slope of the line. The required exposure time, for a given X-ray tube at its peak power will determine the maximum speed of inspection. The targeted SNR is related to the image quality being sought.

9.4 Detectability of a feature using a certain X-ray source and DDA is related to the spatial resolution of the system (SR) and contrast sensitivity (relevant factors are SNR, CSa, SMTR, and CNR).

9.4.1 System resolution is derived from the focal spot size, the magnification and the DDA intrinsic resolution capability. The focal spot unsharpness discussion is given in E2698. DDA intrinsic resolution capability can be obtained using the basic spatial resolution measurement as described in Practice E2597. SRb data reported using Practice E2597 describes the smallest geometrical feature that can be seen using the DDA without magnification. The users need to consider the geometric magnification and the focal spot size to derive the overall system resolution for their application as discussed in E2698.

9.4.2 Required radiographic sensitivity can be obtained from the CSa data reported using Practice E2597 and is published by the manufacturers. CSa represents the optimum contrast sensitivity (as defined in Terminology E1316) using the standard phantom and an optimum technique and is dependent on the DDA SNR and CNR. In accordance with Practice E2597 the manufacturers report the CSa data for three materials (Fe [Inconel-718], Titanium [Ti-6Al-4V] and Aluminum [Al-6061]). Users need to refer to the available CSa data for the targeted material for inspection. Lower value of CSa represents better discriminating power of the DDA.

9.4.3 The required material thickness range over which a desirable image quality is required can be obtained from the SMTR data in accordance with Practice E2597. A rough estimation for 1 % and 2 % sensitivity Practice E2597 recommends a minimum of SNR of 250 and 130, respectively. Higher levels might be desired where possible. A wider range is typically needed for complex shaped parts, and a narrower range is needed for parts that are more monolithic in nature.

9.5 Similarly, the other factors that need to be considered are the typical number of bad pixels in the DDA and lag of the DDA. The end user needs to decide the inspection specification against the typical number of bad pixels (mainly the relevant clusters and the location of these clusters). The lag of the DDA limits the speed at which the DDA can be used without any noticeable artifacts in the image. Hence, lag of the DDA as recommended in Practice E2597 should be examined from the manufacturer report in conjunction with the speed at which the DDA is expected to operate.

9.6 Figure 11 represents a qualitative guideline for detectability of a feature with respect to contrast-to-noise (CNR)

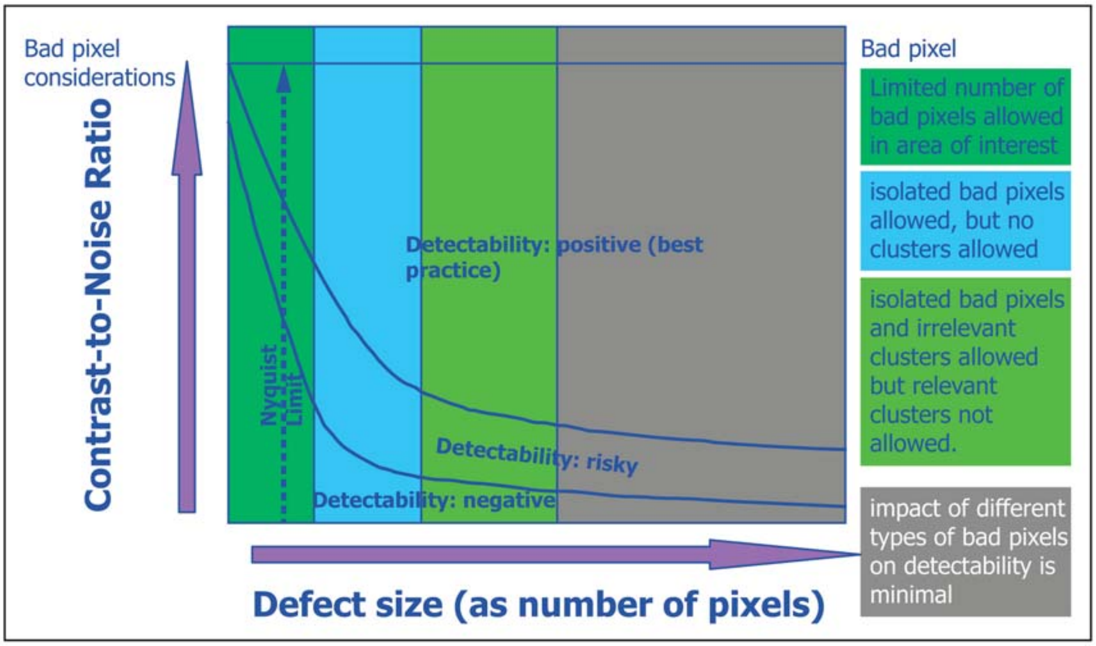


FIG. 11 A Qualitative Guideline for Deciding the CNR Required for a Defect Size and the Bad Pixels Management Rule.

ratio. Typically lower CNR is adequate for larger features while higher CNR is required for smaller features. Figure 11 indicates a feature size in terms of effective number of pixels on the DDA after geometric magnification. Typically reliable detection is always limited by the Nyquist frequency of the system (**4**). The numbers shown in the graph axis in Fig. 11 are approximate qualitative numbers based on experience. Similarly there are four areas marked in the figure, which have different bad-pixel requirements. When the required flaw size is of the order of 2-3 pixels then DDA area is required to have a relatively low number of bad pixels, or those bad pixels shall not interfere with the area of interpretation. The bad pixel criteria can be relaxed as the required flaw size to be detected increases. These are marked in Fig. 11. For sufficiently large size defects covering more than 15-20 pixels, most bad pixels, including clusters will have minimal impact on detectability of the feature.

10. Imaging Considerations for Detector, Technique, Display, and Storage and Retrieval

10.1 *Detector Considerations:*

10.1.1 Final selection of a DDA requires testing under realistic conditions to assure the DDA will perform adequately for the most stringent inspection scenarios. The measurements listed above provide a means for comparing devices initially to determine if that device is appropriate for the application. There is considerable flexibility in settings selections for each DDA, as well as techniques used to generate imagery with these devices. The purchaser is encouraged to test devices using different settings, and x-ray techniques to determine performance/cost/technique tradeoffs prior to making a final decision. This is typically achieved by using real test objects or representative quality indicators (RQIs), Practice E1817. Numerous adjustments to the following parameters may result in enhancements to performance, and one DDA may prove to be fully acceptable, even though its properties appear to be lesser than another detector upon initial review of the Practice E2597 characteristics. That standard, and the resulting data that is being made available from suppliers is only a first step in narrowing down a selection. Some of the parameters or settings that may be varied are discussed below.

10.1.2 *Enhancements to image quality*—As mentioned in discussions above, two of the main characteristics that describe the image quality are CNR (and SNR), and spatial resolution of a specific inspection. Other characteristics tested such as a specific material thickness range, efficiency, and image lag can impact overall image quality, but might also affect productivity, as multiple images might be needed to compensate for deficiencies in these properties. For example, a limited specific material thickness range simply indicates that multiple exposures at different settings would be needed to cover the part's thickness range in relation to a detector that has a wide thickness range. Similarly, for a detector that has a poor efficiency, more frames of averaging might be needed to achieve a desired result, although comparable image quality may not be achieved when compared to a DDA with improved efficiency. For image lag, if lag is observed in one frame, it must be "removed" prior to achieving a successful exposure in a subsequent frame, again resulting in a reduced productivity. The following discussion will focus on potential enhancements to SNR and spatial resolution of a given DDA that will improve the image quality in a final image, but may also impact productivity. Subsection 10.2 provides additional options for technique enhancement to image quality.

10.1.2.1 *SNR enhancement (Gain/offset/bad pixel calibrations)*—. DDA SNR performance can be improved with proper calibration. Manufacturers of DDA systems can guide users here. Section 7 provides some additional guidance for calibration processes.

10.1.2.2 *SNR enhancement (Higher absorbed dose in a single frame)*—The SNR in DDAs is related to the detected signal of the X-ray pattern transmitted through the object. As the detected signal increases, the noise in the signal improves by the square root of the signal in accordance with Poisson statistics. The variance, the square of the noise, in most DDAs is linear with signal up to the DDA's saturation level, on the high side, and to its noise floor on the low side. As discussed in Section 6, one way to improve SNR is to initially select a DDA that has a high efficiency.

10.1.2.3 *SNR enhancement (Pixel averaging)*—SNR may be enhanced by averaging pixels into larger "super" pixels. This is typically referred to as binning. Since the pixel-to-pixel variation goes down with averaging, the SNR is improved. Again, without other extenuating circumstances that might influence the benefit of averaging, such as low frequency smear from the phosphor or photoconductor, averaging pixels should result in nearly a square root benefit in SNR with the number of pixels binned. For example, a 2 by 2 pixel binning (four pixels averaged) should approach an SNR improvement of nearly a factor of 2. Of course, this may reduce the basic spatial resolution by a factor up to 2.

10.1.2.4 *Spatial Resolution Enhancement*—Lens coupled CCD systems. Most DDAs do not have an adjustment to their intrinsic spatial resolution. Certain lens coupled CCD systems viewing X-ray phosphors might employ a zoom lens where the spatial resolution may be adjusted. This of course reduces the field of view of the scene.

10.2 *Technique Considerations*—Practice E2698, a related ASTM standard, establishes the basic parameters for the application and control of the digital radiologic method. This practice is written so it can be specified on the engineering drawing, specification, or contract. It requires a detailed procedure delineating the technique or procedure requirements and shall be approved by the cognizant engineering officer. Figure 2 of that standard provides a flow chart on achieving an optimized technique to establish required detection of the image quality indicator (IQI). The following sections provide guidance for enhancement of the elements in that flowchart—SNR (CNR) and Spatial Resolution.

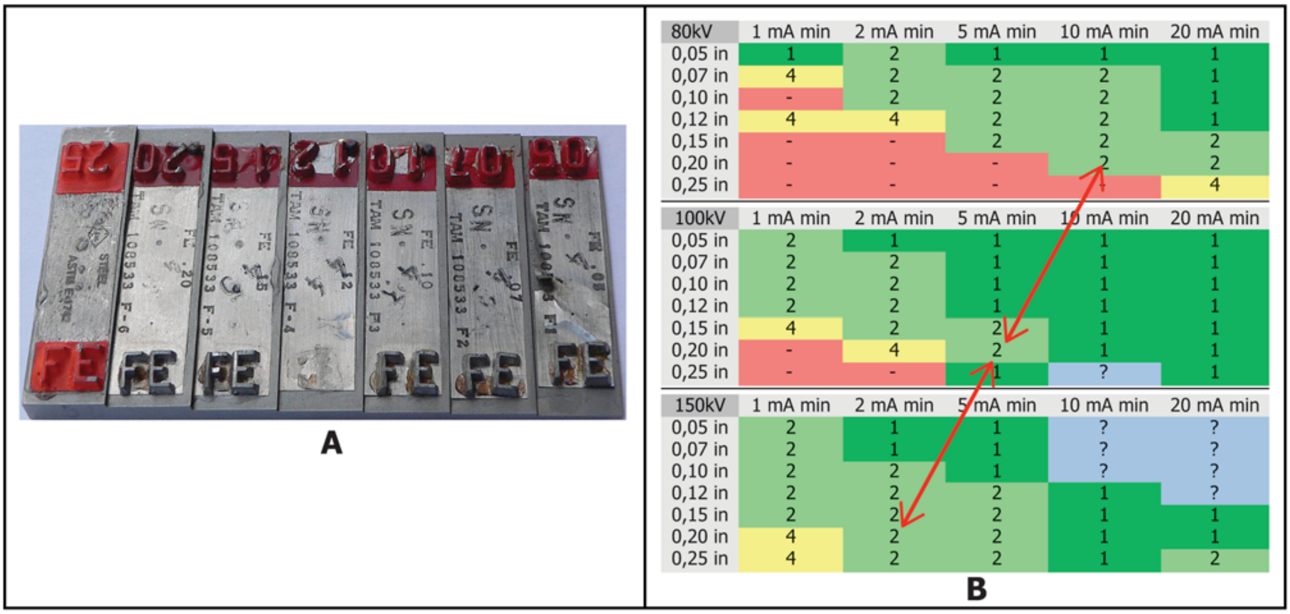
10.2.1 *SNR Enhancement*—Technique improvements to improve SNR include: (*1*) the use of longer exposure times (longer frame times, or a greater number of frames to average) acquired by the DDA; (*2*) the use of a higher beam current; (*3*) a shorter source to detector distance, or (*4*) a higher X-ray energy. It should be noted that with (*3*), the shorter distance might impact geometric unsharpness (discussed below), and with (*4*) the higher energy might adversely impact feature contrast (discussed below).

10.2.1.1 *SNR Enhancement (increasing beam current)*—The simplest method to improve SNR is to increase the beam current. This in turn results in higher signals within the DDA. The SNR improves by the square root of the increased signal, and therefore increases by the square root of the increased beam current. For example an increase in the beam current by 2× increases the SNR within the DDA by 1.4 assuming the higher signal level falls within the linear range of performance of a gain/offset corrected DDA.

10.2.1.2 *SNR Enhancement (longer exposure time and/or frame averaging)*—The SNR can be further enhanced by either extending the exposure time of the DDA, and/or averaging subsequent frames in those static inspections that do not involve motion. Either of these will improve the SNR by the square root of the total time data is collected when other noise factors such as detector artifacts, or internal detector scatter radiation are under control. Frame averaging is typically a useful technique, as some DDAs might be limited in useful linear range, or be restricted in the adjustment of exposure times. If total exposure periods become unacceptably too long, then other means to improve SNR might be best completed (see section below). If those other settings, or hardware do not provide the benefit, frame averaging might be a practical alternative, as well as pixel averaging (if some spatial resolution reduction may be tolerated) as discussed in 10.1.2.3.

10.2.1.3 *SNR enhancement (increased energy)*—If an initial X-ray energy that previously might have been ideal for other detection media such as film or computed radiography is used and a feature of interest is still not visible within the time frame allotted for the inspection, than a SNR compensation approach might be warranted. A means to further improve SNR, albeit, with some loss in detected contrast is to increase the X-ray energy. Here, the greater penetration through the object tends to reduce the subject contrast, but the SNR at the resulting DDA may be higher if the efficiency of the DDA is high enough to capture the higher X-ray energies. For example for a given total dose, if the DDA has a poor efficiency at higher X-ray energies, this practice may not be effective. But if the material remains efficient at the higher energy, then the lower noise achieved through the higher signal (noise reduces by square root of the signal as discussed above), may improve overall feature recognition. This compensation effect is shown in Fig. 12. It should be noted, that where possible, signal enhancement by other approaches as listed above should be exhausted first before increasing energy, to avoid loss of contrast. In some circumstances, a combination of maximum mAs, shortest distance, along with an increase in energy beyond typical values, will result in an overall improvement in image quality, over a technique where the energy is held lower. This approach might be helpful in applications where high frame rates are employed, or where very fast frame times are required for throughput purposes.

10.2.2 *Spatial Resolution Enhancement*—Geometric Magnification. Setting the spatial resolution of the inspection is highly dependent on the indication of interest. Figure 5 provides guidance on how many pixels should cover a defect and is related to the contrast of the object, the CNR of the inspection, and the size of the defect. The choice to use geometric magnification is dependent on the resulting geometric unsharpness that might result from a focal spot that is too large to accommodate the geometry. It should be noted that in many situations, a defect can be detected that might even be fully encapsulated in a single pixel. This is because there is a change in signal for at least that pixel, and possibly in neighboring pixels, as there is always signal spread to neighboring pixels. This is not recommended, as it represents the



80kV	1 mA min	2 mA min	5 mA min	10 mA min	20 mA min
0,05 in	1	2	1	1	1
0,07 in	4	2	2	2	1
0,10 in	-	2	2	2	1
0,12 in	4	4	2	2	1
0,15 in	-	-	2	2	2
0,20 in	-	-	-	2	2
0,25 in	-	-	-	-	4

100kV	1 mA min	2 mA min	5 mA min	10 mA min	20 mA min
0,05 in	2	1	1	1	1
0,07 in	2	2	1	1	1
0,10 in	2	2	1	1	1
0,12 in	2	2	1	1	1
0,15 in	4	2	2	1	1
0,20 in	-	4	2	1	1
0,25 in	-	-	1	?	1

150kV	1 mA min	2 mA min	5 mA min	10 mA min	20 mA min
0,05 in	2	1	1	?	?
0,07 in	2	1	1	?	?
0,10 in	2	2	1	?	?
0,12 in	2	2	2	1	?
0,15 in	2	2	2	1	1
0,20 in	4	2	2	1	1
0,25 in	4	2	2	1	2

FIG. 12 Fig. 12a. Step Wedge of Steel with Practice E1025 IQIs for Determination of Image Quality Fig. 12b: Achieved IQI Quality (Smallest Visible Hole Of 2 % IQI. It means: 1: 1T hole, 2: 2T hole, 4: 4T hole) as function of kV, mA min and wall thickness in inch for test object in accordance to fig. 3a.

lowest probability of detection. Additionally, analysis on the type of defect it is might prove impossible, for example the type of shrink it might be. Furthermore, bad pixels might appear to be defects, or more importantly, a defect might be mistaken for a bad pixel resulting in a missed interpretation.

10.2.2.1 Geometric magnification selection. It is important, at least in one dimension to have several pixels covering a defect. One way to achieve this is to optimize the geometric magnification of the inspection. A methodology that is set in Practice E2698 provides guidance for setting the geometric magnification. Geometric magnification shall be considered in the final purchase selection of the DDA, and prior to setting the technique using the DDA in practice. It is to be understood that when geometric magnification techniques are employed, detection and bad pixel management improves, but the object coverage is reduced, which might impact productivity. Similarly, if microfocus X-ray beams are employed to achieve the desired magnification, this will also impact inspection productivity given their very low beam currents. This would then increase exposure times to achieve an acceptable result.

10.2.2.2 *Effective Pixel Size to Select—Detectability Perspective*—From a detectability perspective, having a larger number of pixels covering a defect at least in one dimension will result in improved performance as pixel averaging either by a human interpreter or by the computer will again enhance statistics for that detection. As the number of pixels covered is decreased, higher contrast to noise (change of signal across the defect/noise in the image) of the feature is needed to see the feature. Either the signal difference has to be greater; the noise must be lower, or both. If a signal contrast is very low, then the noise in the image must also be low; otherwise the differentiation is lost in that noise. This might also be true for features that are covered by larger pixel segments, but increased pixel coverage will result in improved detection capability over smaller pixel coverage, if the feature can be detected at all.

10.2.2.3 *Effective Pixel Size to Select—Bad Pixel Management Perspective*—From a bad pixel management perspective, having a large number of pixels covering a defect, in at least one dimension reduces the probability that a single bad pixel (most prevalent type) will influence the interpretation of that defect.

10.2.3 *SNR Compensation for Marginal Spatial Resolution*—There have been studies that have shown that in many cases DDA performance is better than film, even for defects that are very small, where film methods would be expected to outperform the larger pixel DDAs . This is because DDA CNR levels can be much higher than film levels. This is due to their higher detection efficiency, and high fidelity calibration to remove structure noise. Figure 13 shows a comparison of a film image with a DDA image. Here, the higher CNR compensates for the lower spatial resolution, since even where the defect is smaller than a pixel dimension, there is some change in signal in that pixel, and the higher SNR (CNR) of the DDA can sense that difference. Figure 14 provides an example of this performance enhancement where experienced interpreters were shown both film and DDA imagery, and they performed significantly better with interpreting the DDA imagery.

10.2.3.1 As stated above, a technique, or detector design should not be selected where the defects are expected to be roughly the size of a pixel in all dimensions. With a sufficient CNR it may be possible to detect these defects. With sufficient CNR the defects must have (*1*) high contrast (where the defect is likely a large percentage of the base material, and an optimal X-ray energy is used for differentiation), or (*2*) the SNR of the inspection must be high enough so that the noise in the image

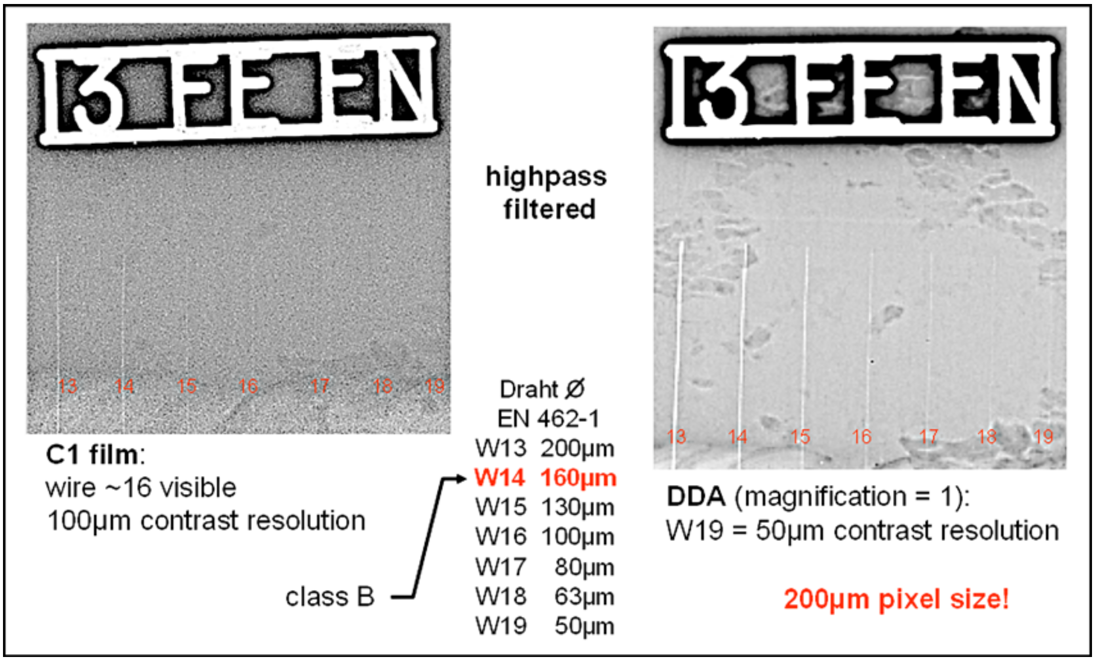
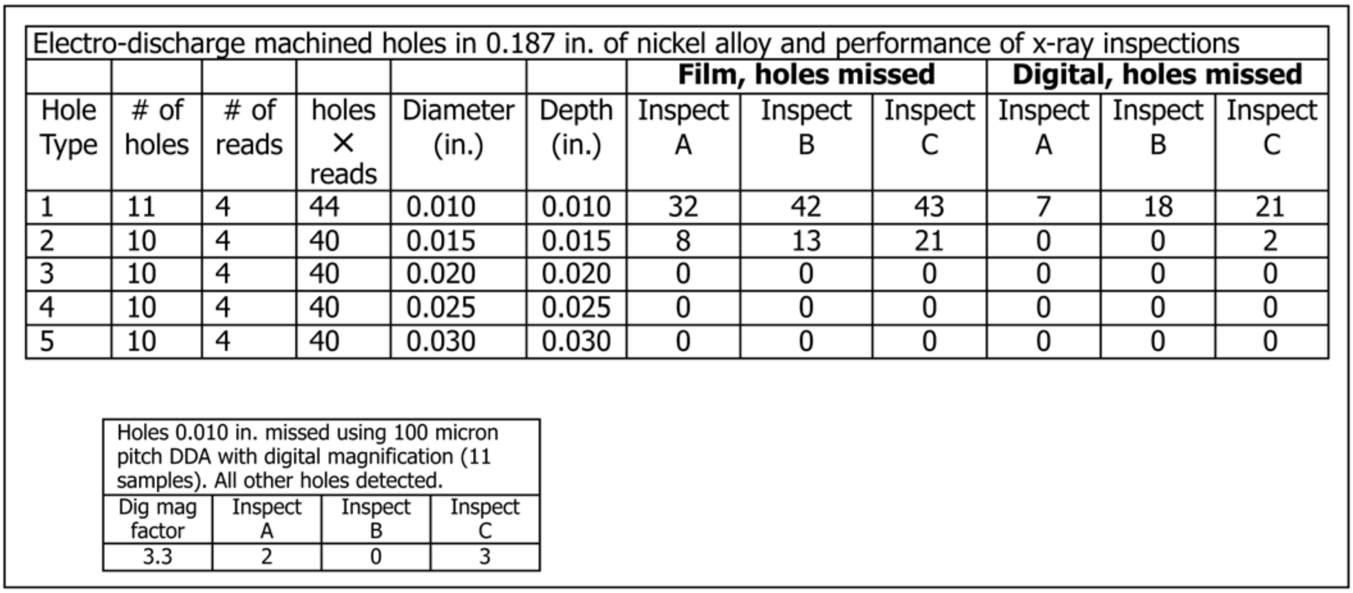


FIG. 13 Comparison of Visibility of Wire Type IQIs According to En 462-1 for Film (left) and DDA (right) at 8mm Wall Thickness (Images High Pass Filtered for Better Visualization). The improved SNR of the DDA detects wire W19 (50 µm diameter) at a detector pixel size of 200µm without using a magnification technique



Electro-discharge machined holes in 0.187 in. of nickel alloy and performance of x-ray inspections

						Film, holes missed			Digital, holes missed		
Hole Type	# of holes	# of reads	holes × reads	Diameter (in.)	Depth (in.)	Inspect A	Inspect B	Inspect C	Inspect A	Inspect B	Inspect C
1	11	4	44	0.010	0.010	32	42	43	7	18	21
2	10	4	40	0.015	0.015	8	13	21	0	0	2
3	10	4	40	0.020	0.020	0	0	0	0	0	0
4	10	4	40	0.025	0.025	0	0	0	0	0	0
5	10	4	40	0.030	0.030	0	0	0	0	0	0

Holes 0.010 in. missed using 100 micron pitch DDA with digital magnification (11 samples). All other holes detected.

Dig mag factor	Inspect A	Inspect B	Inspect C
3.3	2	0	3

FIG. 14 Performance of Three Experienced Interpreters Using Film (D4) and a DDA, 100 micron pixel pitch, indicating that the interpreters performed better reviewing an image from a DDA than with film, even though film has higher spatial resolution, and is the current method of production radiography. The digital magnification at the monitor was initially set at 1.7 for the digital image, vs normal read magnification of 1 for film. When the digital monitor resolution was increased to 3.3, the result improved immensely, indicating that this may be a consideration in this improvement. Note that the DDA performed significantly better for the smallest holes, 0.010-in and 0.015-in.

is low with respect to the contrast of the features. If the contrast of the defects is in the range of the noise level, there is a high probability that the defect will be missed. If bad pixels, and clusters are prevalent, these will compete with the defect size and may lead to false positive results, or missed defects mistaken for a bad pixel or bad cluster. The effective pixel size of the DDA must be expanded, either through the use of a different DDA with a finer pixel pitch, one with a lower prevalence of bad pixels for the same pixel size, or through the use of geometric magnification techniques as discussed in 10.2.2.

10.2.4 SNR compensation for bad pixel corrections. Bad pixel corrections are usually addressed by using neighborhood interpolation provided no cluster kernel pixels are present as defined in Practice E2597. Usually interpolation for bad pixels results in reduction of contrast. Hence higher SNR techniques can help in overcoming this loss in contrast.

10.3 Summary of factors that influence image quality. Figure 15 provides a table of those important factors that influence the signal (S), the noise (N), and therefore SNR, as well as the contrast (S1-S2), and the spatial resolution (SR). The table is split into DDA factors and technique/X-ray source factors that respectively influence these properties. Note that X-ray beam current influences signal, and thereby SNR, while X-ray beam energy influences signal with respect to X-ray absorption efficiency at a given energy, and also impacts contrast, S1-S2, based on the beam energy used.

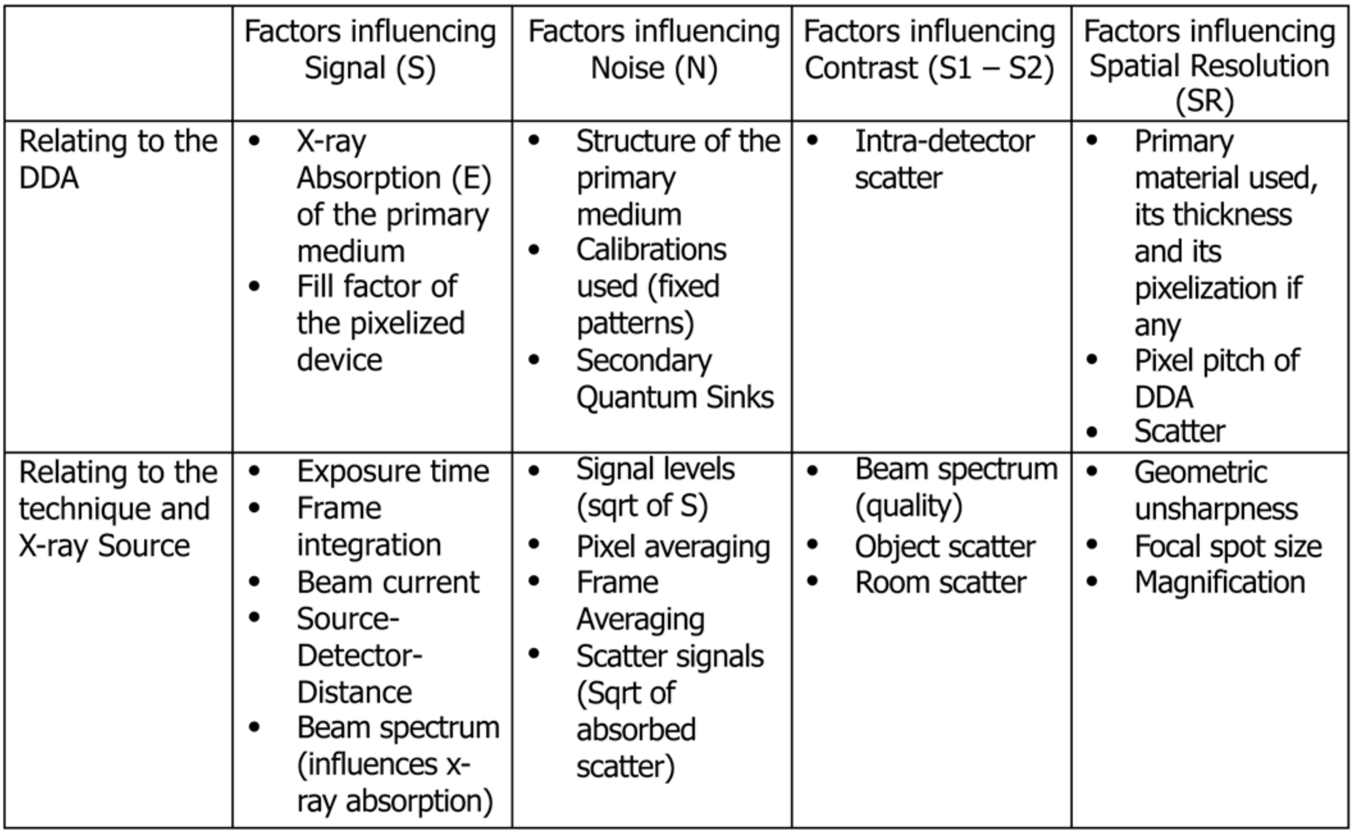
10.4 Monitor considerations. Hardware. Currently, most inspections that employ DDAs use human interpretation. In addition to assuring excellent image quality from the DDA, it is imperative that the monitor meet industry standards for performance and that its performance is monitored over time to identify any subtle degradation. The process for checking monitor performance may be found in section 7.5 of Practice E2698.

10.5 *Monitor Considerations—Viewing software*. Each DDA system is usually delivered with viewing software that has many common elements across DDA types, and might include window width and leveling operations, zoom and pan of static imagery, and other tools if the imagery is streaming. Some guidance is needed to assure that the imagery being presented is adjusted correctly to detect potential anomalous conditions.

10.5.1 Bit depth mismatch with the monitor. The DDA devices offered today have bit depths from 8-bits to 16-bits, and beyond. Monitor technology, be it CRT, LCD, or plasma cannot display much more than 10-bits, and typically display 8 bits of data. Therefore, the gray level of the DDA image has to be chosen, as does the window width to display.

10.5.2 Selecting the appropriate gray level and window width will depend on the thickness range that needs to be viewed in a single view, and the contrast level in the image. Typically, the level is set so that the area of interest is well within discernable gray levels, for example not saturated white or black. The window width must be set so that the desired penetrameter hole or wire is fully visible, while maintaining the interpretable gray levels of the area of interest.

10.5.3 If due to changes in thickness and or density of the part, the full area of coverage cannot be viewed using the same window width/level settings, then a second or third set of window width/level settings needs to be established to interpret that region of the object. For each window width/level setting the required sensitivity level must be visible on the appropriate penetrameter.



	Factors influencing Signal (S)	Factors influencing Noise (N)	Factors influencing Contrast (S1 – S2)	Factors influencing Spatial Resolution (SR)
Relating to the DDA	• X-ray Absorption (E) of the primary medium • Fill factor of the pixelized device	• Structure of the primary medium • Calibrations used (fixed patterns) • Secondary Quantum Sinks	• Intra-detector scatter	• Primary material used, its thickness and its pixelization if any • Pixel pitch of DDA • Scatter
Relating to the technique and X-ray Source	• Exposure time • Frame integration • Beam current • Source-Detector-Distance • Beam spectrum (influences x-ray absorption)	• Signal levels (sqrt of S) • Pixel averaging • Frame Averaging • Scatter signals (Sqrt of absorbed scatter)	• Beam spectrum (quality) • Object scatter • Room scatter	• Geometric unsharpness • Focal spot size • Magnification

FIG. 15 Factors that Influence Image Quality; Signal, Noise, Contrast and Spatial Resolution. Note that X-ray beam current influences signal, and thereby SNR, while X-ray beam energy influences signal with respect to X-ray absorption efficiency at a given energy, and also impacts contrast, S1-S2, based on the beam energy used.

10.5.4 Where possible, if there is a wide range of thickness to inspect, penetrameters should be used that are appropriate for the extremes of thickness under test. As discussed in Practice E2698, the quality levels shall be met for all areas to be interpreted.

10.5.5 The viewing software shall provide proper statistical tools for Signal, Noise and Contrast measurement and geometrical measurement functions for the spatial resolution to allow a qualification of the DDA system.

10.5.6 The viewing software shall provide functions to add comments to features in the image.

10.6 *Storage and Retrieval*—The complete bit depth and spatial information of the DDA imagery shall be maintained upon storage and retrieval. The image shall be stored in an unaltered form. Overlays and other annotation are possible, but these additions shall be removable to reveal the base DDA image with its full spatial resolution and bit depth either during initial review or upon retrieval after a period of storage. Filtered versions may also be saved under the parent image, but the original image must be stored unaltered, and easily accessible, even when filtered imagery might provide a better view of a particular defect. This assures that upon retrieval that the information originally acquired is maintained for the storage life of the data.

10.7 *Digital Reference Images*—Reference catalogues are widely used to train personnel for interpretation of radiographs and to provide a scale of severity of discontinuities in the inspected objects. Well known catalogues are Reference Radiographs E155 for light alloy castings, E192 for steel casting, and E1320 for titanium casting. These catalogues were digitized for use with digital technology such as CR and DR, and new standards were formed: Reference Radiographs E2422 (Aluminum), E2660 (Steel), and E2669 (Titanium). A special software tool was developed, that permits the transformation and presentation of the reference images from master copies of film to any digital detector and detector resolution. This transformation requires the input of the detector properties.

10.7.1 The reference images define different categories and severity levels of discontinuities for different material thicknesses in castings that may be revealed by examination. Before usage, the reference images have to be loaded and adjusted with an available software tool (a DVD associated with Reference Radiograph E2422 provides the software tool along with the digitized reference images) in relation to the pixel size and all magnification used resulting in several sets of images of each type. Negative and positive images are possible. The viewing software provides the reference image in a side-by-side manner with the production image on the same or a second monitor with similar brightness and contrast. The user can select material thickness and discontinuity type and shall compare the "intensity" of the flaw in the production image with the appropriate level of the reference image.

10.7.2 The viewing software shall be capable to perform the following tasks:

(1) Provide contrast normalization between the production image and the reference image such that the same difference in gray levels on the monitor show the same actual material thickness difference (for example, with a locked window width),

(2) Adjust the brightness of both images separately,

(3) Lock the zoom level between both images such that features are displayed with same size in both images,

(4) Display production image and reference image with one-to-one pixel mapping,

(5) Display the raw gray value and the monitor gray value at the current cursor position,

(6) Measure the distance between two locations in the images,

(7) Draw line profiles using the raw data and the monitor gray values,

(8) Do statistical evaluations including mean value and noise level (standard deviation / sigma)measurements,

(9) Provide image processing functions on both the production and reference image, such as filtering.

10.7.3 The digital reference images may be used to transfer an inspection application from film to digital using the same specification in discontinuity type and level.

11. Keywords

11.1 amorphous selenium; amorphous silicon; bad pixels; CMOS; contrast sensitivity; DDA; digital detector array; digital reference images; image lag; image processing; image quality indicator; image storage and retrieval; material thickness range; monitor; nondestructive testing; penetrating radiation; pixel; radiography; radiologic examination; scintillator; SNR; spatial resolution; X-ray

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