Date: Aug. 18th, 2011

Guidelines for the Use of Digital Detector Arrays and Computed Radiology for Aerospace Casting Inspections

1 Scope

1.1 This document establishes the minimum requirements for the radiological examination of aerospace castings using either a Computed Radiography (CR) or a Digital Detector Array (DDA) system.

1.2 This document applies only to radiologic examination using an x-ray source.

1.3 Either discrete criteria and/or the use of ASTM digital reference images will be required.

1.4 This document 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 document to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2 Referenced Documents

2.1 The following references form a part of this document to the extent specified herein:

2.2 ASTM Documents

a. E 746 Standard Practice for Determining Relative Image Quality Response of Industrial Radiographic Imaging Systems

b. E 747 Standard practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators Used in Radiology

c. E 1000 Standard Guide for Radioscopy

d. E 1025 Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality indicators Used for Radiology

e. E 1030 Standard Test Method for Radiographic Examination of Metallic Castings

f. E 1165 Standard Test Method for Measurement of Focal Spots of Industrial X-ray Tubes by Pinhole Imaging

g. E 1316 Standard Terminology for Non-destructive Evaluations

h. E 1647 Standard Practice for Determining Contrast Sensitivity in Radiology

i. E 1734 Standard Practice for Radioscopic Examination of Castings

j. E 1742 Standard Practice for Radiographic Examination

k. E 1817 Standard Practice for Controlling Quality of Radiological Examination by Using Representative Quality Indicators (RQIs)

l. E 2104 Standard Practice for Radiographic Examination of Advanced Aero and Turbine Materials and Components

m. E 2002 Standard Practice for Determining Total Image Unsharpness in Radiology

n. E 2007 Standard Guide for Computed Radiology

o. E 2033 Standard Practice for Computed Radiology

p. E 2339 Standard Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)

q. E 2422 Standard Digital Reference Images for Inspection of Aluminum Castings

r. E 2445 Standard Practice for Qualification and Long-Term Stability of Computed Radiology Systems

s. E 2446 Standard Practice for Classification of Computed Radiology Systems

t. E 2597 Standard Practice for Manufacturing Characterization of DDA's

u. E 2660 Standard Digital Reference Images for Investment Steel Castings for Aerospace Applications

v. E 2698 Standard Practice for Radiological Examination Using Digital Detector Arrays

w. E 2669 Standard Digital Reference Images for Titanium Castings

x. E 2736 Standard Guide for Digital Detector Array Radiology

y. E 2737 Standard Practice for Digital Detector Array Performance Evaluation and Long-Term Stability

2.3 Other Documents

a. EN 12543-5, Non-destructive testing - Characteristics of focal spots in industrial X-ray systems for use in non-destructive testing - Part 5: Measurement of the effective focal spot size of mini and micro focus X-ray tubes

b. NAS410, NAS Certification and Qualification of Nondestructive Test Personnel

c. USAF report AFRL-RX-WP-TR-2009-4069, Development Of The USAF Computed Radiography (CR) Process Control

3 Terminology

3.1 Please see ASTM E 1316 as well as the other ASTM CR and DDA standards listed in Section 2 for a complete set of standard NDT x-ray definitions.

3.2 1:1 Pixel Mapping: An image display scenario where each pixel value received from the digital detector array, or imaging plate scanner, is mapped to a single native pixel on the display monitor.

3.3 Digital Magnification (Zoom): Any change in the pixel mapping ratio from the initially displayed (1X) image. 1X digital magnification is defined as a mapping of the entire data set from the digital detector array, or imaging plate, to the maximum available display window.

4 Significance and Use

4.1 This document describes the recommended procedure for aerospace casting inspection using either CR or DDA's. Additional USAF Specific Guidance is listed in Appendix A.

4.2 Unless specific direction is received from the purchaser, radioscopic inspection sources may continue to use equipment, personnel, and procedures which were previously approved for a particular part or assembly identification number.

4.3 This document is *not a tutorial*. Please see the following documents for background and tutorial information on radiography of castings, CR, or DDA's:

4.3.1 ASTM Documents

a) E 1000 Standard Guide for Radioscopy

b) E 1030 Standard Test Method for Radiographic Examination of Metallic Castings

c) E 1734 Standard Practice for Radioscopic Examination of Castings

d) E 1742 Standard Practice for Radiographic Examination

e) E 2007 Standard Guide for Computed Radiology

f) E 2104 Standard Practice for Radiographic Examination of Advanced Aero and Turbine Materials and Components

g) E 2446 Standard Practice for Classification of Computed Radiology Systems

h) E 2736 Standard Guide for Digital Detector Array Radiology

4.3.2 Other Documents

a) C. Bueno. Chapter 11, Digital Radiographic Imaging, in 3rd Edition of the Nondestructive Testing Handbook on Radiographic Testing, Vol. 4. Ed. R. H. Bossi, F. A. Iddings, G. C. Wheeler, P. O. Moore, American Society for Nondestructive Testing, 2002, 283.

b) Yaffe, M.J. and J.A. Rowlands. "X-Ray Detectors for Digital Radiography." Physics in Medicine and Biology. Vol. 42. London, United Kingdom: Institute of Physics in association with the American Institute of Physics and the American Association of Physicists in Medicine (1997): p 1-39.

c) Uwe Zscherpel , Uwe Ewert and Klaus Bavendiek, "Possibilities and Limits of Digital Industrial Radiology - The new high contrast sensitivity technique - Examples and system theoretical analysis", International Symposium on Digital industrial Radiology and Computed Tomography, June 25-27, 2007, Lyon, France.

d) Klaus Bavendiek, Uwe Heike, William D. Meade, Uwe ZscherpeL, Uwe Ewert, New Digital Radiography Procedure Exceeds Film Sensitivity Considerably in Aerospace Applications, ECNDT 2006.

e) 2009-09-01 FWG-IDR Guide for the Qualification of Digital Radiography Systems and Processes

f) 2009-09-01 FWG-IDR Recommended Training Curriculum for Digital Radiography Personnel (Level III)

g) 2009-09-25 FWG-IDR Guide for the Standardization and Management of NDT Data

h) 2009-10-30 FWG-IDR Guide on Hardware for High Energy Applications

5 Requirements for DDA and CR System Performance Evaluation for Casting Inspection

5.1 System Performance Evaluation Protocol

5.1.1 When CR or DDA systems are first implemented for casting inspection, system performance shall be verified as specified in Appendix B and the references cited therein.

5.1.2 Additional information regarding CR performance checks is provided in Appendices B1 and B2.

5.2 Determine allowable technique parameters to meet minimum image quality requirements.

5.2.1 The technique shall be documented and include, at a minimum where applicable:

a) Drawing sketch or photograph of the setups, showing the location and orientation of the part and IQI (Image Quality Indicator) with respect to the x-ray source, detector or image plate (IP)

b) Kilovoltage (kV)

c) Tube current (mA or microA)

d) Exposure time (for CR)

e) DDA image capture settings (e.g. frame rate or frame exposure time, number of frames averaged, total exposure time)

f) X-ray tube manufacturer, model, and focal spot size used (includes variable focal spot size settings)

g) Focal Spot to Detector Distance (FDD)

h) Focal Spot to Object Distance (FOD)

i) Geometric magnification per view (if required per Section 7.2)

j) Normalized Image Unsharpness (U_{Im} see Paragraph 7.4) for each view with a unique magnification and/or material thickness

k) Detector screens and/or filters and usage

l) DDA manufacturer and model, pixel size, basic spatial resolution

m) Imaging plate manufacturer and type/size (CR only)

n) Cassette type (CR only)

o) CR scanner settings (e.g. gain setting, resolution setting and others parameters if available)

p) X-ray beam filtration (at tube), collimator, diaphragm and/or part masking

q) Initial image review Window Level (brightness) and Width (contrast) and Digital Magnification (Zoom)

r) Image processing (settings and software revision used)

s) IQI material, type, and material thickness designation, also add frequency of use

t) Part number or equivalent

u) Part material & alloy type

v) Part thickness

w) Customer name

x) Revision level and date of the technique

y) Name and address of inspection facility

z) Required image quality level

aa) Radiographic Level III approval

5.2.2 The criteria by which the components are judged acceptable shall be indicated in the controlling documentation (e.g., the inspection procedure, technique, or interpreter sheet, etc.). Complex components may be divided into zones and separate criteria assigned to each zone in accordance with its design requirements. When used, direct references to ASTM reference radiographic standards shall include the grade level for each type of discontinuity permitted for each part or zone.

5.2.3 The requirements of this document are based on the use of Hole–type IQI's in accordance with ASTM E 1025 or ASTM E 1742. Wire IQI's per ASTM E 747, or RQI's, may only be used when approved by contract or purchase order agreements. The use of alternate IQI's or RQI's shall be described and documented in the approved procedure or technique sheet.

5.2.4 IQI selection shall be based on a thickness not greater than the nominal thickness to be radiographed. For multi-wall exposure and multi-wall viewing techniques, the IQI shall be based on the multi-wall thickness of the component. For multi-wall exposures and single-wall viewing techniques, the IQI shall be based on the single-wall thickness of the component.

5.2.5 The IQI shall be placed on each part radiographed, unless a number of identical parts are simultaneously exposed in a single image. In such a case, a single IQI shall be placed upon the source side of a part at the outer edge of the cone of radiation or farthest extremity from the central beam of radiation. For examination of irregular objects, the IQI shall be placed on the area of the part farthest from the detector. The IQI shall be placed adjacent to the area of interest since accept/ reject decisions cannot be made in the area directly beneath the IQI. Where it is impractical to place the IQI upon the part radiologically inspected, the IQI shall be placed on the source side of a separate shim, block, or like section, from the same material group. The shim, block, or like section and IQI shall be placed onto the detector at the outer edge of the cone of radiation. The shim, block, or like section shall exceed the IQI dimensions so that at least three sides of the IQI shall be visible in the image.

5.2.6 When it is impractical to continually place IQI's on a part requiring more than one exposure, or a series of similar parts, using the same radiologic technique, a single exposure taken with the applicable IQI's both before and after an inspection interval may be used to qualify the examination process. As long as the radiologic technique is not changed, subsequent exposures may be performed without IQI's and at intervals not to exceed once per shift. The examination results shall be invalid if the before and after IQI images fail to demonstrate the required sensitivity. The before and after IQI images shall be considered a part of interpretation and archiving.

5.2.7 Scattered radiation shall be controlled during radiologic inspection as necessary to meet the minimum image quality requirements. Images not displaying the required image quality shall be re-acquired. Filters (as defined is ASTM E1316 Section D) shall be used as required to achieve required image quality, IQI sensitivity, or both.

5.2.8 Each IQI shall represent an area of interest in which radiographic pixel values are +/- 15% of the pixel (gray) value measured through the body of the IQI.

5.2.9 Additional IQI's shall be used, as necessary to cover the entire thickness range of the object. When the pixel (gray) value of the IQI varies by more than +/-15% from the area of interest, two IQI's used in the following manner are acceptable. If one IQI shows an acceptable sensitivity in the darkest portion (+/-15%) of the image, and the

second IQI shows an acceptable sensitivity in the lightest portion (+/-15%) of the image , the two IQI's shall serve to qualify the image within these thickness limits.

5.3 Quality Control Requirements

5.3.1 Process control procedures shall be in place, demonstrated and documented. These shall include long term stability tests of CR or DDA hardware and image review monitors. See Appendix B.

5.3.1.1 Process control checks listed in Appendix B shall be conducted using a documented technique or procedure.

5.3.1.2 Tolerance limits for process control checks shall as specified by this document or the applicable reference listed in Appendix B. Tolerance for geometric distortion in Appendix B shall be ± 0.15".

5.3.1.3 Tolerances for process control checks requiring the use of Statistical Process Control (SPC) data shall be determined using the protocol defined in Appendix B.

5.3.1.4 Where tolerance limits for a process control check are not specified, they shall be determined by the Level III.

5.3.2 Technique documentation shall be established and include the items in Paragraph 5.2.

5.3.3 A Digital Radiography Personnel Training and Certification Program shall be documented as required. See Appendix C and D.

5.3.4 Certification of compliance and/or calibration for all gages and IQI's shall be in accordance with the referenced ASTM standards unless otherwise agreed by the Prime/CEO (Cognizant Engineering Organization).

5.3.5 The user shall demonstrate system mechanical repeatability when using a programmable part manipulation system to ensure complete part coverage.

5.3.5.1 Programmable parts and/or system component manipulators shall be tested in all axis and full range of motion to document a level of accuracy and repeatability that will ensure complete part coverage during radiological examinations.

5.3.6 A system qualification shall be conducted to document the performance of the system. The qualification shall use: parts or test objects with known characterized defects/indications, IQI's, or RQI's.

5.3.7 A system qualification shall be conducted for each focal spot used in a given x-ray system. The SR_b and contrast sensitivity shall be qualified per Appendix B.

5.3.8 For DDAs, the PV where saturation occurs shall be established.

5.4 Bad Pixel Management (DDA only).

5.4.1 Bad pixel clusters as defined in ASTM E 2597 containing a Cluster Kernel Pixel(s) (CKP) are not allowed unless they are identified and displayed by the imaging software so that they may be treated as an image artifact(s).

5.5 Artifact Management

5.5.1 Any image containing artifacts in the inspection area of interest shall be re-acquired when the artifact interferes with image interpretation or can be interpreted as a defect.

5.5.2 For detailed artifact management of CR images refer to ASTM E 2445.

5.5.2.1 If the artifacts are determined to be caused by the imaging plates and result in a degradation of image quality or ability to interpret the area of interest, the imaging plates shall be replaced.

5.5.2.2 Evidence of slippage, jitter, scan line drop out, and fading effects shall be resolved through reimaging or scanner maintenance.

5.5.3 For detailed artifact management of DDA images refer to ASTM E 2698 Standard Practice for Radiological Examination Using DDA's.

5.5.4 Radiologic images with evidence of ghosting or latent images shall be re-acquired when the condition interferes with interpretation of the image.

5.6 Minimum Bit Depth

5.6.1 For the raw data / image acquisition in hardware, the minimum bit depth shall be 12.

5.7 Gain and Offset Correction (DDA's only)

5.7.1 DDA systems shall be calibrated prior to use for casting inspections based on the recommendations or procedures supplied with the DDA or the DDA acquisition software.

6 Requirements for Implementation

6.1 Training and Qualification of Personnel

6.1.1 Personnel performing examinations in accordance with this guideline shall be qualified in accordance with NAS 410 and certified by the employer or certifying agency as applicable. Other personnel qualification and certification documents may be used when specified in the contract or purchase order.

6.1.2 Additional training and experience specific to digital radiography shall be provided for radiographers, including certified film radiographers, as part of the qualification for digital radiography prior to certification and the inspection of aerospace castings for final part acceptance.

6.1.3 A recommended training outline for digital radiography should include topics shown in Appendix C.

6.1.4 Additional hours of formal training as on-the-job experience shall be provided to currently qualified film radiographers to become qualified digital radiographers. The required supplemental hours are listed in Appendix D.

6.1.5 Inspectors shall not continuously read images for more than two hours at a time. To reduce eye fatigue, a minimum of 15 minutes must elapse with no activity requiring high visual concentration prior to resuming inspection.

6.2 Image Archival

6.2.1 When required, images shall be archived using a reproducible electronic medium. Data file format and storage compliance with ASTM E 2339, Digital Imaging and Communication in Nondestructive Evaluation (DICONDE). Current systems not in compliance with ASTM E 2339 will have until December 31, 2012 to meet this requirement, unless agreed upon by the Prime/CEO. (Note: the stated bit resolution is referring to the actual format of the image data file, not the digitization capability of the CR/DDA system).

6.2.2 Image archival method shall be documented and proven (at system installation). This shall include the image file nomenclature to enable the retrieval of images at a later date.

6.2.3 Archived image files shall maintain the bit depth and spatial resolution of the original image. Image data compression is not allowed.

6.2.4 The initial image presented by the CR or DDA system shall be preserved (stored) without altering the original spatial resolution and pixel intensity. The final image used for disposition shall also be preserved (stored) when additional image processing is applied (excluding window/level and digital magnification) to achieve the required image quality level. Annotations made to the image shall be stored in a manner which will not mask or hide diagnostic areas of the image.

6.2.5 Recording media shall meet the contractual record retention requirements.

6.2.6 Records shall be grouped, indexed and identified in a manner that allows for access and retrieval.

6.2.7 Images submitted to customers shall meet the requirements of this section.

6.3 Environmental Conditions

6.3.1 Humidity and temperature shall be maintained within the limits stated by the system manufacturers. This applies during the use of the system as well as during the transportation and storage of the system hardware.

6.3.2 If, during the course of system operation, the environmental conditions recommended by the system manufacturer are exceeded, a system performance check (Appendix B) shall be conducted.

6.4 Inspection Room Cleanliness

6.4.1 Inspection facilities, including equipment and materials, shall be capable of producing uniform images free of blemishes or artifacts, which interfere with interpretation in the area of interest. Therefore, environmental conditions shall be controlled to prevent introduction of artifacts into the images and minimize wear on the system hardware components. See Section 6.3.

6.5 Handling Imaging Plates

6.5.1 Imaging plate cassettes shall be visibly clean and free of dust, dirt and debris prior to insertion into the imaging plate reader. Imaging plates shall be cleaned in accordance with the manufacturer's instructions.

6.5.2 Imaging plates shall be erased prior to use.

6.5.3 Exposed imaging plates shall be handled in conditions of subdued background lighting free from any source of ambient red light such as darkroom safelights.

6.5.4 Imaging plate cassettes shall be constructed of material that does not interfere with the quality or sensitivity of the radiographic images.

6.6 System Preventative Maintenance

6.6.1 Preventative maintenance (per manufacturer's recommendations) shall be performed and documented to ensure the system generates uniform images free of blemishes or artifacts, which interfere with interpretation in the area of interest.

6.7 System Malfunctions

6.7.1 Where there is reasonable doubt about the ability to interpret the radiographic image because of improper technique or equipment malfunction, the test object shall be re-examined using the correct procedure. If the problem is not resolved by re-examination, the procedure shall be reviewed by the Level III of the NDE facility and adjusted if necessary. If the reexamination was caused by equipment malfunction, the equipment may not be returned to service until the equipment is re-qualified to the current qualification requirements.

6.8 Measurement Accuracy

6.8.1 A system of measurement verification shall be documented. When a physical standard is included in the image, it shall be positioned to be subjected to the same geometric magnification as that of the area of interest of the part. The physical standard shall be calibrated or measured with a calibrated tool when establishing software calibration. The user and the CEO shall agree to the level of measurement accuracy required.

6.9 Correlation Study

6.9.1 A correlation qualification study between film and images shall be conducted and documented. This study will be defined based on complexity of hardware and volume of production. Correlation study requirements shall be defined and provided to the cognizant Level III.

6.9.2 Correlation studies may be waived by the cognizant Level III if similarity to prior correlation qualification studies is documented (e.g. like parts).

7 Image Quality Requirements

7.1 Image Quality Level

7.1.1 Acceptance criteria may require higher image quality requirements, as determined by the Prime/CEO, than those listed below.

7.1.2 Image quality shall be 2-2T unless otherwise specified by the Prime/CEO.

7.1.3 The following measurements/calculations shall be established at technique development:

a) Minimum geometric magnification (υ) - see Paragraph 7.2

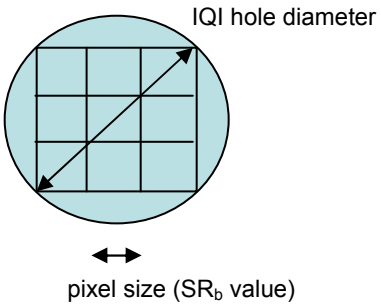
b) Normalized image unsharpness (U_{lm}) - see Paragraph 7.4

c) Contrast to noise ratio (CNR) - see Paragraph 7.5

7.2 Magnification (Geometric) Technique

7.2.1 The magnification shall be set to ensure that an IQI hole contains enough pixels to accurately identify the shape of the discontinuities of interest for casting inspection. The required effective pixel density shall be achieved when a 3x3 pixel matrix, with

the pixel size defined as the basic spatial resolution of the detector (SR_b - see Paragraph 7.3 below), fits inside the diameter of the required IQI hole of interest as shown in the figure below:



7.2.2 If the requirements of 7.2.1 cannot be met without the use of geometric magnification at the area of interest on the part, then the minimum required geometric magnification (υ_{min}) required to achieve the required 3x3 pixel matrix shall be defined by the following equation:

$$\upsilon_{\min} = \frac{4.25 * (SR_b)}{d}$$

Where SR_b is the value measured per Paragraph 7.3, and d is the diameter of the IQI hole.

7.3 Measurement Procedure for Basic Spatial Resolution (SR_b)

7.3.1 Calculation of image unsharpness and determination of minimum magnification per this document requires measurement of the basic spatial resolution (SRb) of the detector and image plate / CR scanner. Note: use the method specified in E2597 for both DDA's and CR systems.

7.4 Image Unsharpness Requirements:

7.4.1 U_{Im}, describes the image unsharpness in the object plane. The maximum allowable value of image unsharpness (U_{Im}) for casting inspection is given in the following table and shall be determined by E2002 or the calculation outlined in 7.4.2. This applies to both CR and DDA's.

Casting Section Thickness	Maximum Image Unsharpness (U_{Im})
0.5 inch and below. [≤ 12.7 mm]	0.010 in. [0.254 mm]
Over 0.5 in. through 1 inch [>12.7 through ≤ 25.4 mm]	0.015 in. [0.381 mm]
Over 1 inch through 2 inches [>25.4 through 50.8 mm]	0.020 in. [0.508 mm]
Over 2 through 4 inches [>50.8 through 101.6 mm]	0.030 in. [0.762 mm]
Over 4 inches [>101.6 mm]	0.040 in. [1.016 mm]

7.4.2 For DDA's U_{Im} may alternatively be computed using the following formula:

$$U_{\mathrm{Im}} = \frac{1}{\upsilon} \cdot \sqrt[3]{U_g^3 + (1.6 \cdot SR_b)^3}$$

Where:

$$U_g = (\upsilon - 1) \cdot \phi$$

and υ[1] is the largest geometric magnification present in the inspection image (i.e., the maximum distance from the source to the detector/imaging plate divided by the minimum distance between the source and the part), ϕ is the focal spot size per ASTM E 1165[2], and SR_b as calculated using the method specified in ASTM E 2597.

[1] Note: υ in this equation is different from υ_{min} in paragraph 7.2.2.

[2] Note For calculating focal spot sizes on mini-focus or micro-focus tubes use EN12543-5.

7.5 Contrast to Noise Measurement for DDA's

7.5.1 Once magnification has been set and the IQI sensitivity level has been established visually, the CNR shall be measured as follows:

7.5.2 The appropriate IQI shall be placed on the object in the area of interest, or on a shim block of equivalent thickness, and the mean (gray) value of the pixels inside the 4T hole on the IQI of interest and a neighbouring region on the IQI (outside of the hole) shall be measured. The difference in the two pixel (gray) value means shall be

divided by the standard deviation of the pixel (gray) value region outside of the hole and the resulting quantity is the contrast to noise ratio (see formula below).

$$CNR = \frac{Mean\ pixel\ value\ inside\ IQI\ 4T\ Hole - Mean\ pixel\ value\ on\ IQI}{S\tan dard\ deviation\ \ of\ \ pixel\ values\ on\ IQI\ adjacent\ \ to\ 4T\ Hole}$$

7.5.3 The CNR lower limit shall be 2.5 for DDA's.

8 Image Viewing Protocol and Requirements

8.1 Window Width (Contrast) and Level (Brightness)

8.1.1 The initial window width and level values shall be approved by the Level III, when developing the inspection technique, such that the required image quality level is visible.

8.1.2 The initial window width and level values shall be documented in the part specific inspection technique, either with quantitative values or by defined viewing presets. This includes any multiple width and level values or viewing presets required due to changes in thickness or material of the part.

8.1.3 Due to normal variations in part thickness the operator may need to adjust the window width and level of the image to interpret and/or evaluate indications or other areas, however, the following restrictions shall apply.

a) If no IQI is present in the image the window width shall not be changed. The maximum change in window level (brightness) shall be within ±15% of that specified in written technique.

b) If an IQI is in the image, the inspector may change both the window width and level of the image with no restrictions provided that the required quality level is visible at the new values.

8.2 Image Processing (Software)

8.2.1 Image processing used for final product acceptance shall be approved by the Level III and documented in the part specific inspection technique.

8.2.2 Since some filters can increase image noise and/or generate artifacts, the operator may remove the filter for the purpose of evaluating whether an indication is real or

an artifact, however, initial image review must be done with the filter applied if required by the inspection technique.

8.2.3 Image processing requirements for digital reference images shall be performed in accordance with the applicable ASTM digital reference image standard.

8.3 Ambient Viewing Conditions

8.3.1 Subdued lighting in the viewing room is preferred rather than total darkness and shall preclude objectionable reflective glare on the surface of the viewing monitor that could interfere with the interpretation. A viewing room or enclosure with variable control lighting is preferable as each operator may have different background lighting needs.

8.3.2 Ambient light measured at any monitor used for image disposition shall be a maximum of 30 lux [3 foot-candles]. Ambient light shall be measured at the viewing surface with the viewing monitor off.

8.3.3 When entering the viewing room to perform final product acceptance, the inspector shall wait sufficient time, after entering the viewing area, before interpreting radiographs such that the features of the IQI are visible (hole and IQI outline), or after 1 minute has passed.

8.4 Digital Magnification (a.k.a Zoom)

8.4.1 Digital magnification shall be based on the minimum size of the feature of interest, and the size and resolution of the image display monitor.

8.4.2 For the purpose of making measurements or a correct disposition, the image may be digitally magnified beyond that specified in the technique.

8.5 Software Tools for Casting Inspection

8.5.1 The following tools have proven useful in aiding the inspector with image evaluation and are required:

a) The ability to mirror and rotate the production image at 90 degree intervals.

b) The ability to display of the production image and reference radiographic image in either negative or positive polarity.

c) A line profile function capable of displaying the pixel (gray) value and mapped gray scale values (DDL) between two points of a user defined line.

d) A histogram tool capable of displaying the pixel (gray) value and mapped gray scale values (DDL) of a user defined region of interest.

e) The ability to display the image at 1:1 pixel mapping.

f) The ability to digitally magnify the image and display the digital magnification (zoom) level.

g) A thumbnail view indicating the displayed portion of the image relative to the entire image when using digital magnification.

h) Shall be capable of panning the image,

i) Adjust the image window width (contrast) and window level (brightness),

j) Shall display corrected bad pixels of the DDA (toggle on/off),

k) Perform measurements for distance or sizing of discontinuities, the software shall be capable of calibrating the measurement tool to a reference standard.

8.6 Specialized Software Tools and Algorithms

8.6.1 Specialized software tools or algorithms may be developed to aid the operator and/or provide quantitative data for product acceptance.

8.6.2 Where specialized software tools and algorithms are written for a unique or particular application, the algorithm/tool and its application to the images must be approved by the Level III and detailed in the written technique.

8.7 Use of Digital Reference Radiographs

8.7.1 This standard is intended for use with the following ASTM digital reference radiograph standards as applicable:

a) ASTM E 2422 Standard Digital Reference Images for Inspection of Aluminum Castings

b) ASTM E 2660 Standard Digital Reference Images of Investment Steel Castings for Aerospace Applications

c) ASTM E 2669 Standard Digital Reference Images for Titanium Castings

8.7.2 Contrast adjustment shall be performed when viewing digital reference radiographs. This may be conducted using a process of contrast normalization between the production image and the reference image, or by an alternative process approved by the Prime/CEO.

8.7.3 Viewer software may apply image processing parameters to the displayed production images. This includes, but is not limited to; image processing functions such as filters, smoothing functions, edge enhancement or the conversion of data through logarithmic or exponential transformation. Application of these non-linear functions or filters to the reference image shall only be made with the approval of the cognizant Level III. A suitable function or look up table that maps the raw value grey levels to the same range of DDL for monitor display shall be used for both the production and reference images. This shall not be interpreted to mean that the window level must be the same for the production and reference images due to the possible difference in thickness between the area of interest of the production part and the reference hardware.

8.7.4 When automated contrast normalization is used, the software shall be validated through a defined image test plan and revision controlled.

9 Reports

9.1 Examination Report

9.1.1 The results of all radiologic examinations shall be documented. The examination report shall reference the acceptance criteria and revision, provide traceability to the specific part or the lot of parts examined, the disposition of the part(s) (accept/reject),

the reason for rejection of any items, and shall include the name and/or signature of the interpreter(s), or their acceptance stamp when applicable.

9.2 System Performance

9.2.1 The results of all system performance evaluations shall be documented and shall be available upon request. System Performance reports shall provide traceability to the specific DDA or CR scanner.

9.3 System Qualification

9.3.1 The results of all system qualification testing shall be documented and shall be available upon request. System qualification reports shall include the Qualification Test Plan and shall provide traceability to all system components and examination techniques.

Appendix A: USAF Specific Guidance for Implementation of Digital Radiography for Inspection of Production Aerospace Castings

Introduction

This set of appendices (A, A1, A2) provide guidelines for evaluation and authorization of digital detector arrays and/or computed radiography for in-process weld repair inspections and final acceptance inspections of USAF production aerospace castings. The term Digital Radiography refers to both digital detector arrays and computed radiography.

These guidelines were established by consensus of a USAF Digital Radiography Implementation Task Group with representatives from the Air Force Research Laboratory Materials and Manufacturing Directorate (AFRL/RXSA) and the Aeronautical Systems Center (ASC/ENFS, ASC/ENSM). The guidelines are based on experience of the task group members and the document titled "Guidelines for the Use of Digital Detector Arrays and Computed Radiology for Aerospace Casting Inspections" developed under the USAF Metals Affordability Initiative (MAI) program entitled "Digital Radiography for Final Acceptance of Production Aerospace Castings".

Questions concerning these appendices can be addressed to Air Force Research Laboratory Materials and Manufacturing Directorate, Systems Support Division, Materials Integrity Branch (AFRL/RXSA).

The long term goal is for this document to be superseded by the appropriate industry or military specification if and when they become available.

Applicability

This appendix is applicable for inspection agencies responsible for in-process weld repair inspections and final acceptance inspections of production USAF aerospace castings.

Guidelines

The USAF recommends an inspection agency to comply with the following procedures to authorize Digital Radiography for in-process weld repair and final acceptance of production aerospace castings:

1) For all cast aerospace components, compliance with the guidance document, Guidelines for the Use of Digital Detector Arrays and Computed Radiology for Aerospace Casting Inspections, is recommended.
2) Inspection agencies should develop an internal company process specification that is in compliance with the guidance document, or outsource the inspection to an inspection agency that has an internal company specification in compliance with the guidance document. Teaming with a manufacturer that is an MAI team member to develop the process specification is encouraged (Appendix A1). This process specification should be approved by the responsible USAF System Program Office prior to implementation. Original Equipment Manufacturers (OEMs) with internal company process specifications reviewed and approved by the USAF Technical Monitor Office (AFRL/RXSA) are listed in Appendix A2.
3) Inspection agencies that have satisfied items 1 and 2 above may have review and approval authority for subordinate inspection agency internal company process specifications.
4) For safety-of-flight, fracture critical, or durability critical components. Inspection agencies must demonstrate the required inspection capability. This demonstration shall be documented,

reviewed, and approved by the responsible USAF System Program Office prior to implementation. The demonstration shall be accomplished by the following means.

a. Detection capability shall be demonstrated with parts or specimens of like thickness of the part being inspected, fabricated using materials and processes representative of the part being inspected, and contain known/characterized defects[1] of the size and type which define the minimum acceptance criteria of the part being inspected.

    i. For existing film radiography applications: Side-by-side comparisons of current production film radiographs with digital radiographs are required to demonstrate equivalent detection capability. Equivalency will be achieved when the defects* are detected with equivalent fidelity as film, as determined by visual evaluation of film and digital radiographs by the Level III.

    ii. For new applications (i.e. no prior film radiography technique): Detection capability shall be determined by visual evaluation of digital radiographs by the Level III.

b. Families of parts (e.g. same alloy, thickness, similar geometry, etc.) may be qualified by similarity to existing approved digital radiography techniques as approved by the responsible USAF System Program Office.

*In lieu of defects, Image Quality Indicators (IQIs) and/or Reference Quality Indicators (RQIs) may be used if approved by the responsible USAF System Program Office.

Appendix A1: Implementation Requirements for Use of Digital Radiography for Production Aerospace Castings – MAI Program Participants

Cast material manufacturers:

- Precision Castparts Corporation (PCC) Inc.
- Howmet Castings (Alcoa)

Aircraft and aircraft engine manufacturers:

- Boeing
- General Electric
- Honeywell
- Lockheed Martin
- Pratt & Whitney
- Rolls-Royce

Digital Radiography Equipment vendors:

- Fuji
- General Electric Inspection Technologies
- North Star Imaging
- VJ Technologies
- Yxlon

Appendix A2: OEMs with Internal Company Process Specifications for Implementation of Digital Radiography for Final Acceptance of Aerospace Castings, Reviewed and Approved by USAF Technical Monitor Office (AFRL/RXSA)

Aircraft and aircraft engine manufacturers:

- Boeing (AFRL approval pending)
- General Electric Aviation (AFRL approval pending)
- Honeywell (AFRL approval pending)
- Lockheed Martin (AFRL approval pending)
- Pratt & Whitney (AFRL approval pending)
- Rolls-Royce (AFRL approval pending)

Appendix B: System Performance Evaluation Protocol

			Process Check Frequency						
	Test	Reference[3]	Initially	Quarterly	Monthly	Weekly	Daily	per shift	Repair/Replace
Computed Radiography	SRb (system spatial resolution)[1,4,5]	See Paragraph 7.3	√	√					√
	Plaque IQI block shot (visual) (contrast & spatial resolution)	See Appendix A-2	√					√	√
	Contrast sensitivity[5]	USAF App A - para. 2e	√	√					√
	Shading	USAF App A - para. 2e	√	√					√
	Jitter	ASTM E2445 6.2.2.2 or USAF App A - para. 2c	√	√					√
	Afterglow (Blooming/Flare)	ASTM E2445 6.2.3 or USAF App A - para. 2b	√	√					√
	Geometric Distortion	ASTM E2445 6.2.1 or USAF App A - para. 2a	√	√					√
	EPS	See Appendix A-1	√						√
Digital Detector Arrays	System spatial resolution[4]	ASTM E2737 para. 9.4.1	√					√	√
	Contrast Sensitivity (uses CNR)[4]	ASTM E2737 para. 9.4.2	√					√	√
	Signal-to-Noise Ratio (SNR)[4]	ASTM E2737 para 9.4.4	√						√
	Signal Level[4]	ASTM E2737 9.4.5	√				√[2]		√
	Bad Pixel Mapping	ASTM E2597 para. 6.2, 7.1.2	√	√					√
Display Monitors	Full modulation check	ASTM E2698 para. 7.5.3	√			√			
	Flicker check	ASTM E2698 para. 7.5.5	√			√			
	Distortion check	ASTM E2698 para. 7.5.4	√			√			
	1% line contrast	ASTM E2698 para. 7.5.7	√			√			
	5% contrast blocks	ASTM E2698 para. 7.5.6	√			√			
	Contrast ratio	ASTM E2698 para. 7.5.2	√		√				
	Luminous intensity	ASTM E2698 para. 7.5.1	√		√				

Flagnotes

[1] Test shall be performed using one IP type per system; [2] Required for microfocus tubes only; [3] "USAF" in this column refers to USAF report AFRL-RX-WP-TR-2009-4069, [4] Upper & lower control limits set by +/-3 sigma using SPC during daily tests the first 30 days of use, [5] SRb and Contrast sensitivity shall be qualified for each focal spot in a given x-ray system

Appendix B1: Equivalent Penetrameter Sensitivity (EPS) for Computed Radiography Systems

B1.1 The EPS performance of all CR systems shall be established by visual evaluation of computed radiographs of the ASTM E 746 Relative Image Quality Indicators placed on a 0.75 inch absorber (see figure B.1.1) for CR system qualification (B1.3 through B1.6, and for long term stability B1.7). Materials other than mild steel, as called out in E746, may be used, but the RIQI and absorber shall be made of the same materials and the energy selection shall be appropriate for the chosen material and thickness. The surface finish of the absorber shall be a maximum of 6.3 μm (250 μin) Ra ground finish, both faces.

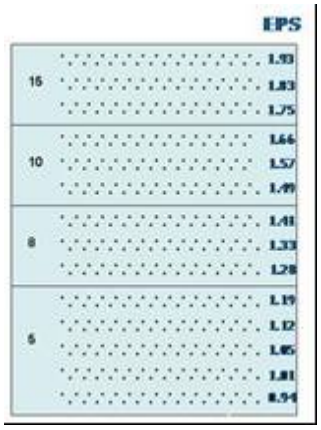


Figure B1.1: E746 RIQI (EPS plaques) placed on 0.75 inch thick absorber. Corresponding EPS values are listed alongside each row.

B1.2 The CR system is defined by components described in Section 5.2 (k, m, n, o, p, and r). If any components are altered, the CR system must be tested as a different CR system.

B1.3 Using the test standard in figure B1.1, produce a series of exposures similar those illustrated in figure B1.2. Align an X-radiation source in the approximate center of the plate between the #8 and #10 EPS plaques (plates may be slightly separated for this purpose). Focal Detector Distance (FFD) shall be a minimum of 36 inches (or 1 meter) from X-ray source. General radiographic technique parameters shall comply with this standard. Radiograph the plate series with a minimum of 10 exposures using similar technique parameters (i.e. the only technique variable is exposure time) for a range of

dose sufficient to produce a distinguishable increase in EPS at low dose and an EPS "plateau" as dose increases (see Figure B1.2). Identify the EPS "plateau" as the dose range exhibits a relatively low and consistent EPS value. Exposures should not exceed 90% MPV (i.e. for a 16 bit system, 100% MPV~65000). Determine the pixel value (PV) in the approximate center of the computed radiograph on the base plate between the #8 and #10 EPS plaques in an area free of any holes or alternatively, within a central area of the base plate alongside the EPS plaques. All CR system processing parameters, energy level and exposure data for each exposure shall be recorded and maintained.

B1.4 For each exposure, record the EPS performance by determining the duplex row where a minimum of 20 holes (out of 30 holes in each duplex row) are clearly visible. Table B1.1 provides EPS values per ASTM E 1025 for each duplex row on the standard shown in figure B1.1.

step thickness	hole dia	plate thickness	EPS% (E1025)
0.015	0.028	0.750	1.98
0.015	0.025	0.750	1.83
0.015	0.023	0.750	1.75
0.010	0.031	0.750	1.66
0.010	0.028	0.750	1.58
0.010	0.025	0.750	1.49
0.008	0.028	0.750	1.41
0.008	0.025	0.750	1.33
0.008	0.023	0.750	1.28
0.006	0.032	0.750	1.19
0.006	0.028	0.750	1.12
0.006	0.025	0.750	1.06
0.006	0.023	0.750	1.01
0.006	0.020	0.750	0.94

Table B1.1: EPS values for ASTM E 746 RIQI on 0.75 inch absorber. Thicknesses and diameters are measured in inches.

B1.5 Establish the EPS value vs. exposure. An example plot is shown in Figure B1.2

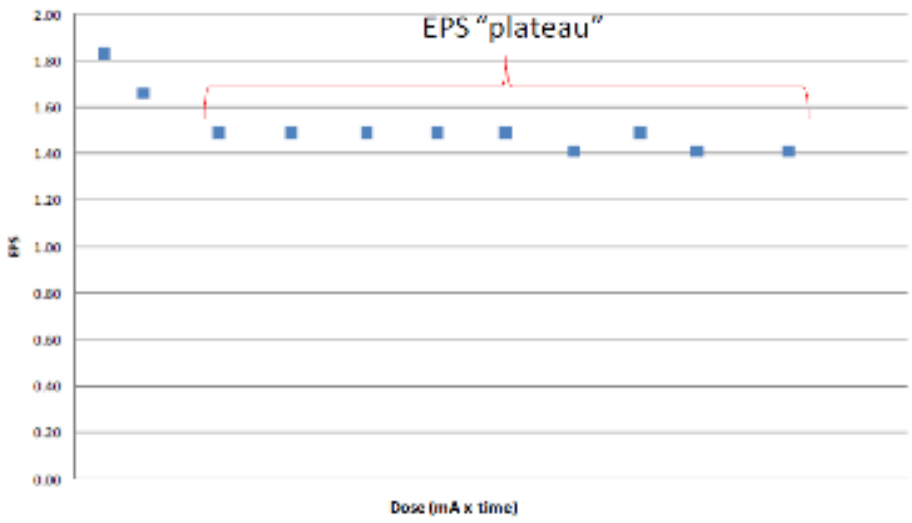


Figure B1.2 EPS vs. Exposure

B1.6 Record the EPS performance as the maximum EPS value in the EPS "plateau".

B1.7 For long-term stability tests, the EPS established in B1.6 only needs to be verified at a selected dose in the "plateau" region (i.e. only one exposure required).

Appendix B2: Plaque IQI Block Test for CR

a) CR system contrast sensitivity and spatial resolution shall be established at system installation and monitored on a per shift basis, or when system components are repaired or replaced.

b) The system performance shall consist of taking an exposure of a block of known material & thickness using a standard technique (fixed exposure parameters, scanning parameters and IP type). An appropriate 2% IQI and ASTM E 2002 duplex wire gauge shall be placed on the source side of the block.

c) At the time of installation the following shall be established using the standard technique and noted for comparison to subsequent tests:

   (1) The pixel value (grey scale value) adjacent to the 4T hole

   (2) The Contrast to Noise Ratio (CNR) value as calculated per the following formula:

$$CNR = \frac{Mean\ pixel\ value\ inside\ IQI\ 4T\ Hole - Mean\ pixel\ value\ on\ IQI}{S\tan dard\ deviation\ \ of\ \ pixel\ values\ on\ IQI\ adjacent\ \ to\ 4T\ Hole}$$

   (3) The smallest wire pair clearly visible on the Duplex Wire Gage.

d) Once per shift an image shall be obtained using the standard technique and evaluated for the following:

   (1) The 2T hole and outline of the IQI shall be clearly visible

   (2) The required Duplex Wire Gage wire pair shall be clearly visible

   (3) The pixel value (grey scale value) adjacent to the 4T hole shall be within the tolerance specified on the standard technique

   (4) The CNR value shall be within the tolerance specified on the standard technique

e) Failure of any of the above requirements requires corrective action before inspecting any production hardware.

Appendix C: Level I, II and III Training Outline

LEVEL I OUTLINE

1. Digital Introduction
   - 1.1 Definitions and Terminology
   - 1.2 Digital Images
     - 1.2.1 Bits
     - 1.2.2 Bytes
     - 1.2.3 Pixels
     - 1.2.4 Bit Depth
     - 1.2.5 Window and Level
     - 1.2.6 Spatial Resolution
2. Digital System Overview
   - 2.1 Basic Components and Functions
   - 2.2 Digital versus Film Procedural Steps
3. Digital System Operation
   - 3.1 Process Control
4. Image Fidelity
   - 4.1 Image Fidelity Indicators
     - 4.1.1 Line Pair Gauges
     - 4.1.2 Phantoms
     - 4.1.3 IQI's
     - 4.1.4 Monitor Test Patterns
     - 4.1.5 EPS Plaques
   - 4.2 Image Attributes
     - 4.2.1 Grey Value/Pixel Value
     - 4.2.2 SNR
     - 4.2.3 CNR
     - 4.3.4 Detector Saturation
5. Detectors
   - 5.1 Scatter Sensitivity
   - 5.2 Radiation Exposure Tolerance
   - 5.3 Portability
   - 5.4 Detector Handling
   - 5.5 Ghosting
   - 5.1 Aliasing
   - 5.2 Imaging Plate Erasure
   - 5.3 Image Artifacts
6. Techniques
   - 6.1 Comparison Between Digital and Film-based Technique Sheets
   - 6.2 Setting-up Exposures
   - 6.3 Setup Geometry
   - 6.4 Detector Setting
     - 6.4.1 Frame Averaging
     - 6.4.2 Frame Rates
   - 6.5 CR Scanner Settings

6.5.1 PMT Gain
6.5.2 Sampling Rate
6.5.3 Resolution (preset or variable)
6.5.4 Look Up Table (LUT) Selection

LEVEL II OUTLINE

1. General Overview of DR/CR
   1.1. Digital Basics - Bits / bytes / pixels
   1.2. Advantages / disadvantage of each (DR/CR)
   1.3. Film, CR, DDA Comparisons
   1.4. Handling DDA's and Imaging Plates
   1.5. Environmental Considerations
2. Technique Requirements and Documentation
   2.1. Technique Development per the MAI guide
   2.2. Minimum Image Bit Depth
   2.3. Measurement for SR_b
   2.4. Magnification requirements if needed (Geometric-Magnification)
   2.5. Image Unsharpness (U_{Im}) Requirements / calculations
   2.6. Contrast to Noise Ratio (CNR)
   2.7. Gain / Offset Corrections (DDA)
   2.8. IQI Selection, placement and usage (or RQI's)
   2.9. Image Review
      2.9.1. Window width/level
      2.9.2. Image Filtering (software)
3. Image Review and Evaluation
   3.1. Software Tools for Casting Inspection
   3.2. Digital Magnification (Zoom)
   3.3. Image Filtering (software)
   3.4. Window Width/Level
   3.5. Artifact Management
   3.6. Use of Digital Reference Images
   3.7. Indication measurement (and calibration of software tool)
   3.8. Accept/Reject evaluation
   3.9. Image Archiving
4. Process Control
   4.1. Ambient Viewing Conditions
   4.2. Inspection Room Cleanliness
   4.3. System Process Controls and Performance Evaluation
   4.4. System Preventative Maintenance
   4.5. Artifact Management

4.6. Bad Pixel Management

5. Lab Time (25% per day for hands on activities)
   5.1. Technique Development
   5.2. Image Acquisition
   5.3. Image Analysis
      5.3.1 System Performance Evaluations

LEVEL III OUTLINE

1. Non Film Radiology Overview
   1.1 Computed Radiography
   1.2 DDA Radiography
   1.3 Radioscopy
   1.4 Computed Tomography
   1.5 X-ray Sources for digital radiography
   1.6 Conventional sources
   1.7 Mini, & microfocus sources
   1.8 Linear accelerators
2. Common Digital System Elements and Digital Image Properties
   2.1 Digital Image Properties
      -1 Bits / Bytes
      -2 Pixels / Voxels
   2.2 Image file formats and compression (JPEG, TIFF, DICONDE)
      2.2.1 Advantages/disadvantages
      2.2.2 Lossy vs. lossless
   2.3 Sampling Theory (Digitizing)
      2.3.1 Pixel size (Aperture)
      2.3.2 Pixel pitch
      2.3.3 Bit depth
      2.3.4 Nyquist Theory
   2.4 Digital System Components
      2.4.1 Computer
      2.4.2 Operator Interface
      2.4.3 System Controller
      2.4.4 Image Processor
      2.4.5 Image display monitors
         2.4.5.1 Flat panel displays (LCD,LED,OLED)
         2.4.5.2 Display bit depth
         2.4.5.3 Monitor resolution
         2.4.5.4 Monitor testing
         2.4.5.5 Monitor Brightness and Contrast
         2.4.5.6 Test Patterns
         2.4.5.7 Monitor calibration
   2.5 Data Archive & Retrieval
      2.5.1 Removable Media - Single media (CD, DVD, tape)
      2.5.2 Redundant Array of Inexpensive Disks (RAID)

- 2.5.3 Central archive
- 2.5.4 Image retrieval

2.6 Digital System Specific Image Processing Topics
- 2.6.1 Region of Interest (ROI) and Measurements
- 2.6.2 Line Profiles
- 2.6.3 Histograms (Mean / Standard Deviations)
- 2.6.4 Discontinuity Sizing
  - 2.6.4.1 Length
  - 2.6.4.2 Area
  - 2.6.4.3 Wall thickness
  - 2.6.4.4 Blob / Cluster Analysis
- 2.6.5 Gray scale display adjustments
  - 2.6.5.1 Window Width and Level
  - 2.6.5.2 Look Up Tables (LUT)
  - 2.6.5.3 Thresholding
  - 2.6.5.4 Histogram equalization
  - 2.6.5.5 Pseudo color
- 2.6.6 Arithmetic
  - 2.6.6.1 Addition (integration)
  - 2.6.6.2 Subtraction
  - 2.6.6.3 Division
  - 2.6.6.4 Multiplication
  - 2.6.6.5 Averaging
- 2.6.7 Filtering (kernels)
  - 2.6.7.1 Convolution
  - 2.6.7.2 Low pass
  - 2.6.7.3 High pass
  - 2.6.7.4 Median
  - 2.6.7.5 Unsharp mask

2.7 System characterization
- 2.7.1 Measuring Image Fidelity
  - 2.7.1.1 Contrast & Resolution
  - 2.7.1.2 Modulation Transfer Function (MTF)
  - 2.7.1.3 Signal-to-Noise Ratio (SNR)
- 2.7.2 Image Fidelity Indicators
  - 2.7.2.1 Image Quality Indicators (IQI): Hole and Wire types
  - 2.7.2.2 Line pair gauges
  - 2.7.2.3 Phantoms
  - 2.7.2.4 Reference Quality Indicators (RQI)

3. Computed Radiography Testing:

3.1 CR System Overview
- 3.1.1 CR vs. film procedural steps
- 3.1.2 Film vs. CR Images
- 3.1.3 Linearity &Latitude
- 3.1.4 Image Plate Classifications

Appendix D: Additional Training Hours Requirement

Currently certified film radiographers shall require additional formal training and on-the-job experience prior to digital certification.

For transition to Computed Radiography, an additional 8 hours of formal training and 20 hours of supervised on-the-job experience is required for Level I, an additional 40 hours formal training and 120 hours of supervised on-the job experience is required for Level II, and an additional 40 hours formal training and 240 hours of supervised on-the-job experience is required for Level III. Following training, a Specific and Practical Exam shall be administered to reflect the comprehension of digital technologies.

For transition to Digital Radiography (employing DDA's), an additional 8 hours of formal training and 20 hours of supervised on-the-job experience is required for Level I, an additional 40 hours formal training and 120 hours supervised on-the job experience is required for Level II, and an additional 40 hours formal training and 240 hours of supervised on-the-job experience is required for Level III. Following training, a Specific and Practical Exam shall be administered to reflect the comprehension of digital technologies.

If an individual is transitioning to both modalities; CR and DR, formal training and on-the-job hours may be combined as defined in the employer's written practice.