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Standard Guide for Computed Radiography[1]

This standard is issued under the fixed designation E2007; 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 guide provides general tutorial information regarding the fundamental and physical principles of computed radiography (CR), definitions and terminology required to understand the basic CR process. An introduction to some of the limitations that are typically encountered during the establishment of techniques and basic image processing methods are also provided. This guide does not provide specific techniques or acceptance criteria for specific end-user inspection applications. Information presented within this guide may be useful in conjunction with those standards of 1.2.

1.2 CR techniques for general inspection applications may be found in Practice E2033. Technical qualification attributes for CR systems may be found in Practice E2445. Criteria for classification of CR system technical performance levels may be found in Practice E2446. Reference Images Standards E2422, E2660, and E2669 contain digital reference acceptance illustrations.

1.3 The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are for information only.

1.4 *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
E746 Practice for Determining Relative Image Quality Response of Industrial Radiographic Imaging Systems
E747 Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology
E1025 Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiology
E1316 Terminology for Nondestructive Examinations
E1453 Guide for Storage of Magnetic Tape Media that Contains Analog or Digital Radioscopic Data
E2002 Practice for Determining Total Image Unsharpness and Basic Spatial Resolution in Radiography and Radioscopy
E2033 Practice for Computed Radiology (Photostimulable Luminescence Method)
E2339 Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)
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 Manufacturing Characterization of Computed Radiography Systems
E2660 Digital Reference Images for Investment Steel Castings for Aerospace Applications
E2669 Digital Reference Images for Titanium Castings

2.2 *SMPTE Standard:*

RP-133 Specifications for Medical Diagnostic Imaging Test Pattern for Television Monitors and Hard-Copy Recording Cameras[3]

3. Terminology

3.1 Unless otherwise provided within this guide, terminology is in accordance with Terminology E1316.

3.2 *Definitions:*

3.2.1 *aliasing*—artifacts that appear in an image when the spatial frequency of the input is higher than the output is capable of reproducing. This will often appear as jagged or stepped sections in a line or as moiré patterns.

3.2.2 *basic spatial resolution (SR_b)*—terminology used to describe the smallest degree of visible detail within a digital image that is considered 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] Available from Society of Motion Picture and Television Engineers (SMPTE), 3 Barker Ave, 5th Floor, White Plains, NY 10601.

3.2.2.1 *Discussion*—The concept of basic spatial resolution involves the ability to separate two distinctly different image features from being perceived as a single image feature. When two identical image features are determined minimally distinct, the single image feature is considered the effective pixel size. If the physical sizes of the two distinct features are known, for example, widths of two parallel lines or bars with an included space equal to one line or bar, then the effective pixel size is considered ½ of their sums. Example: A digital image is determined to resolve five line pairs per mm or a width of line equivalent to five distinct lines within a millimetre. The basic spatial resolution is determined as 1/ [2 × 5 LP/ mm] or 0.100 mm.

3.2.3 *binary/digital pixel data*—a matrix of binary (0's, 1's) values resultant from conversion of PSL from each latent pixel (on the IP) to proportional (within the bit depth scanned) electrical values. Binary digital data value is proportional to the radiation dose received by each pixel.

3.2.4 *bit depth*—the number "2" increased by the exponential power of the analogue-to-digital (A/D) converter resolution. Example *1*) In a 2-bit image, there are four (2^2) possible combinations for a pixel: 00, 01, 10 and 11. If "00" represents black and "11" represents white, then "01" equals dark gray and "10" equals light gray. The bit depth is two, but the number of gray scales shades that can be represented is 2^2 or 4. Example *2*): A 12-bit A/D converter would have 4096 (2^{12}) gray scales shades that can be represented.

3.2.5 *blooming or flare*—an undesirable condition exhibited by some image conversion devices brought about by exceeding the allowable input brightness for the device, causing the image to go into saturation, producing an image of degraded spatial resolution and gray scale rendition.

3.2.6 *computed radiographic system*—all hardware and software components necessary to produce a computed radiograph. Essential components of a CR system consisting of: an imaging plate, an imaging plate readout scanner, electronic image display, image storage and retrieval system and interactive support software.

3.2.7 *computed radiographic system class*—a group of computed radiographic systems characterized with a standard image quality rating. Practice E2446, Table 1, provides such a classification system.

3.2.8 *computed radiography*—a radiological nondestructive testing method that uses storage phosphor imaging plates (IP's), a PSL stimulating light source, PSL capturing optics, optical-to-electrical conversion devices, analogue-to-digital data conversion electronics, a computer and software capable of processing original digital image data and a means for electronically displaying or printing resultant image data.

3.2.9 *contrast and brightness*—an application of digital image processing used to "re-map" *displayed* gray scale levels of an *original* gray scale data matrix using different reference lookup tables.

3.2.9.1 *Discussion*—This mode of image processing is also known as "windowing" (contrast adjustment) and "leveling" (brightness adjustment) or simply "win-level" image processing.

3.2.10 *contrast-to-noise ratio (CNR)*—quotient of the digital image contrast (see 3.2.13) and the averaged standard deviation of the linear pixel values.

3.2.10.1 *Discussion*—CNR is a measure of image quality that is dependent upon both digital image contrast and signal-to-noise ratio (SNR) components. In addition to CNR, a digital radiograph must also possess adequate sharpness or basic spatial resolution to adequately detect desired features.

3.2.11 *digital driving level (DDL)*—terminology used to describe displayed pixel brightness of a digital image on a monitor resultant from digital mapping of various gray scale levels within specific look-up-table(s).

3.2.11.1 *Discussion*— DDL is also known as monitor pixel intensity value; thus, may not be the PV of the original digital image.

3.2.12 *digital dynamic range*—maximum material thickness latitude that renders acceptable levels of specified image quality performance within a specified pixel intensity value range.

3.2.12.1 *Discussion*—Digital dynamic range should not be confused with computer file bit depth.

3.2.13 *digital image contrast*—pixel value difference between any two areas of interest within a computed radiograph.

3.2.13.1 *Discussion*—digital contrast = **PV2 – PV1** where PV2 is the pixel value of area of interest "2" and PV1 is the pixel value of area of interest "1" on a computed radiograph. Visually displayed image contrast can be altered via digital re-mapping (see 3.2.11) or re-assignment of specific gray scale shades to image pixels.

3.2.14 *digital image noise*—imaging information within a computed radiograph that is not directly correlated with the degree of radiation attenuation by the object or feature being examined and/or insufficient radiation quanta absorbed within the detector IP.

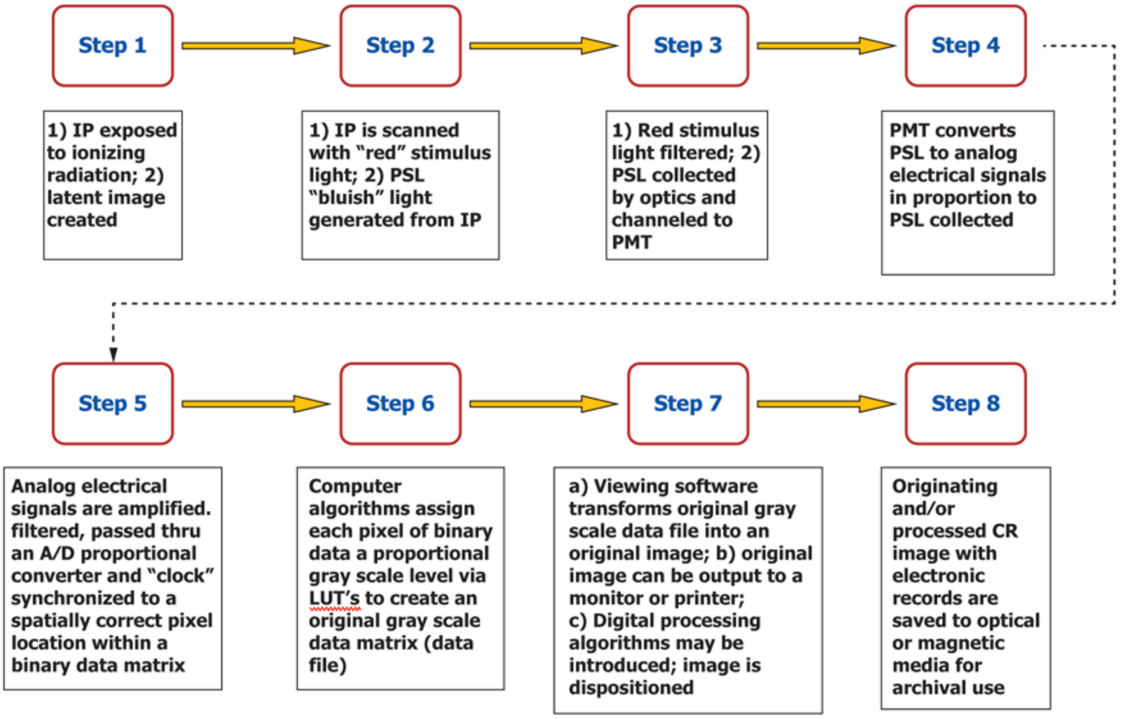
3.2.14.1 *Discussion*—Digital image noise results from random spatial distribution of photons absorbed within the IP and interferes with the visibility of small or faint detail due to statistical variations of pixel intensity value.

3.2.15 *digital image processing*—the use of algorithms to change original digital image data for the purpose of enhancement of some aspect of the image.

3.2.15.1 *Discussion*—Examples include: contrast, brightness, pixel density change (digital enlargement), digital filters, gamma correction and pseudo colors. Some digital processing operations such as sharpening filters, once saved, permanently change the original binary data matrix (Fig. 1, Step 5).

3.2.16 *equivalent penetrameter sensitivity (EPS)*—that thickness of penetrameter, expressed as a percentage of the section thickness radiographed, in which a 2T hole would be visible under the same radiographic conditions. EPS is calculated by: EPS% = 100/ X (√ Th/2), where: h = hole diameter, T = step thickness and X= thickness of test object (see E1316, E1025, E747, and Practice E746).

3.2.17 *gray scale*—a term used to describe an image containing shades of gray rather than color. Gray scale is the range



1) IP exposed to ionizing radiation; 2) latent image created

1) IP is scanned with "red" stimulus light; 2) PSL "bluish" light generated from IP

1) Red stimulus light filtered; 2) PSL collected by optics and channeled to PMT

PMT converts PSL to analog electrical signals in proportion to PSL collected

Analog electrical signals are amplified. filtered, passed thru an A/D proportional converter and "clock" synchronized to a spatially correct pixel location within a binary data matrix

Computer algorithms assign each pixel of binary data a proportional gray scale level via LUT's to create an original gray scale data matrix (data file)

a) Viewing software transforms original gray scale data file into an original image; b) original image can be output to a monitor or printer;
c) Digital processing algorithms may be introduced; image is dispositioned

Originating and/or processed CR image with electronic records are saved to optical or magnetic media for archival use

FIG. 1 Basic Computed Radiography Process

of gray shades assigned to image pixels that result in visually perceived pixel display brightness.

3.2.17.1 *Discussion*—The number of shades is usually positive integer values taken from the bit depth. For example: an 8-bit gray scale image has up to 256 total shades of gray from 0 to 255, with 0 representing white image areas and 255 representing black image areas with 254 shades of gray in between.

3.2.18 *image morphing*—a potentially degraded CR image resultant from over processing (that is, over driving) an original CR image.

3.2.18.1 *Discussion*—"Morphing" can occur following several increments of image processing where each preceding image was "overwritten" resulting in an image that is noticeably altered from the original.

3.2.19 *look up table (LUT)*—one or more fields of binary digital values arbitrarily assigned to a range of reference gray scale levels (viewed on an electronic display as shades of "gray").

3.2.19.1 *Discussion*—A LUT is used (applied) to convert binary digital pixel data to proportional shades of "gray" that define the CR image. LUT's are key reference files that allow binary digital pixel data to be viewed with many combinations of pixel gray scales over the entire range of a digital image (see Fig. 5-A).

3.2.20 *original digital image*—a digital gray scale (see 3.2.17) image resultant from application of original binary digital pixel data to a linear look-up table (see 3.2.24 and 3.2.19 prior to any image processing.

3.2.20.1 *Discussion*—This original gray scale image is usually considered the beginning of the "computed radiograph", since without this basic conversion (to gray scales) there would be no discernable radiographic image (see Fig. 5-B).

3.2.21 *photostimulable luminescence (PSL)*—photostimulable luminescence (PSL) is a physical phenomenon in which a halogenated phosphor compound emits bluish light when excited by a source of red spectrum light.

3.2.22 *pixel brightness*—the luminous (monitor) display intensity of pixel(s) that can be controlled by means of electronic monitor brightness level settings or changes of digital driving level (see 3.2.11).

3.2.23 *pixel density*—the number of pixels within a digital image of fixed dimensions (that is, length and width).

3.2.23.1 *Discussion*—for digital raster images, the convention is to describe pixel density in terms of the number of pixel-columns (width) and number of pixel rows (height). An alternate convention is to describe the total number of pixels in the image area (typically given as the number of mega pixels), which can be calculated by multiplying pixel-columns by pixel-rows. Another convention includes describing pixel density per area-unit or per length-unit such as pixels per in./mm. Resolution (see 7.1.5) of a digital image is related to pixel density.

3.2.24 *pixel value (PV)*—a positive integer numerical value directly associated with each binary picture data element (pixel) of an original digital image where gray scale shades (see 3.2.17) are assigned in linear proportion to radiation exposure dose received by that area.

3.2.24.1 *Discussion*—Computed radiography uses gray scale shades to render visual perceptions of image contrast; thus, linear pixel value (PV) is used to measure a specific shade of gray that corresponds to the quantity of radiation exposure absorbed within a particular area of a part. With this relationship, a PV of “0” can correspond with “0” radiation dose (white image area of a negative image view) whereas a PV of “4095” can correspond with a saturated detector (black image area of a negative image view) for a 12 bit CR system. PV is directly related to original binary pixel data via a common linear look-up-table (Fig. 5 A and B illustrate). The number of available pixel value integers within an image is associated with the number of available gray scale shades for the bit depth of the image.

3.2.25 *PSL afterglow*—continued luminescence from a storage phosphor immediately following removal of an external photostimulating source.

3.2.25.1 *Discussion*—A bluish luminescence continues for a short period of time after termination of the photostimulating source as illustrated in Fig. 12.

3.2.26 *relative image quality response (RIQR)*—a means for determining the image quality performance response of a given radiological imaging system in relative comparison to the image quality response of another radiological imaging system.

3.2.26.1 *Discussion*—RIQR methods are not intended as a direct measure of image quality for a specific radiographic technique application. Practice E746 provides a standard RIQR method.

3.2.27 *signal-to-noise ratio (SNR)*—quotient of mean linear pixel value and standard deviation of mean linear pixel values (noise) for a defined detector area-of-interest in a digital image.

3.2.27.1 *Discussion*—Notwithstanding extraneous sources of digital image noise, SNR will normally increase as exposure dose is increased.

3.2.28 *spatial resolution*—terminology used to define a component of optical image quality associated with distinction of closely spaced adjacent multiple features.

3.2.28.1 *Discussion*—The concept of optical resolution involves the ability to separate multiple closely spaced components, for example, optical line pairs, into two or more distinctly different components within a defined unit of space. Example: an optical imaging system that is said to resolve two line pairs within one mm of linear space (that is, 2 Lp/mm) contains five individual components: two closely spaced adjacent line components, an intervening space between the lines and space on the outside boundaries of the two lines.

3.2.29 *storage phosphor imaging plate (IP)*—a photostimulable luminescent material that is capable of storing a latent radiographic image of a material being examined and, upon stimulation by a source of red spectrum light, will generate luminescence (PSL) proportional to radiation absorbed.

3.2.29.1 *Discussion*—When performing computed radiography, an IP is used in lieu of a film. When establishing techniques related to source focal geometries, the IP is referred to as a detector (i.e. source-to detector-distance or SDD).

3.2.30 *unsharpness*—terminology used to describe an attribute of image quality associated with blurring or loss of distinction within a radiographic image.

3.2.30.1 *Discussion*—Measured total unsharpness is described with a numerical value corresponding with a measure of definition (that is, distinction) associated with the geometry of exposure and inherent unsharpness of the CR system (that is, inherent or total unsharpness). Guide E94 provides fundamental guidance related to geometrical unsharpness and Practice E2002 provides a standard practice for measurement of total unsharpness.

4. Significance and Use

4.1 This guide is intended as a source of tutorial and reference information that can be used during establishment of computed radiography techniques and procedures by qualified CR personnel for specific applications. All materials presented within this guide may not be suited for all levels of computed radiographic personnel.

4.2 This guide is intended to build upon an established basic knowledge of radiographic fundamentals (that is, film systems) as may be found in Guide E94. Similarly, materials presented within this guide are not intended as “all-inclusive” but are intended to address basic CR topics and issues that complement a general knowledge of computed radiography as described in 1.2 and 3.2.28.

4.3 Materials presented within this guide may be useful in the development of end-user training programs designed by qualified CR personnel or activities that perform similar functions. Computed radiography is considered a rapidly advancing inspection technology that will require the user maintain knowledge of the latest CR apparatus and technique innovations. Section 11 of this guide contains technical reference materials that may be useful in further advancement of knowledge associated with computed radiography.

5. Computed Radiography Fundamentals

5.1 This section introduces and describes primary core components and processes of a basic computed radiography process. The user of this standard guide is advised that computed radiography is a rapidly evolving technology where innovations involving core steps and processes are continually under refinement. Tutorial information presented in this section is intended to illustrate the fundamental computed radiography process and not necessarily any specific commercial CR system.

5.2 *Acquiring the CR Image:* Computed radiography (CR) is one of several different modes of digital radiography that employs re-usable photostimulable luminescence (PSL) storage phosphor imaging plates (commonly called IP’s) for acquisition of radiographic images. Figure 1 illustrates an example of the fundamental steps of a basic CR process arrangement.

In this illustration, a conventional (that is, Guide E94) radiographic exposure geometry/arrangement is used to expose a part positioned between the radiation source and IP. *Step 1* involves exposure of the IP (Fig. 2 illustrates typical cross section details of an IP) and creation of a residual latent image with delayed luminescence properties (Section 6 details physics).

Step 2 involves index scanning the exposed IP with a stimulus source of red light from a laser beam (Fig. 3 illustrates Steps 2 through 8).

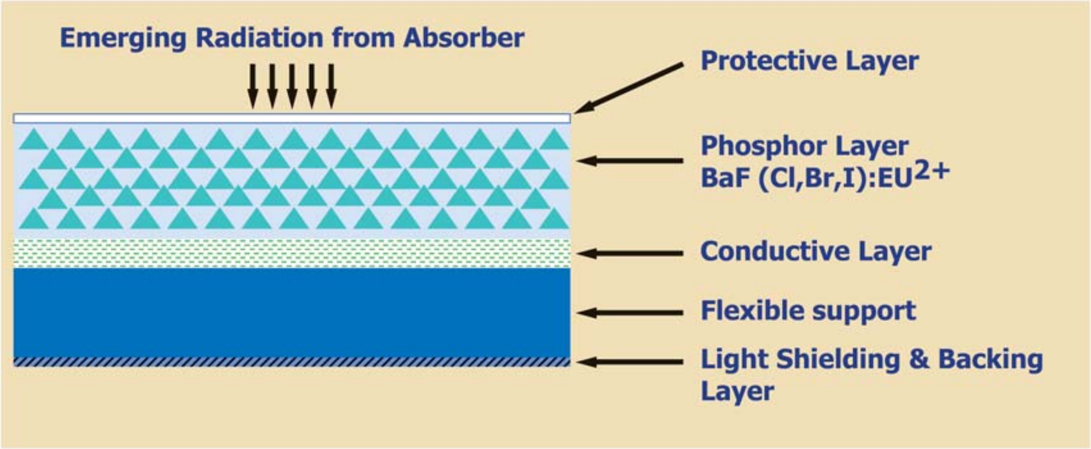


Illustration courtesy of Fujifilm NDT Systems

FIG. 2 Cross Section of a Typical Storage Phosphor Imaging Plate

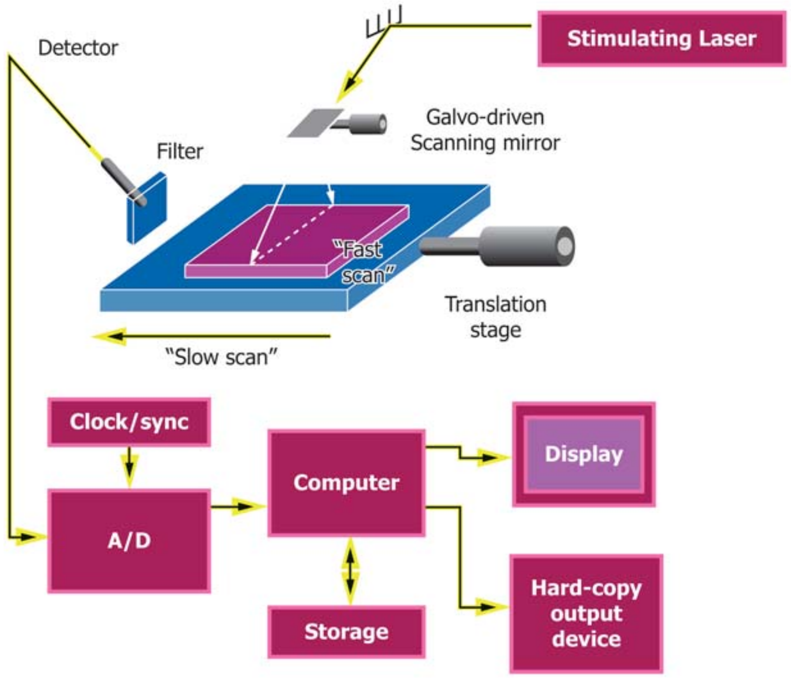


Illustration courtesy of Carestream Health

FIG. 3 Fundamental CR Image Acquisition and Display Process

During the scan, the IP is stimulated to release deposited energy of the latent image in the form of bluish photostimulated visible light. *Step 3:*the bluish photostimulated light (PSL) is then collected by an optical system containing a chromatic filter (that prevents the red stimulus light from being collected) and channeled to a photo-multiplier tube (PMT). *Step 4:*PSL light is converted by the PMT to analogue electrical signals in proportion to quantity of PSL collected. *Step 5:*analog electrical signals are amplified, filtered, passed through an analog-to-digital (A/D) converter and "clock" synchronized to a spatially correct pixel location within a binary data matrix (Fig. 4 illustrates assignment of binary data to a pixel matrix).

The actual size of the binary pixel element (length and width) is determined by the scanning speed of the transport mechanism in one direction and the clock speed of the sampling along each scan line (how fast the laser spot moves divided by the sampling rate). Although resolution is limited by pixel size, the size of individual phosphor crystals, the phosphor layer thickness of the image plate, laser spot size and optics also contribute to the overall quality (resolution) of the image. Each of these components thus becomes a very essential contributor to the overall binary matrix that represents the digital image. These individual elements represent the smallest unit of storage of a binary digital image that can be discretely controlled by the CR data acquisition and display system components and are commonly called "pixels." The term "pixel" is thus derived from two word components of the digital matrix, that is, picture (or pix) and elements (els) or "pixels." Picture elements or pixels become the basis for all

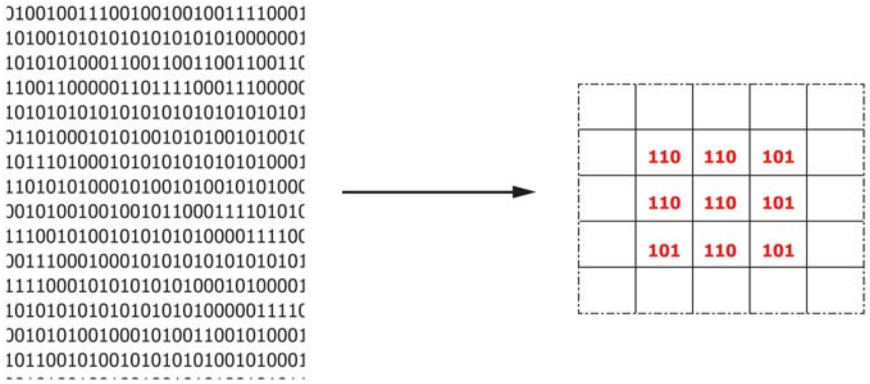


FIG. 4 Assignment of Binary Data to a Pixel Matrix (3-bit depth illustrated)

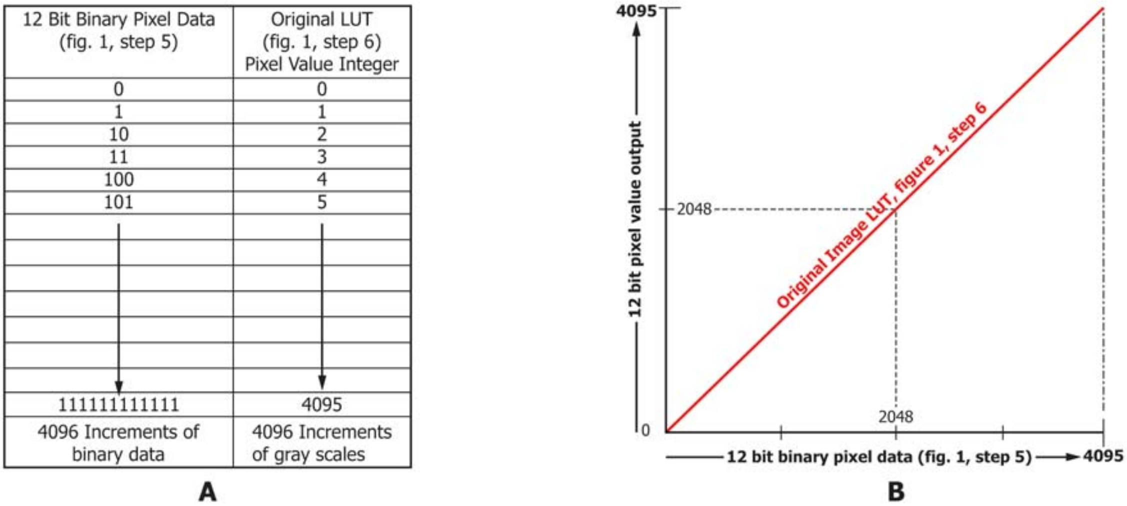
technical imaging attributes that comprise quality and composition of the resultant image. An organized matrix of picture elements (pixels) containing binary data is called a binary pixel data matrix since proportional gray levels have not yet been assigned. (see 11.1.2) contains basic tutorial information on binary numbering system and its usefulness for digital applications).

Step 6: Computer algorithms (a string of mathematical instructions) are applied that match binary pixel data with arbitrary files (called look-up-tables) to assign individual pixel gray scale levels. Example: for 4096 possible shades or levels of gray for a 12-bit image, gray scale levels are thus derived when a computer assigns equal divisions between white ("0") and black ("4095") with each incremental division a derivative (shade) of black or white (that is, gray) for a negative view image. An example is to assign gray scale levels in linear proportion to the magnitude of the binary numbers (that is, a higher binary number associated with a greater amount of photo stimulated light for that pixel registration can be assigned a corresponding darker gray value) to create an original gray scale data matrix with a standard format (DICONDE, TIFF, BITMAP, etc.) ready for software transformation. Fig. 5-A illustrates a simple linear look-up-table for an original gray scale data matrix where binary numbers are also represented by their corresponding numerical integers (called pixel value integers). In this example for a 12-bit image, there are 4096 gray scale divisions that precisely correspond with 4096 numerical pixel value integers. Fig. 5-B illustrates a graphical version of the application as might be applied by an algorithm to produce an image with a gray tonal appearance (visually similar to a radiographic film). Most algorithms employed for *original* CR images assign gray scale values in *linear* proportion to the magnitude of each binary pixel (value). The range (number) of selectable gray values is defined within the image viewing software as "bit depth."

Step 7: a) Viewing software is used to transform the original gray scale data matrix into an original image; *b*) The original image can be output to an electronic display monitor or printer; the resultant CR digital image can have a similar gray tonal appearance as its film counterpart (as illustrated with the LUT shown in Fig. 5-A in that as gray values become larger, displayed luminance becomes smaller. With the digital image display, inspected features can be characterized and dispositioned similar to a radiographic film. Both image modalities require evaluations within environments of subdued background lighting. Aside from these basic similarities, however, the CR digital image is an entirely different imaging modality that requires some basic knowledge of digital imaging fundamentals in order to understand and effectively apply the technology; *c*) Once the original digital image is visualized, additional image processing techniques (see Section 8) may be performed to further enhance inspection feature details and complete the inspection evaluation process. This entire process is called *computed* radiography because of the extreme dependence on complex computational processes in order to render a meaningful radiographic image. Finally (*Step 8*), original and/or processed digital images and related electronic records may be saved to optical, magnetic or print media for future use. Some applications may benefit from a high quality digital print of the saved image. Typical CR system commercial hardware components are illustrated in Fig. 6. Computed radiographic technology is complex in nature; therefore, subsequent sections of this standard are intended to provide some additional levels of detail associated with the *basic* computed radiography process. Additional levels of information may be found within the bibliography, Section 11.

6. Brief History and Physics of Computed Radiography

6.1 *Photo-Stimulated Luminescence (PSL)* is a physical phenomenon in which a halogenated phosphor compound emits bluish light when excited by a source of red spectrum light. In other words, phosphors capable of "PSL" exhibit a unique physical property of delayed release of visible light subsequent to radiation exposure; thus, the reason this type of phosphor is sometimes referred to as a "storage phosphor." illustrates the photo excitation process when this phosphor is exposed (following exposure of the phosphor to radiation) to a source of red light (He-Ne or semiconductor laser). The "bluish-purple" light emitted during this stimulation is referred to as "photostimulated luminescence" or "PSL" for short. During collection of PSL light for computed radiography, the red light source is **separated** from PSL using a chromatic filter (see Fig. 3). The "PSL" process is the very heart of CR technology and is thus important for understanding how computed radiography works.



12 Bit Binary Pixel Data (fig. 1, step 5)	Original LUT (fig. 1, step 6) Pixel Value Integer
0	0
1	1
10	2
11	3
100	4
101	5
111111111111	4095
4096 Increments of binary data	4096 Increments of gray scales

FIG. 5 (A) Original 12-bit Linear Look-Up Table / (B) Graph Version of Applied Linear LUT

Illustrations courtesy of Carestream Health & Fujifilm NDT Systems

FIG. 6 Typical CR Scanner, Workstation, and Image Plate

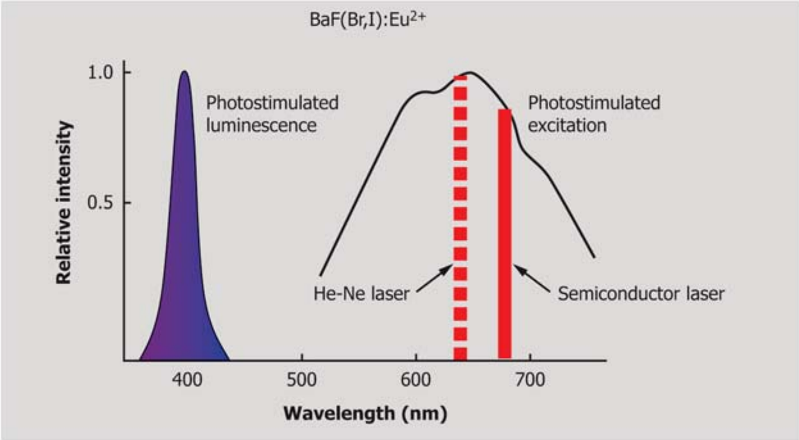


Illustration courtesy of Fujifilm NDT Systems

FIG. 7 Spectra of Photostimulated Luminescence and Excitation

6.2 *Early History of Photo Stimulated Luminensce:* The earliest written reference to fluorescence, the phenomenon that causes materials to emit light in response to external stimuli, dates back to 1500 B.C. in China. This phenomenon did not attract scientific interest until 1603, when the discovery of the Bolognese stone in Italy led to investigation by a large number of researchers. One of these was Becquerel, who, in his 1869 book **La Lumiere**, revealed that he had discovered the phenomenon of stimulated luminescence in the course of his work with phosphors. Photo stimulated luminescence (PSL) is a phenomenon which is quite common since photostimulable phosphors cover a broad range of materials—compounds of elements from Groups IIB and VI (for example, ZnS), compounds of elements from Groups 1A and VIIB, diamond, oxides (for example, Zn2Si04:Mn and LaOBr;Ce,Tb), and even certain organic compounds. The materials, therefore, lend themselves to data storage because radiation could be used to write data to the material, the light or secondary excitation to read the data back. Storage phosphor imaging plate (IP) is a name given to a two dimensional sensor (see Fig. 2) that can store a latent image obtained from X-rays, electron beams or other types of radiation, using photostimulable phosphors.

6.3 *Recent History of Computed Radiography:* With the introduction of photostimulable luminescence imaging systems in the early 1980's in combination with continued advancements in computer technologies, CR was "born." In the early 1990's, further advancements in computer technologies in conjunction with refined phosphor imaging plate developments initiated limited applications, mostly driven by the medical industry. The medical industry became interested in CR for two reasons: *1*) The desire for electronic transport of digital images for remote diagnostics and *2*) The increased latitude of diagnostic capability with a single patient exposure. Throughout the 90's, technology advancements in CR were driven primarily by the medical industry for similar reasons. In the late 90's, as image quality attributes continued to improve, industrial radiographers became more interested in CR for its ability to detect small features within heavier materials with reliabilities approaching some classes of film systems. In 1999, continued industrial user interests led to the development and publication of ASTM's first computed radiography standard, Practice E2033. ASME adopted its first article for ASME Code compliant computed radiography in 2004. In 2005, further interests from industrial users led to the development and publishing of Practices E2445 and E2446. ASTM published its first ever set of all-digital reference images (E2422) for the inspection of aluminum castings in 2005.

6.4 *PSL Crystal Structure:* Fig. 8 illustrates the basic physical structure of a typical Barium Fluorohalide phosphor crystal. illustrates a photo-micrograph of these type crystal grains as seen through a scanning electron microscope at approximately 5 microns. These crystal structures are the basis of the phosphor layer shown in Fig. 2 and constitute the heart of the physical "PSL" process described in the following text.

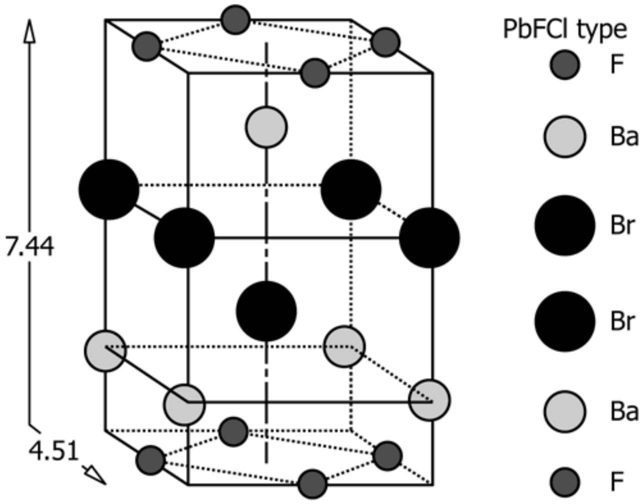


Illustration courtesy of Fujifilm NDT Systems

FIG. 8 BaFBr Crystal Structure

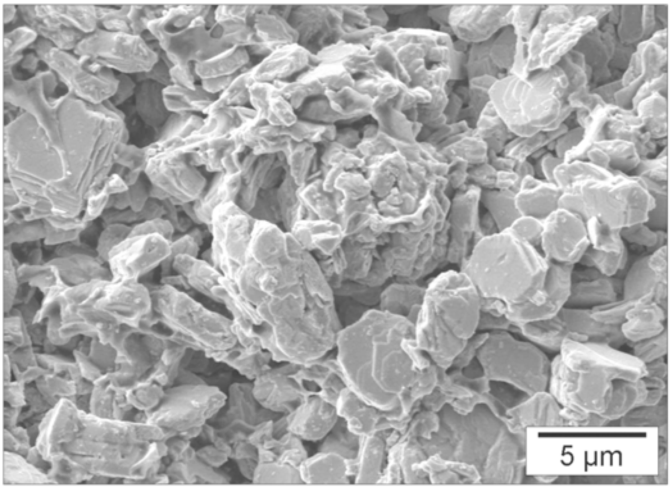


Illustration courtesy of Carestream Health

FIG. 9 Conventional BaFX: Eu Grains (5 microns)

6.5 *Latent Image Formation:* A widely-accepted mechanism for PSL in europium-activated halides was proposed by Takahashi et al (see 11.1.10). In the phosphor-making process, halogen ion vacancies, or "F^{+}" centers, are created. Upon exposure of the phosphor particles to ionizing radiation (Fig. 10 provides an energy level diagram that illustrates this process), electrons are excited to a higher energy level (conduction band) and leave behind a hole at the Eu2^{+} ion (valance band). While some of these electrons immediately recombine and excite the Eu2^{+} to promptly emit, others are trapped at the F^{+} centers to form metastable F centers, also known as color centers, from the German word "Farbe," which means color. The energy stored in these electron-hole pairs is the basis of the CR latent image and remains quite stable for hours. This mechanism has been disputed by some and supported by others; however, the end result is photostimulable luminescence.

6.6 *Processing the Latent Image:* When this phosphor (bearing the latent image) is subsequently exposed (that is, scanned with a laser as shown in Fig. 3) to a source of red light, most of the trapped electrons are "liberated" and return to the lower energy level (valence band) of the phosphor molecule causing PSL to be emitted. Fig. 11 provides a simplified graphic illustration of this process that may be helpful in better understanding the fundamentals of this unique process.

6.7 *Residual Latent Image Removal:* Following a normal latent image process scan (see Fig. 3), all phosphors on the imaging plate must be further exposed to a high intensity source of white light in order to remove any remaining

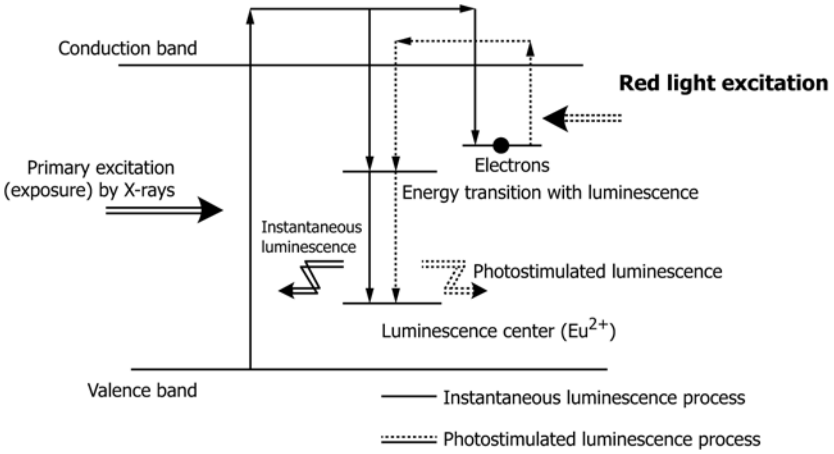


Illustration courtesy of Fujifilm NDT Systems

FIG. 10 Energy Level Diagram Illustrating Mechanism for Generating PSL in BaFBr: Eu^{+2} Crystal

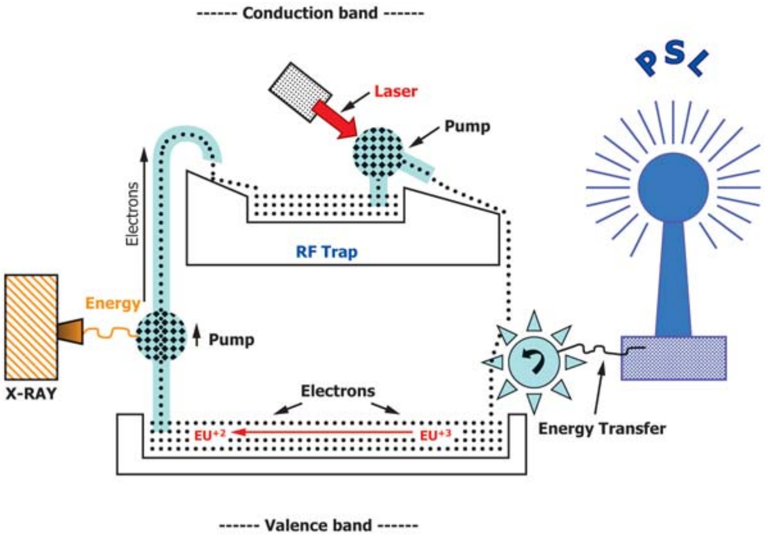


Illustration courtesy of Fujifilm NDT Systems

FIG. 11 Illustration of PSL Generation

"residual" trapped electrons in the F centers. This process is referred to as an IP "erasure" and is usually performed subsequent to the IP scan and prior to any subsequent re-exposures of the IP. If an erasure cycle is not performed, an unwanted residual latent image may be superimposed on the next CR exposure if the IP is re-exposed soon after the first exposure. In the event no subsequent re-exposure of the IP is performed, any residual latent image (trapped electrons) will eventually fade as natural sources of red light energy (heat, etc.) cause remaining electrons to be liberated via the same physical process described above. Similarly, if erased IP's are stored near sources of radiation (background or other sources of ionizing radiation) an unwanted residual latent image (background) may develop within affected phosphors of the IP. Fig. 12 illustrates a typical life cycle for the eventual generation of PSL with bluish X-ray luminescence *during* radiation exposure, bluish after-glow luminescence *subsequent* to radiation exposure, a bluish luminescence (PSL) *during* exposure to a high intensity source of "red" light stimulus (scanning) followed by a bluish luminescence after-glow (see 3.2.25) *subsequent* to scanning. Since this process is primarily passive, the actual phosphor is often referred to as a "storage phosphor."

6.8 *CR Latent Image Issues:* Now that some of the fundamental physics of CR are established, we need to understand how this knowledge relates to everyday use and production of quality CR images. Most radiographers have a good understanding of the importance in the use of lead intensifying screens during film applications. It is known, for example, that lead foil placed in intimate contact with film during exposure to radiation will intensify the formation of the film latent image and the physical mechanism (see 11.1.11) responsible for this is electrons liberated during radiation absorption within the lead screens. In this case, production of secondary electrons is desirable and actually contributes to the productive formation of the radiographic latent image. With CR, however, electrons generated within lead screens do not result in any appreciable gain or accelerated formation of latent image sites. CR latent image formation is thus primarily dependent upon radiation absorption within the phosphor layer of the image plate. For

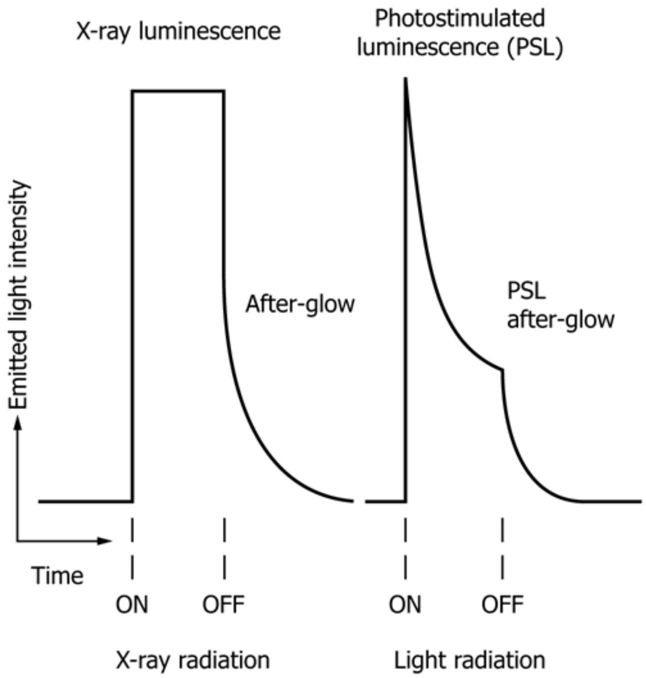


Illustration courtesy of Fujifilm NDT Systems

FIG. 12 Typical PSL Life Cycle

this reason, *unfiltered* CR image plates are usually more sensitive to direct exposure of ionizing radiation than film. At higher levels of radiation energy (in the approximate range of 750 keV or higher), radiation absorption within lead screens (as well as the part under examination) will be more proportionately influenced by the Compton process (see 11.1.14). The greater proportion of Compton absorption within lead screens results in an increased proportion of secondary (non-directional) radiation photons that can be re-distributed to the image plate during part exposure reducing overall image quality results. It is therefore, important to control unwanted secondary radiation from lead screens as well as other sources during the acquisition of quality CR images with higher energy applications. A relatively thin layer of copper or steel filter screen positioned between the image plate and lead screen is often sufficient to control unwanted secondary scattering from lead screens.

7. Basic Computed Radiography Techniques

7.1 Many exposure and technique arrangements for CR are often very similar to conventional film radiographic methods as described in Guide E94, dependent upon the application. There are; however, numerous technical and physical issues that differentiate CR exposure techniques from film that require careful consideration during development of specific CR techniques. Successful CR techniques are usually dependent upon exposure technique (Step 1, Fig. 1) in conjunction with adequate image processing techniques (see Section 8) to achieve required image quality/dynamic range objectives. Similar to film systems, CR techniques are dependent upon control of contrast, noise and resolution imaging properties.

7.1.1 *Exposure Level and Image Quality:* In general, CR image quality is directly proportional to the quantity of meaningful radiation exposure received by the IP, just as it is with film. Exposure level is most effectively determined in CR via measuring the linear *pixel value* within the image area of interest, similar to measuring a film system's optical density with a densitometer device. With a digital "negative" image, a darker pixel value means more radiation reached that pixel (on the scanned IP) than a lighter pixel value. A good fundamental place to begin adapting to CR techniques is with the CR exposure curve. A good practice is to create an exposure relationship (exposure dose/quanta versus pixel value) for each major material (including thickness ranges inspected) and type of radiation used. Fig. 13-A illustrates a typical CR exposure relationship for a specific material, specific thickness, type of radiation source and exposure arrangement. Exposure is measured in units of time at a specified intensity and SDD, that is, 180 seconds @ 10 milliamps; 90 seconds @ 60 curies (minimum), etc. An alternate means of controlling exposure could be expressed as 1800 mA-s at a specified SDD, not to exceed 180 seconds, or 5400 Curie seconds at a specified SDD, not to exceed 90 seconds. The concept is to achieve a specified exposure level within a specified time "window," thus controlling quanta and dose. CR exposure data can be linear (within a specified linearity tolerance) or logarithmic (depending upon LUT's and equipment used) over a fairly wide range of exposure levels resulting in predictable contrast (PV 2-PV 1) level for the same material thickness difference (illustrated in Fig. 13-A). Additionally, as exposure level is increased with CR, image quality performance will normally improve to a point due to increase of contrast-to-noise ratio (CNR). In other words, as pixel value increases, CR system signal-to-noise (SNR) performance and Practice E746 equivalent penetrameter sensitivity (EPS), as illustrated in Fig. 13-B usually improves as well. (Note, SNR usually does not increase linearly with increasing exposure dose and will eventually achieve a maximum value beyond which additional exposure dose will not generate further improved SNR performance). Each user should qualify a specific pixel value range using exposure data that demonstrates satisfactory levels of image quality performance for the inspection application. Although dependent upon the particular CR system used, most all CR systems will reach a point of exposure saturation at some point on the higher end of the exposure range where image quality can become significantly diminished. A CR system is considered "saturated" when a sufficiently large amount of phosphor crystals are overexposed (or the PMT can no longer differentiate, depending on the scanner settings) to the extent that no meaningful contrast is obtained between an inspected feature and its surrounding background. For example: the overall image quality of a 12 bit high-resolution CR system (as determined by EPS or SNR) can become significantly diminished as pixel values exceed approximately ¾ bit depth or ≈3000 pixel value at a particular scanner setting. Again, the exact determination will depend upon the specific CR system used to measure image quality values. In order for a user to change contrast from that shown in Fig. 13-A, the slope of the curve must be increased or decreased. This can be potentially accomplished with a change of IP/scanner system or via image processing (covered in Section 8).

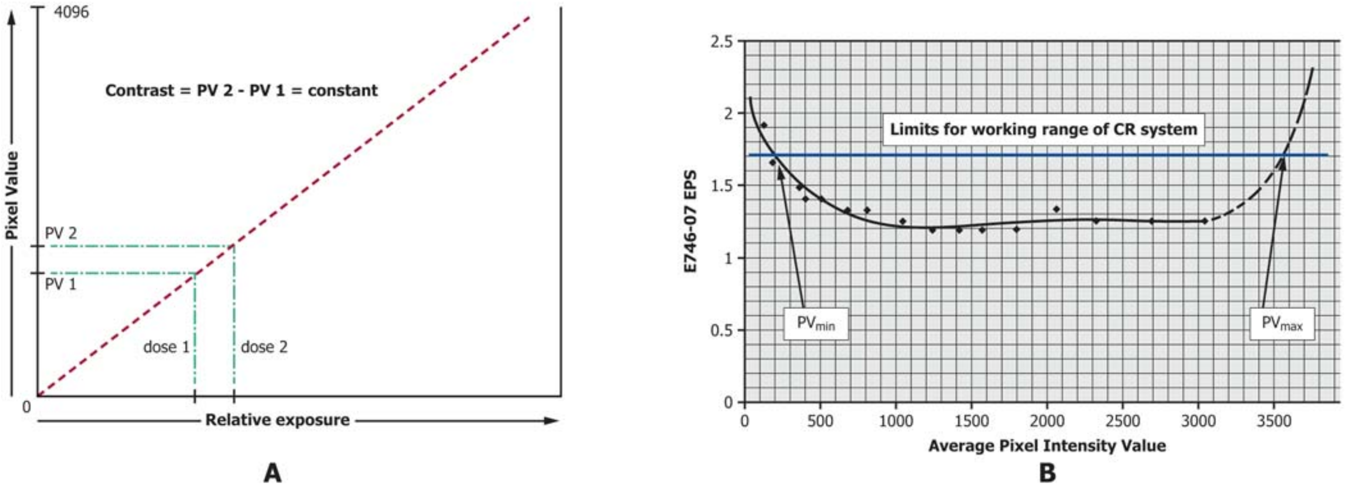


FIG. 13 (A) Exposure vs. Pixel Value / (B) EPS Image Quality vs. Pixel Value

7.1.2 *Dynamic (Pixel Value) Range:* CR has the unique property (when compared to single film systems) of displaying a wide range of visible gray scale levels for a defined range of material thickness, especially when image processing is used; however, CR image quality is very dependent upon achieving good signal-to-noise performance in order to achieve required image quality levels for inspection applications. Simply stated, the IP must obtain sufficient exposure quanta levels to render effective image quality results. For this reason, dynamic range is defined as the material thickness range that renders acceptable levels of image quality performance (usable contrast range). In general, the more liberal are image quality requirements, the greater will be CR's total dynamic range performance in comparison to single film systems.

7.1.3 Digital image noise within a computed radiograph generally originates from several complex sources that result in an "overly" random spatial variation of pixel values associated with random distribution of photons absorbed within the detector IP. These undesirable events interfere with visibility of small or faint detail due to statistical variations of pixel value. Fig. 14 illustrates the effect of increased noise on image quality.

The root causes of undesirable noise events are usually attributable to one or more of the following: *1*) non-uniformities within the phosphor materials of the IP detector (that is, irregular size, non-uniformly spaced or simply an insufficient mass of crystals); *2*) the IP detector receives an insufficient quanta of radiation photons to affect an adequate signal-to-noise ratio (SNR); *3*) primary radiation scattering (absorption) within the test part material under examination; *4*) secondary radiation scattering from the exposure environment. Computed radiography image plate detectors that employ (PSL) materials are especially prone to higher noise levels since these materials are generally more sensitive to ionizing radiation than silver-based film, especially to lower energy photons. Noise levels in computed radiographs can usually be controlled or minimized by: *1*) use of a phosphor detector with fine, uniformly distributed and dense crystal materials; *2*) use of a radiation source and exposure arrangement for the specific mass (of the examined material) that results in higher quanta of radiation absorbed within the detector for a given exposure interval; *3*) careful attention to control of all sources of secondary radiation exposure (adequate use of filters, diaphragms, collimators and other scatter reducing materials). Although all three of these sources are important, relatively low absorbed radiation quanta in conjunction with a "noisy" image plate or CR system detector is often the predominantly objectionable source of image noise with computed radiography (Fig. 15 illustrates). Radiation quanta (absorbed within the image plate detector) are affected by: *1*) material composition and thickness of the examined part; *2*) penetrating energy level of radiation being used; *3*) the intensity of radiation or activity levels of the primary exposure source. Dosage of radiation received by the detector is also an important consideration in control of image noise provided that all other CR exposure attributes are "balanced" to minimize noise or maximize contrast-to-noise ratio (CNR).

7.1.4 *Image Plate Efficiency:*The efficiency (noise and resolution) of the IP detector will be determined, in large measure, by the meaningful PSL that is directly returned to the CR optics for each spatially correct pixel area. As the phosphor imaging layer becomes thicker, for example, there is greater likelihood that a "stray" PSL photon will be captured outside of the spatially correct pixel area (see Fig. 15). When this happens, resolution will be diminished and the image quality will be worse. This is significantly more important for the phosphor IP than silver-based film emulsions since the IP contains a light reflective backing material that must reverse the direction of some PSL light photons as much as 180 degrees prior to travel to the CR optics. In other words, the further PSL light must travel before being captured by the CR optics; the potentially worse will be the image resolution. Most modern CR IP designs use two concepts to improve absorption efficiency (other than the actual chemistry of the phosphor crystal): *1*) increased thickness of phosphor layer and/or *2*) increased density of the phosphor material. In general, the IP design that has a more dense (and radiation absorbent) phosphor material in conjunction with a thinner cross sectional thickness will likely produce better resolution and CR image quality. Alternatively, a very thin phosphor layer cannot store as much

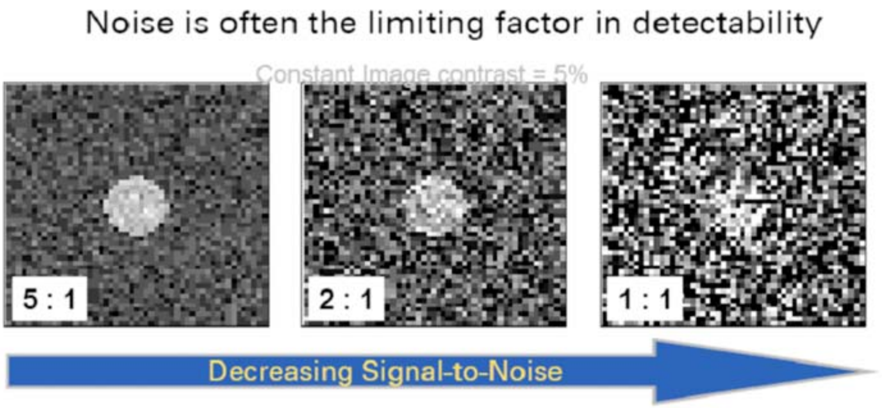


Illustration courtesy of General Electric IT

FIG. 14 Effects of Noise on Digital Image Quality

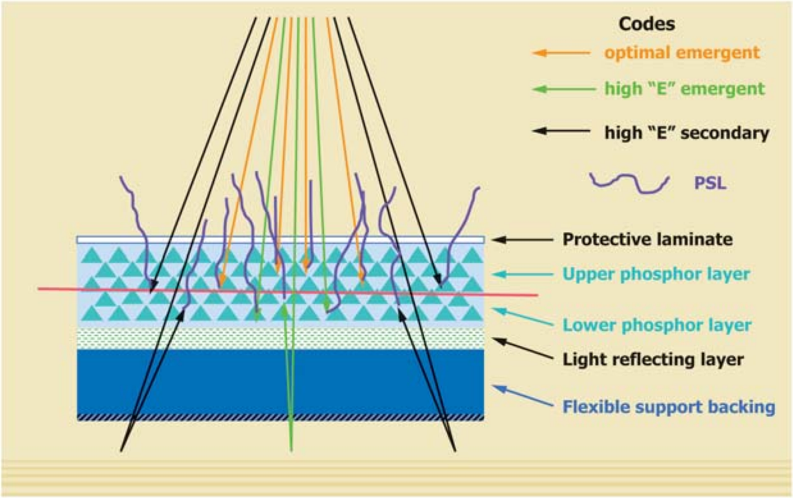


FIG. 15 Illustration of Noise and Unsharpness in the CR Detector

energy as a thicker layer and the resulting reduction in PSL (lower signal) presents a tradeoff between noise and resolution. CR optics also play a significant role in the degree of inherent unsharpness exhibited from the detector; however, current technology seems predominantly limited by the IP detector design. Some CR equipment suppliers offer several different versions of IP designs (and Practice E2446 IP classes) based upon trade offs between ISO speed and resolution (similar to current film system classes). In addition to careful selection of IP's, users should also consider the particular IP class when developing CR exposure techniques. Some degree of detector unsharpness and noise can be minimized by developing CR exposure techniques that optimize absorption efficiency within the imaging layer of the IP. Generally, better IP efficiency will occur when radiation energy levels emerging from a material absorber are as low as practical for the inspection application (while achieving maximum quanta possible) resulting in absorption within the upper layer of phosphor material (see Fig. 15). Higher energy levels of emergent radiation tend to penetrate deeper into the phosphor layer or pass through the detector unabsorbed followed by unwanted secondary radiation that can further degrade detector signal-to-noise performance of the process. In addition to controlled exposure techniques described in 7.1.3, achieving optimal IP efficiency is vitally dependent upon selection of the correct image plate design in conjunction with filtration materials (screens) optimized for the range of radiation energy used.

7.1.4.1 *Screens:* Many CR techniques will render more optimal image quality results when metallic screens are employed within IP exposure cassettes. Typically, a sandwich type arrangement is used where a metallic screen is positioned between the radiation source and the IP within the exposure cassette (usually referred to as a front screen). An additional screen can be positioned behind the IP within the same exposure cassette (usually called a "back" screen). In both cases, screen efficiency is usually improved if screens are in intimate contact with the IP surfaces. Specific screen types and thicknesses are very dependent upon inspection technique requirements, radiation energy levels employed and other considerations (see 6.8) of the application. As a general rule, screens employed during CR inspections are used to filter exposing radiation and to control undesirable secondary radiation scattering resulting in improved image quality. Practice E2033 provides recommended screen details for general CR techniques.

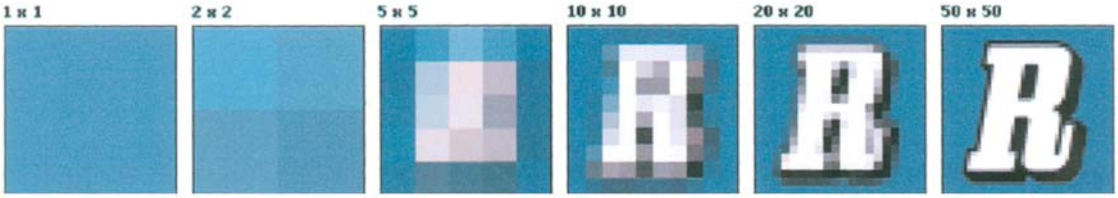


FIG. 16 Effects of Pixel Density on Digital Image Quantity

7.1.5 *Spatial resolution:* Two terms, spatial resolution and basic spatial resolution (see definitions 3.2.2 and 3.2.28), are used to describe an image quality component that expresses how much detail an image can possess. Higher resolution usually means more visible image detail. For digital raster images, the convention is to describe the image resolution in terms of the number of pixel-columns (width) and number of pixel rows (height). Another convention is to describe the total number of pixels in the image (typically given as the number of mega pixels), which can be calculated by multiplying pixel-columns by pixel-rows. Another convention includes describing resolution per area-unit or resolution per length-unit such as pixels per inch or pixels per mm. The resolution of a digital image (as measured by columns and rows of the image) can be determined by the number of pixels per inch (PPI) or pixel density in either direction (or, as sometimes preferred, in both dimensions). The actual pixel size of an image that has fixed pixel density will be determined by the number of pixels within the columns and rows of the image. A pixel is described by its horizontal and vertical location within a digital image matrix. Most all commercial CR scanners scan the imaging plate with a fixed degree of resolution, that is, acquisition of PSL at a certain pixel density in the "fast scan" (laser spot rastering along an image line) and "slow scan" (mechanical transport of the IP through the scanner) directions (see Fig. 3). Scanner resolutions are usually expressed in terms of pixels per mm. For example, a scanner that scans an imaging plate at the rate of 10 pixels per mm is said to have a nominal resolution of about 100 µm. Thus, the pixel dimension (for this dimension of the image) is 100 µm (0.004 in.). To obtain the other pixel dimension, one would have to determine it from the scan resolution for that scan direction. Some commercial scanners acquire at the rate of 20 pixels per mm or a 50 µm (0.002 in.) resolution. In any event, it is this pixel density that initiates the basic spatial resolution or effective pixel size of the digital image. In some cases, acquired pixel density can exceed the pixel density display capability of a high quality (that is, 3 mega pixel) monitor. When this happens, display software can interpolate (or average) pixels to affect a lesser pixel display density to match a non-magnified display capability of the monitor. Similarly, a zoomed-in or enlarged image area of the monitor may be capable of displaying the full pixel density of the scanned image. High-end digital printers can usually handle a greater pixel density than can electronic display monitors and thus render a higher visual quality printed image. As a general rule, the greater the pixel density displayed on the monitor, the greater will be the visual image resolution. The resultant visual image resolution, then, is actually a combination of pixel density input (from the scanned IP) and visual pixel display output of the monitor (or printed image). Figure 16 illustrates the effect of pixel density upon image resolution using a series of progressively greater number of pixels (and pixel density) within the image.

Resolution (length-units) is usually measured with a radiological test device (that is, line pair gauge) that contains a series of parallel lines (or image bars) that has been imaged with an exposure from the CR system (see Fig. 17). The series of lines with these devices usually increases in spatial frequency across the device. Resolution (measured visually or mechanically) of the digital image is usually defined as the last resolved series of line pairs.

In the illustration of Fig. 17, a modulation transfer function (MTF) gauge has been evaluated with a pixel profile scan (manual measurement) and the resultants superimposed above the gauge corresponding with the changes of spatial frequency. Resolution limits from this evaluation are about five lines per mm or 100 micrometres (0.004 in.) for both *visual* and *manual* methods. "Resolution" is an image quality parameter useful for defining a digital imaging systems broad capability to distinguish multiple closely spaced features as individual features. "Basic spatial resolution" is an image quality parameter useful for defining the effective pixel size required to achieve a specific degree of resolution. These scientific methods of image quality assessments are not intended to supplant every day practical computed radiography applications/techniques where plaque, wire or other image quality indicator devices may be effectively used. Digital imaging systems possess unique capabilities where contrast and noise processing can potentially be used to a degree that resolution dependant features could go relatively undetected or not as reliably detected during an inspection. The purpose of independent assessments of contrast, noise and resolution is thus to provide added assurance whereby digital imaging systems are not "resolution deficient" and sustain the desired feature detection capabilities for the intended user applications.

Figure 18 illustrates the overall relationship of digital image quality associated with bit depth and the number of pixels. As a general rule, the greater the number of pixels and shades of gray (bit depth), the greater can be the level of digital image quality. The greater the number of pixels and bit depth, the greater will be the resultant digital image file size (usually measured in mega-bytes of storage space).

7.1.6 *Balance of Contrast, Noise, and Resolution:* Most modern radiological imaging systems depend upon contrast, noise level and resolution in some degree of balance to render desired overall image quality results. In theory, you can not have any amount of resolution without some amount of

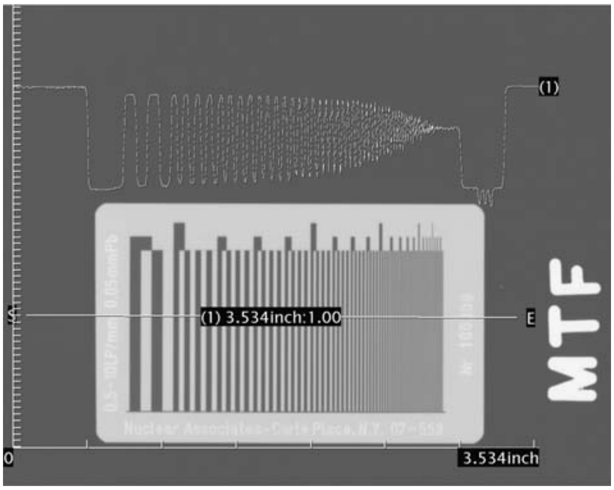


FIG. 17 Determining Resolution of Imaging Systems

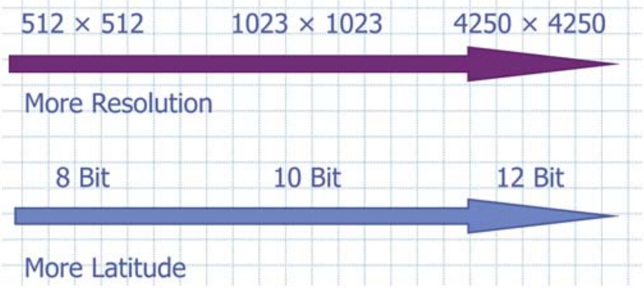


Illustration courtesy of Fujifilm NDT Systems

FIG. 18 Pixel Density and Bit Depth vs. Image Quality

contrast and vice versa. CR and film system imaging technologies both employ combinations of contrast, noise and resolution performance attributes to achieve overall image quality requirements; however, CR and film systems do **not** necessarily have the same balance among these three attributes. In general, CR imaging technologies employ higher levels of contrast and lower levels of resolution than film systems to achieve image quality performance requirements. This often leaves "noise level" as the primary control attribute for both image modalities. Film systems commonly employ film granularity variance (with change of film type) to a large extent to control image noise with "fixed" levels of film contrast. A similar affect can be achieved with CR by means of contrast-to-noise ratio (CNR). This concept assumes that differences of resolution (between imaging systems) are fixed and thus not user controllable. In the case of CR, any contrast advantage (over film systems) may be "moot" unless CR noise level is maintained at acceptable levels. Thus, CNR becomes an important attribute when comparing CR systems or change of individual CR hardware/software components. With many CR techniques, noise can be the predominating physical determinant in attainment of satisfactory image quality results. In simple language, lose control of image noise and any contrast sensitivity advantage of CR may be compromised (lower CNR); compromise CNR and CR may not meet image quality requirements.

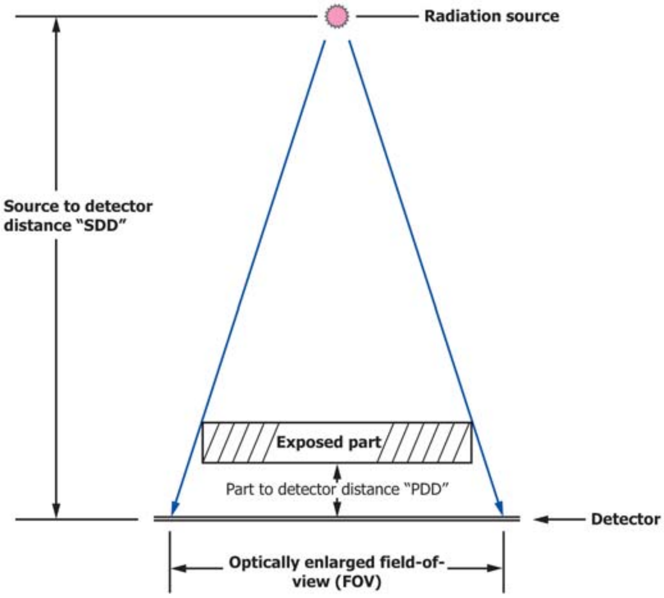


FIG. 19 Optical Enlargement of a Radiographed Part

7.1.7 *Field-of-View (FOV):* FOV is a technique parameter that can have a significant impact upon CR image resolution. Digital field-of-view must not be confused with optical field-of-view, as the two concepts are entirely different. Optical FOV is simply that imagery that can be directly viewed from one's viewing location. Fig. 19 illustrates an optical condition whereby a part can be radiographically enlarged via introducing some distance between the part and the detector. In this example, the part is optically enlarged and the resultant pixel density (on the viewed digital image) has not changed due to part enlargement. The quality of the viewed image is usually reduced due to increase of geometrical unsharpness (U_g) of the optical exposure arrangement. Similarly, as the radiation source may be moved closer to the part, the resultant image may appear larger than its true dimensional size; however, pixel density has not been affected.

Digital FOV is a process that synthesizes the effect of a viewer being closer or further away from an object/image. This process occurs as the result of the computer changing the displayed pixel size (and thus pixels displayed per mm). For example, individual pixels can be displayed at 1×, 2×, 3×, 4×, etc. of their original size. When displayed pixel size changes, the image has the appearance of being zoomed "in" or "out" or becomes larger or smaller on the electronic display. Fig. 16 illustrates six views of a digital image where the optical FOV is the same (that is, each image is displayed the same size); however, the image on the far left has been digitally zoomed "in" to the point that only one pixel can be displayed within this view space. If the optical FOV (for this example) is made larger (as on a large monitor, for example), the entire image will be much larger and may even be too large to fit on the display screen. This image may appear to be "pixilated" or distorted due to the reduced resolution of the image. In Fig. 16, the image on the far right contains pixels of reduced size and thus a larger number (2500:1) of pixels within the same view space. This image has been effectively zoomed "out" and contains a larger number of pixels per view area (greater pixel density). With this example, the effect on image quality is obvious. For similar situations during computed radiography, the effect may be subtle and much less obvious on an electronic display. The issue that is important for high quality CR images is thus related to the degree of digital magnification that can be performed without significantly affecting resolution and detection of important feature details. Without a doubt, image magnification can be a useful tool to the CR evaluator; however, in some instances magnification may reach a point of diminishing returns where loss of resolution exceeds any potential benefits of increased image size.

8. Evaluating the CR Image

8.1 Evaluation of CR digital images is similar to evaluation of film system images in that both are radiographic images usually viewed in conditions of subdued background lighting by qualified and experienced personnel; however, the digital image has unique capabilities as well as potential limitations that require basic understanding to effectively utilize the technology. This section introduces some of the fundamentals of electronic display, image processing and potential limitations that can be encountered during evaluations of the CR digital image.

8.2 *Electronic Displays:* Digital images that are electronically displayed on a monochrome monitor will usually have similar gray tonal characteristics as film counterparts; however, visual fundamentals are notably different. Most high quality monitors used to view digital radiographic images are approximately 12.5 by 16.5 in. in view area and use electronic luminescence to display a digital image. In contrast, a film radiograph may be 14 by 17 in. and use transmitted light to display an analog image. In this example, a standard 14 by 17 in. digital detector will be compressed approximately 13 % in area size when displayed on this type monochrome monitor. Additionally, images displayed via electronic luminescence are subject to variations such as monitor brightness, resolution (horizontal and vertical), noise, contrast and distortion. Electronic monitors are also available with different viewable aspect ratios and varying degrees of resolution (that is, 1.3:1 aspect ratio with five mega pixels of area resolution). Since monitors can deteriorate with usage, periodic assessments should be performed on: *1*) brightness levels (min and max); *2*) linearity of brightness; *3*) contrast levels and *4*) resolution. There are numerous methods/techniques for performing these assessments either individually with the appropriate apparatus (that is, light photometers) or collectively with an electronically generated test image. The Society of Motion Pictures and Television Engineers (SMPTE) have produced a standard SMPTE RP-133 "Specification for Medical Diagnostic Imaging Test Pattern for Television Monitors and Hard-Copy Recording Cameras" that contains a standard electronic image for evaluating most of these display parameters.

8.3 *Digital Image Processing:* Image processing can be simply described as any digital operation performed on an original CR image for the purpose of improving or enhancement of visibility of desired image features. There are numerous modalities and types of processing that can be performed, either as a single operation or in the form of one-step macros that apply several types of processing in a single operation. A processing operation is usually considered a permanent alteration of the original digital image unless there are provisions to "undo" the changes that restore the image to the original state. Digital image processing usually falls into several broad categories and can have a profound effect upon the end results of a CR inspection when evaluating a particular image. For these reasons, a good fundamental understanding of concepts is essential during evaluations of CR images. Digital enhancements are made possible through the use of algorithms and a computer. Algorithms are simply instructions (or a series of organized instructions) that direct a computer to make changes to an original gray scale data matrix (Fig. 1, Step 6). In essence, the digital image is nothing more than a matrix of binary numbers with an assigned gray value association. The uniqueness for digital imaging is that the computer "knows" the physical location of each binary number/gray scale value (that is, pixel value) within the original matrix (see Figs. 4 and 5). With this basic information in mind, it isn't difficult to understand that instructional commands can be generated for the computer whereby any number or combination of pixel values can receive gray value reassignments. This is the fundamental essence of all digital image processing.

8.3.1 *Modalities of Processing:* Contrast and brightness (that is, window and leveling), filters, magnification, histogram normalization, gamma correction and pseudo-color are typical modalities of image processing associated with CR. When selectively applied by a trained and experienced CR inspector for a specific application, each modality can produce unique results. There are often limits as to the extent of how much processing can be applied before the results actually degrade rather than enhance the quality of visibility of a feature. There are also certain features in materials that respond more favorably to one modality than another. In some instances of "digital overdriving," a feature can be processed beyond the capability of the electronic display to faithfully construct the true aspects of the image and the consequences can lead to image distortion such as "aliasing" or "blooming." The following sections provide basic introductions to some fundamental processes.

8.3.2 *Contrast and Brightness:* When processing an original CR image, the user is simply instructing the computer to temporarily reassign different gray values (from a series of reference LUT's) instead of those gray values originally assigned. Fig. 20 illustrates a graphical example of changes of brightness. If a CR evaluator wanted to "lighten" an original image without re-exposure, for example, he could simply direct the computer to relate the original gray scale data matrix (developed in Fig. 1, Step 6 and illustrated in Fig. 5) with a series of lighter gray scale values (to the right of the original data). Similarly, if he wanted to darken the image without re-exposure, he would direct the computer to relate the original gray scale data matrix with a series of darker gray scale values (to the left of the original data). This type of processing is commonly called brightness leveling or simply "leveling" since darker pixels can be lowered in gray scale value while lighter pixels can be raised. Fig. 21 illustrates a similar

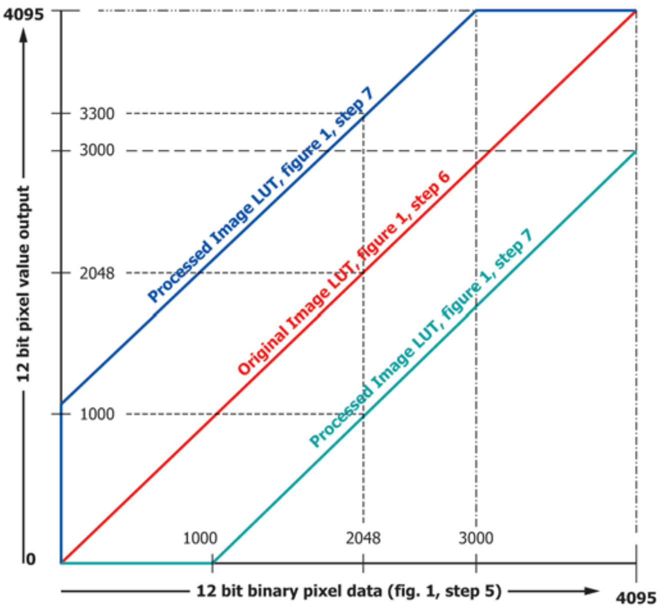


FIG. 20 Change of Pixel Display Brightness

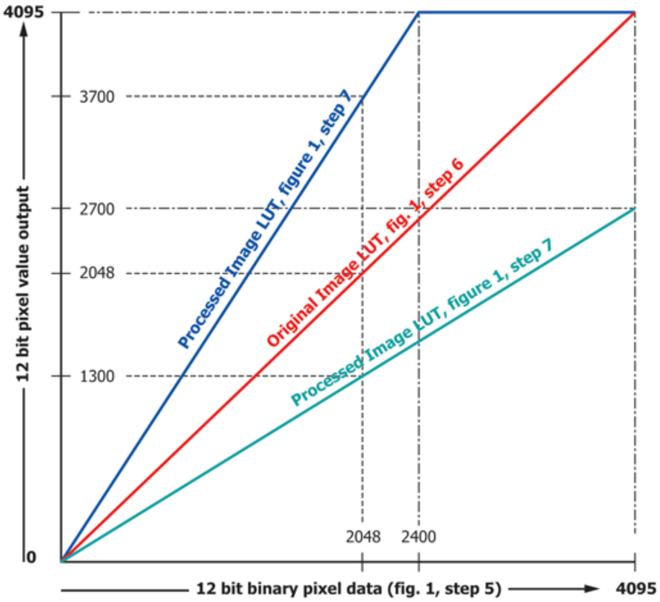


FIG. 21 Change of Pixel Display Contrast

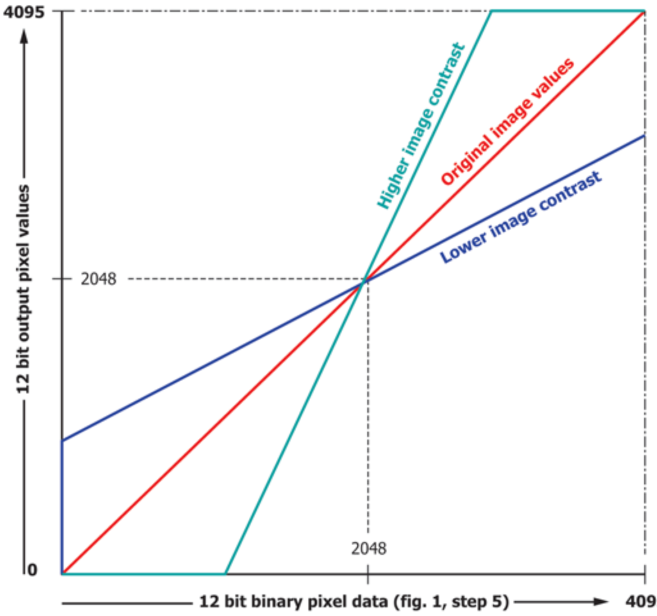


FIG. 22 Contrast and Brightness Processing about a Midpoint

graphical example of changes of contrast of the original image. This operation is usually performed to adjust gray scale contrast of material thickness (or mass) that can be displayed within specified pixel value ranges (windows); thus, the operation is commonly called contrast or "window" adjustment. The term "window" stems from the range of gray scale levels available to the user selected algorithm during display of the processed image. Some CR systems are capable of performing simultaneous changes of contrast (windowing) and gray scale brightness (leveling) during evaluations of the CR image. When a CR evaluator performs these types of processing operations, care must be taken to assure that the original digital image contains sufficiently meaningful CR system signal-to-noise information (SNR) to assure required image quality levels are attained. Some CR applications may need to specify a minimum output pixel value (determined from the original image) to assure that exposure levels are sufficient to achieve image quality requirements. Fig. 22 illustrates an example of changes to contrast while holding overall image brightness (horizontal axis) constant. In this illustration, the rationale behind the terminology windowing is more apparent since original image pixel values can be adjusted for a narrower or wider "window" pixel value range (vertical axis). Additionally, image pixel values can "swing" from a negative image to a positive image while adjusting contrast. The "swing" point (2048 pixel value illustrated here) can be moved left (lighter image) or right (darker image) simultaneously with change in slope (see Fig. 23). The term leveling comes about from the ability to control level of grayscale or brightness of displayed gray values and is associated with the location of the "swing" point of the horizontal axis. Fig. 23 illustrates contrast windowing where the brightness (swing point) has been moved to the left (lighter). The unique aspect of these type algorithms is that both contrast and brightness can be synchronously adjusted by the user during evaluations of changing material and thickness conditions. There are numerous LUT algorithms capable of applying contrast and brightness image processing with varying gradation effects.

Fig. 24 and Fig. 25 illustrate several features within a structural weld with different win-levels (graphical display in upper left corner). Fig. 24 employs high contrast with a lighter display level. With these sample illustrations, it can be observed that higher contrast levels sometimes render better visual details at lighter display levels. The reason is that as the overall display levels become darker, differences in actual pixel values between the feature and the background become less visually distinguishable.

Figs. 26 and 27 illustrate several features within a pipe weld. Win-levels in Fig. 26 result in modest levels of contrast (greater latitude) with slightly less distinct features. Fig. 27

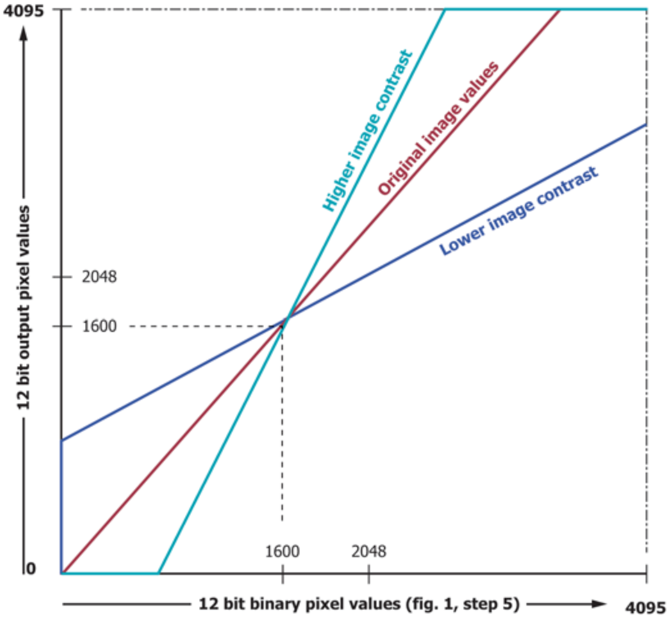


FIG. 23 Contrast and Brightness about a Lighter Midpoint

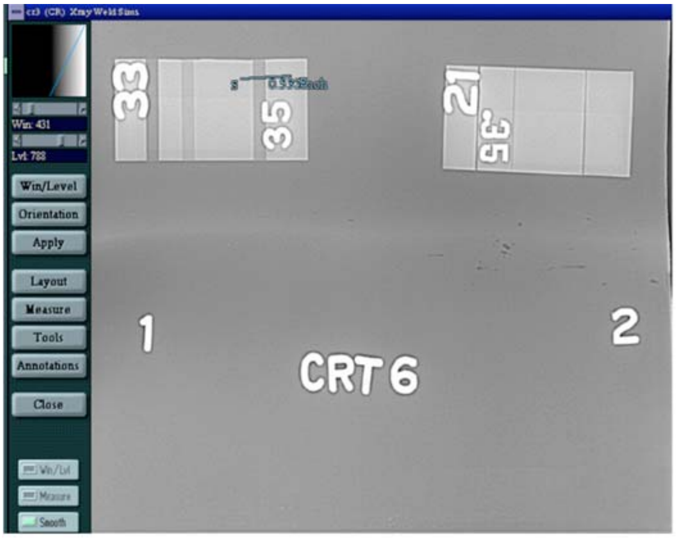


FIG. 24 Narrow Window Width (Higher Contrast)

illustrates the same image with elevated win-levels. While the features in Fig. 27 are more distinct, the overall image contains a greater visual impression of noise. The lower weld root area in Fig. 27 has received increased contrast at the expense of increased noise. This illustration is intended to demonstrate that win-level techniques must be applied discriminately against visual noise levels. Noise level can be monitored by continually assessing IQI performance, and other image details. Some software applications may contain pixel statistics (SNR) tools that can help monitor noise level changes within the image.

8.3.3 *Digital Filters:* Digital filters are a modality of image processing involving the application of algorithms that selectively reassign original pixel values to visually affect a feature, that is, a more distinct feature or an image background with suppressed noise. Although there are many innovative and

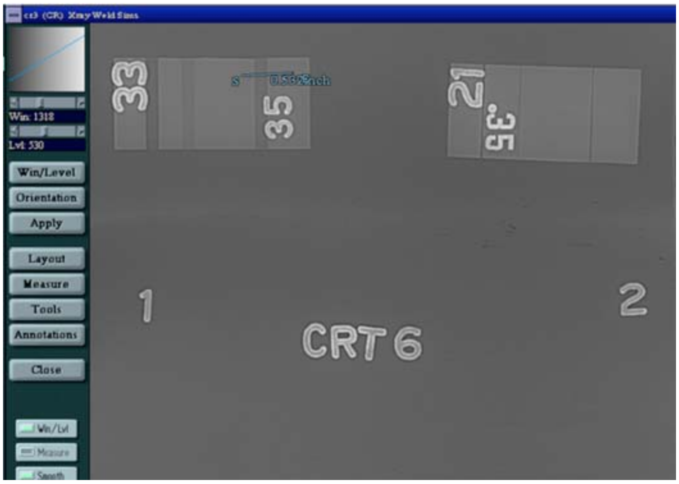
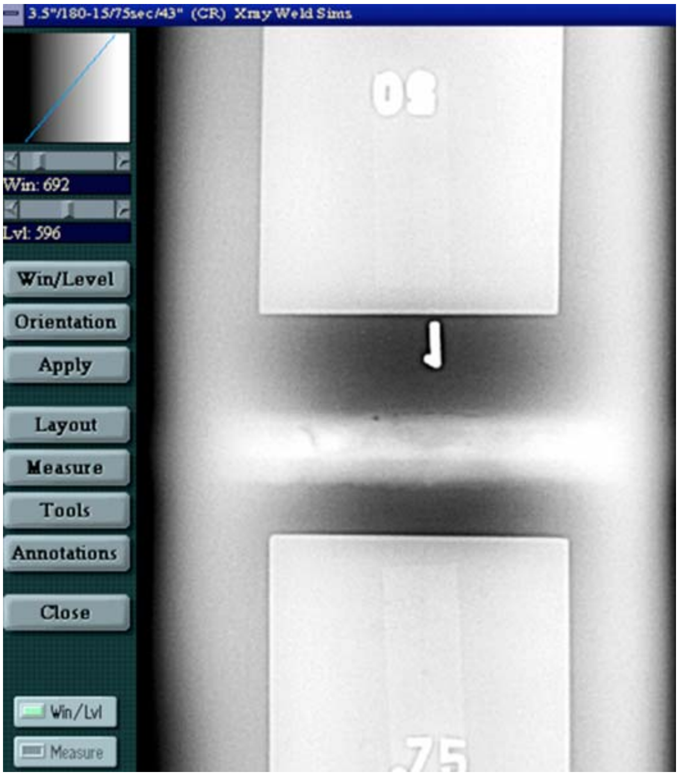


FIG. 25 Wider Window Width (Lower Contrast)

FIG. 26 Pipe Weld Features with Moderate Win-Levels

complex approaches for accomplishing this type of operation, the basic concept is fairly simple. In the course of a digital image feature becoming visually discernible, the two-dimensional geometry of the feature usually involves three categories of pixels: *1*) resident pixels (darkest); *2*) neighboring pixels (lighter shaded); and *3*) neighborhood (lightest) pixels. Fig. 28 illustrates this concept with a rounded feature enlarged to reveal all pixels contained within the image. "Resident" pixels are initially categorized (Fig. 28-A) as those pixels completely occupied within the boundaries of the feature (darker pixels within the circle in this case). "Neighbor" pixels are those pixels immediately adjacent to an original resident


3.5"/180-15/75sec/43" (CR) Xray Weld Sims

Win: 692

Lvl: 596

FIG. 27 Pipe Weld Features with Higher Win-Levels

pixel and may exists either outside or partially within the boundaries of the feature (lighter shaded pixels). "Neighborhood" pixels are all other (lightest) pixels within the surrounding background that promote sufficient contrast difference (within the image) to display the feature (round circle). Fig. 28-A illustrates resident and neighboring pixels of various gray levels within the outermost (dark line) boundary of the image. Actual gray scale (pixel value) assigned to each individual pixel will be determined by an average of original binary data (Fig. 1, Step 5) used during construction of original gray scale matrix (Fig. 1, Step 6); thus, gray scales are more likely to vary with pixels that are partially contained within the boundary of the feature (that is, near the edge) as opposed to a fully contained pixel.

Fig. 28-B illustrates an initial filter (called a high-pass filter) where neighboring (lighter shaded) pixels that have gray values "close" to resident (darker) pixel gray values have been "re-assigned" new gray values closely matching the original residents. As a result of this operation, the visual boundaries of the feature may appear more distinct (from neighborhood pixels) since gradual gray scale transitioning of original edge pixels has been replaced with more abrupt (higher contrast) changes in gray values. Since some of the original boundary neighbor pixels now become "resident" pixels (defined within the new dotted line boundary), the image of the feature now becomes more visually pronounced.

Fig. 28-C illustrates a subsequent application of this same high-pass filter where the computer is again tasked to re-evaluate the gray value relationships between new resident (darker) pixels and new neighboring (lighter shaded) pixels using similar criteria used during the initial high-pass filter. The "relationship" may be user definable (depends upon the software capability) such that smaller or larger differences in gray values between resident and neighboring pixels result in a proportionate conversion of additional neighboring pixels to residents.

Strict definitions of pixel categories are usually determined via a defined percentage difference in pixel values between each of the three categories. For example: a single pixel that may be partially occupied by the feature can be "tagged" (by the software) as any of the three categories (resident, neighbor or neighborhood) based upon its measured pixel value. In general, the more "liberally" the filter is applied, the less strict is the declared percentage difference between a resident pixel and a neighboring pixel before the neighbor is reassigned the same pixel value as the resident. An alternate approach would be the reverse process where a neighboring partially occupied pixel is reassigned the same pixel value as a neighborhood pixel (sometimes called noise reduction). With this basic concept, many algorithms can be designed such that a multitude of filters can be used dependent upon the particular feature geometry and its surrounding neighborhood (background). An algorithm can be applied to the entire image file that samples all pixels within specified values and determines a statistical relationship (within specified standard deviation limits) to neighboring pixel values. Depending upon the base pixel values specified by the filter and the deviation limits, the filter (algorithms) will attempt to adjust values of neighboring pixels to "fit" within limits specified. Some commercial filter applications tend to concentrate on image pixel groups that have adjacent neighboring pixels that are "just" outside of the specified limits. These pixels then become "targets" for reassignment of pixel value, using available LUT's, that bring neighboring pixel values more in-line with larger pixel groups (that is, that have similar pixel values). The effect can result in a significant alteration in pixel value transition (difference) from one group to another such that details can be more readily discernible, both visually and mechanically (using pixel profiling methods). If the filter application was effective, the results may be visually observed as improved image sharpness, reduced noise or both. If the filter application was ineffective, the results may be visually observed as enlargement, geometric distortion or both of the original image feature. Successive re-application of filters (stages) usually repeats the same basic process, except the effect can be accumulative. Most digital filtering processes use some variation of this basic approach; however, there are several noteworthy things to remember when using digital filters. First, if the original image file is saved subsequent to filtering, the modification is usually permanent (cannot be undone); secondly, use or selection of a filter that over samples may distort an image file, introduce noise not previously present or both. This can be done on the first filter application or with subsequent additional uses of filters that have an accumulative effect. The end result can lead to image "morphing" or permanent alterations far from the original image that may be significantly degraded from the desired image quality. The use of filters does not always produce an image feature with enhanced visibility characteristics. Filters can be aggressively applied to an image that is only

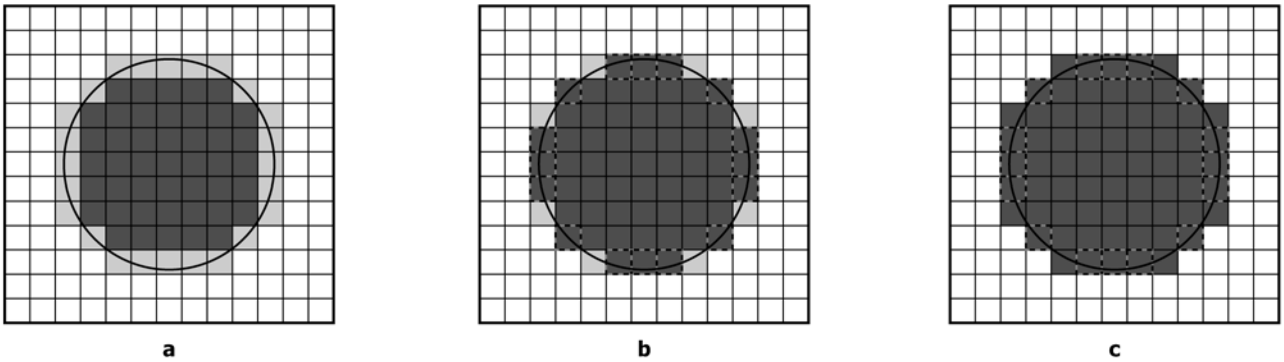


FIG. 28 Illustration of Digital Image Pixel Filtering (Refer to text)

marginally susceptible for improvements due to over use of pixel summation techniques. The results can produce pixel regions that are summed well outside original registration areas associated with the feature; thus, distorting the true shape or boundaries of the feature. Filters must be selectively applied to image features based upon known or anticipated geometry or primary feature shape. For example, when attempting to resolve the smallest line pair group of a line pair gauge, the use of a sharpening filter (for example, edge) may actually lessen the degree of discernible separation between wire pairs indicating that basic spatial resolution of the image is reduced. The cause of this is associated with those algorithms that apply summations and averages of nearby pixels (in this case two lines very close together) to bring the two lines into focus as a single line. Another example is the use of sharpening filters to discern the maximum number of relative image quality indicator (RIQI) holes on an Practice E746 RIQI plaque. *Selective* use of sharpening filters can potentially increase the overall level of discernability; however, over application of this filter may result in increased noise levels that can diminish confidence levels of smaller holes or feature discernability within this RIQI. Filters that are applied to an entire image or region of an image can not usually distinguish or separate background anomalies from an examined feature; consequently, background anomalies may also be enhanced along with the feature resulting in undesirable image noise. A common condition associated with overdriving filters is "blooming" or "flare." Blooming is an undesirable condition exhibited by unusually large differences between light and dark areas of an image feature (that is, dense material adjacent to less dense material). The cause of this undesirable condition is usually the result of excessive averaging of neighboring pixels around the boundaries of the feature which results in degraded spatial resolution and gray scale rendition. Example: images of tungsten inclusions within ferrous welds that have received large degrees of filtering may appear larger or the feature may have a halo of lighter pixels around it. A solution is usually to back-off the degree of filter application to affect a normal feature appearance. Again, the use of reference workmanship samples (and experience) with similar conditions will usually promote correct and consistent dispositions of these conditions.

8.3.4 *Pixel Histograms:* Fig. 29 illustrates a 12-bit digital image pixel histogram for an exposed part. Essentially, this histogram is a compilation of all pixels within the entire image categorized by each pixel's gray scale shade. A pixel histogram should not be confused with a pixel profile plot or scan as they are not the same. A pixel histogram is a frequency distribution of the pixel values within a digital image. Since there are many pixels within a 12-bit digital image, there can be many pixels with the same pixel value. The basic idea with the use of a histogram is for identification of areas within the image that might not be associated with or as important to the primary area(s) under evaluation (exclusion from image processing) or to change pixel brightness/contrast in selected regions of the histogram. For example: overexposed dark areas adjacent to part edges from an oversized detector. These areas can usually be readily identified from the part layout on the detector and discriminators applied to eliminate these pixels from the primary image prior to processing. This not only conserves file space but allows output processing techniques to be more discriminately applied to important areas under evaluation. Histogram information can be applied during output processing or, with some software applications, during input processing. Either approach can be effective provided the user has good control over the process. CR applications that automatically apply histograms in the form of automatic exposure normalizations, or other automated techniques should be well understood and fully controllable prior to any production applications. Histogram processing techniques performed during creation of the original gray scale data matrix are considered original image data, whereas histogram processing performed during subsequent processing (and subsequently saved) will modify the original image file.

8.3.5 *Digital Magnification:* Subsection 7.1.7 introduces field-of-view (FOV), pixel density and their relationship to digital enlargement of images. It is common knowledge among radiographic inspectors that image enlargement can be a valuable tool during inspections. It is probably not as common knowledge that digital enlargement is actually a type of manipulation (processing) of pixels to alter the degree of visibility. So, how does it work? Subsection 7.1.5 introduced acquired pixel density, pixel size and their relationship to a display monitor and image resolution. Example: a 14 by 17 in. CR image plate is scanned with a 100 micron scanner yielding a 16 mega pixel image size. Each pixel is approximately 0.004 by 0.004 in. (0.100 by 0.100 mm) in size. If these pixels are subsequently displayed (on the same size scale as scanned) on a four mega pixel monitor, where do the "extra" pixels go? The

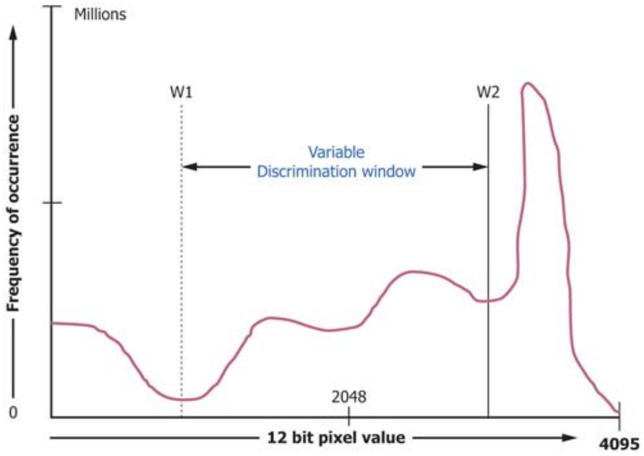


FIG. 29 12-bit Full Digital Image Pixel Histogram Illustration

answer is that most software display algorithms either average or sample available image pixels for a given display area size resulting in a condensed pixel image matrix. The exact procedure will depend upon the software application; however, the original number of image pixels is preserved within the image file. As an image is digitally "enlarged" on the display monitor, the additional pixels are used (by the viewing software) to fill in would be voids within the pixel matrix constituting the image. As long as the displayed digital image is not enlarged by more than about 4× (in this example) there will be sufficient pixels available to match the original scanned pixel density (16 mega pixels) of the CR image. If this same image example is digitally enlarged beyond 4×, the software will usually enlarge each pixel in order to enlarge the image thereby reducing original pixel density. If the digital image continues to receive further enlargements, eventually the image will result in pixel sizes that become visually apparent (pixilation) and distort the image. Digital enlargements of CR images can be a very effective means of visual enhancement of feature details as long as the original pixel density is not compromised. It is also noteworthy that, for this very same reason, CR images printed with DICOM compliant printers may result in higher resolutions than the same image electronically displayed. Most DICOM printers have the capability to print the full pixel density of the original scanned CR image. It is also noteworthy that electronic display monitors should be capable of displaying the greatest pixel density required to meet visual resolution requirements. It should also be noted that software measurements of resolution (that is, duplex wire pairs) using pixel profiling methods may use the full pixel density whereas a visual evaluation of this same gauge will be limited to the display capability of the monitor.

8.3.6 *Pseudo-Color:* As the name implies, an original gray scale image is converted to colors. This is performed with algorithms that assign colors in relative proportion to pixel gray values. The primary advantage of colors to imaging systems is associated with color bit depth (usually measured in billions of colors) and the ability to electronically display and visualize a greater number of colors than gray values. Some image features can potentially reveal significant detail not achievable in gray. This is not a new phenomenon. Many animals have only gray scale vision and consequently are not able to distinguish prey (or potential food sources) that have colors close to their environmental background. Color photographs often reveal details that are remiss in gray or B&W. Pseudo color processing has seen considerable application in industrial CR for corrosion evaluations where feature depths can vary over wide ranges. Since depth directly affects pixel intensity value, different colors can be assigned such that depth limits are more readily distinguishable. Pseudo color processing may not be suitable for all applications since some materials can vary in density due to surface or other anomalies not associated with the intended inspection.

8.4 *Dimensional Measurements:* Prior to performing any electronic dimensional measurements, the display system will require calibration. This is performed within the viewing software by radiographing a part of known dimensions and displaying the image of this part on the monitor. The measurement device may also be automatically calibrated using the known pixel size; however, this pertains only to the detector surface. Care should be taken to consider any optical enlargement (see Fig. 19) or digital enlargement of the image area or feature to be measured. It is recommended that CR systems be periodically evaluated for accuracy of all electronic measuring methods. Acquiring dimensional measurements directly from or on the face of the electronic display is **not** recommended. For information: standard (calibrated) radiopaque rulers are commercially available that can be used (exposed with a part) to measure the accuracy in both horizontal and vertical display dimensions. These are especially useful when evaluating a range of dimensional accuracies. An alternative measurement standard is by means of use of the test phantom prescribed in Practice E2445. It is recommended that the CR user never assume any accuracy of this tool without prior and meaningful validations.

8.5 *Depth Measurements:* Some CR applications may require calibration of pixel value as related to material mass/thickness. Applications like corrosion assessments may find this feature particularly useful. Similar to dimensional calibrations, depth/pixel value will require at least two parts of known mass/thickness to serve as reference points for this calibration. The concept involves taking pixel value measurements directly on two reference parts with the software interpolating all mass/pixel values between these two points. Dependent upon the application accuracy requirements, it may also be desirable to perform linearity assessments of the accuracy of these depth/pixel value correlations. Calibration of any radiographic imaging system, especially in regard to depth, is limited to the accuracy of technique employed. It is highly recommended that these limitations be well established with objective qualification data prior to use in any production applications.

8.6 *Artifacts:* CR image artifacts can be defined as any undesirable anomaly, blemish or image imperfection that could hide, mask or be confused with an indication (either within the area of interest or on the base material). CR artifacts will usually fall within one of three categories of severity (as related to cost and/or disruption): Category **1** artifacts are those that may be absolved via housekeeping practices, that is, cleaning the IP or scanner optics or both. Note, handling IP's with gloves is a common practice to eliminate fingerprint and other human handling artifacts. Special cleaning fluids matched to the manufacturer's IP's are available. It is also a common practice to avoid physical contact of IP's with lead materials (such as lead screens) to prevent contamination of the phosphor and resultant artifacts; Category **2** artifacts are those that can usually be absolved with re-erasures or troubleshooting issues involving the latent image of the IP; Category **3** artifacts are much more serious, such as scratches or abrasions that penetrate into the phosphor layer, and usually necessitate replacement of the IP or other hardware components. Generally, any category of CR image artifact is not desirable on radiographic inspections regardless of the location within the image. CR artifacts that start to show up at random locations within inspection images are a good indication that preventive maintenance (PM) or other operational practices are not effective. It is very important that CR equipment procurements consider things like software PM routines that effectively clean scanner optics and that image plates are as resilient as practical.

8.7 *Ghost Images* or undesirable shadows may also appear from time-to-time. Ghost images are residual or "left-over" images that are the result of incomplete erasures or other unwanted exposure to the IP since the last use. In some cases, these left-over images may be removed by re-erasure cycles of the IP (exposure to very intense white light). Ghost images can also be caused by excessive exposure of the IP to extremely high dosages of radiation. A good example of where this can likely occur during routine inspections is at the boundaries of a part that is smaller than the IP, especially where the same basic part size/geometry is repeatedly exposed during many inspection cycles. As previously mentioned, a good PM program may be required whereby IP's are subjected to multiple or more frequent erasure cycles prior to inspection reuse. An interesting aspect of many CR systems can be observed when an IP is exposed (as in routine radiography) and scanned **without** subsequent erasure of the IP. When this same IP is scanned a second time, there is usually a residual image visible. The reason for this (other than the fact that the IP was not erased) is associated with the fact that most scanners (using high intensity red light) are incapable of 100 % efficiency with conversion of the CR latent image. This is the very reason for IP erasures following image processing; however, if something goes awry during the erasure cycle (that is, a high intensity lamp burns out) there is a good chance that ghost images may appear during review of a subsequent CR inspection. In some instances, an IP may be rescanned without erasure to capture a residual image (of reduced quality) that may be useful under specialized circumstances.

8.8 *Reference Acceptance Methods:* Many CR inspection applications will prefer the use of digital reference images when performing acceptance evaluations. Although somewhat preferential in nature and application dependant, many users will prefer to evaluate CR digital images in conjunction with a digital reference counterpart. Reference Radiographs E2422, E2660, and E2669 consists of a collection of such digital reference images for evaluation of aluminum, steel, and titanium castings, respectively. ASTM Subcommittee E07.02 on "Reference Radiological Images" has been tasked by industrial digital imaging users to develop and publish additional reference digital image standards.

8.9 *Saving CR Inspection Images:* The concept of archival preservation of electronic CR inspection images is complex and involves issues of standardization among users and the various commercial imaging systems that meet technical qualification requirements. Two basic concepts for saving a digital image file include: *1*) The digital image with headers and/or tag files; and *2*) The digital image file structure separately from headers and/or tag files. Header or tag files are usually text files that contain records related information such as technique parameters or image annotations used with the image. These files can also contain image process information (sometimes referred to as metadata) that preserves the specific set of process parameters last used or saved with the image.

8.9.1 *Saving a Processed Image*: Regardless of the type or amount of leveling and brightness that may be applied during image processing, the original digital image file structure normally remains unaltered even when the image is digitally "saved." In the event that a processed image (window and leveling only) is saved, no actual change is usually made to the pixel structural of the original digital image; however, a file is usually generated for this image that retains the last saved parameters. Some CR software applications use file tracking systems whereby any changes made to an original CR image file are made obvious. Some software applications have provisions to save an original image file along with modified image files (as well as multiple file saves for each and every modified image file). Original digital images subjected to filtering and subsequently "saved" however, will have a permanently altered pixel matrix, that is, image feature geometries and/or noise will receive permanent modifications. This is a significant potential issue regarding preservation of original CR images along with text files that track the type of filtering used. When an original image is not preserved and multiple or repeated filters are subsequently re-applied, the digital image file structure can undergo evolutionary changes that can eventually alter (called morphing) the original appearance of the part or part feature.

8.9.2 *Image File Formats*: Digital image files generated from computed radiographic inspections are usually saved in a high quality industrial file format structure such as "DICONDE" or TIFF. DICONDE format is a modified version of the medical industry's DICOM digital file format and is designed for industrial users who want to share CR image files and be able to open and view these original images (with all related records/annotations) on different manufacturer's viewer software and/or CR systems. Practice E2339 is a standard file format that accomplishes this objective.

8.9.3 *Image File Save Media*: There are three basic media types currently available: magnetic, optical, and flash. Each storage media has advantages and limitations that must be considered by the user for the particular application. If data compression techniques are used, a lossless method is recommended. Any storage media should be "write" protected and stored in an environment that preserves the physical character of the media. Guide E1453 is a standard for preserving digital radiographic media. A good practice is that a minimum of two media sets of preservation files be maintained in two separate physical locations of the using activity. Both sets of media preservation files should be protected from potential damage from environmental conditions as well as pilferage or inadvertent misplacements.

9. Calibration

9.1 There are several aspects of the CR system that require routine evaluations to assure maximum performance capability during inspections. Practice E2445 provides the most common scanner and system calibration attributes; however, the following attributes are especially noteworthy.

9.1.1 *Photomultiplier Tube (PMT)*: The gain (voltage) of the PMT (see Fig. 3) should be regularly checked for variation of voltage level output for a standard increment of PSL measured. This is typically performed by a technician who will make a CR test exposure in conjunction with a radiation detection device. The IP is then processed (scanned) using a standard level of gray scale input values. Following processing, the average output pixel value (over several pixels of image area) is compared with the radiation dose given to the IP. If measured output pixel value is out-of-tolerance from the CR manufacturer's standard, the voltage of the PMT is raised or lowered accordingly. The effect of an out-of-tolerance PMT is that CR exposure curves data may not be linear, consistent or an accurate representation of established CR exposure techniques resulting in examination images that are potentially under or over exposed or more noisy than desired.

9.1.2 *Electronic monitors*: As discussed in 8.2, a periodic routine should be established whereby critical attributes of display performance are evaluated.

10. Keywords

10.1 computed; contrast; digital; image plate; media; monitor; noise; pixel; radiography; resolution; scanner

11. Reference Materials

11.1 In addition to reference materials of Section 1, the following literature sources are recommended for additional information and general knowledge pertaining to computed radiography:

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11.1.14 McMaster, Robert C., *Nondestructive Testing Handbook, Volume I*, section 13 on Radiation and Particle Physics, New York, Ronald Press, 1963

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