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Standard Guide for Digital Neutron Radiography[1]

This standard is issued under the fixed designation E3398; 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 covers the evaluation, qualification, and quantification of digital neutron images. These images can be acquired by many methods, including: neutron sensitive imaging plates (Computed Radiography – CR), Digital Detector Arrays – DDA's (amorphous silicon, CMOS, CCD, etc.), micro-channel plates, neutron sensitive fluoroscopes, neutron sensitive scintillators coupled to optical cameras, digitized radiographic films, and linear diode arrays.

1.2 This guide does not purport to establish what is considered an acceptable image but is intended to only give guidance on digital neutron imaging, as well as image quality metrics of importance, and how they can be measured and reported.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E94 Guide for Radiographic Examination Using Industrial Radiographic Film
E545 Test Method for Determining Image Quality in Direct Thermal Neutron Radiographic Examination
E748 Guide for Thermal Neutron Radiography of Materials
E803 Test Method for Determining the *L/D* Ratio of Neutron Radiography Beams
E1316 Terminology for Nondestructive Examinations
E1647 Practice for Determining Contrast Sensitivity in Radiology
E2007 Guide for Computed Radiography
E2597 Practice for Manufacturing Characterization of Digital Detector Arrays
E2736 Guide for Digital Detector Array Radiography
E2861 Test Method for Measurement of Beam Divergence and Alignment in Neutron Radiologic Beams

3. Terminology

3.1 *Definitions*—For definitions of terms used in these practices, see Terminology E1316, Section H.

4. Significance and Use

4.1 *Purpose*—Practices to be employed for the radiographic examination of materials and components with neutrons using digital neutron detectors are outlined herein. They are intended as a guide for the assessment of a digital neutron radiograph's characteristics. For information on neutron beam lines for imaging and film neutron radiography, refer to Guide E748.

4.2 *Limitations*—Acceptance standards have not been established for any material or production process. Neutron radiography, whether performed by means of a reactor, an accelerator, subcritical assembly, or radioactive source, will be consistent in sensitivity and spatial resolution only if the consistency of all details of the technique, such as neutron source, collimation, geometry, imaging system, etc., are maintained. This guide is limited to the use of digital neutron detectors in combination with neutron conversion materials for image recording. This guide is intended for use with thermal and cold neutron spectrums. The production of thermal neutron radiographs by employing the use of film and appropriate conversion screens is covered in Guide E748.

4.3 *Interpretation and Acceptance Standards*—Interpretation and acceptance standards are not covered by this guide. Designation of accept-reject standards is recognized to be within the cognizance of product specifications.

4.4 *Other Aspects of the Neutron Radiographic Process*—For many important aspects of neutron radiography such as

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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.

technique, files, viewing of radiographs, storage of radiographs, film processing, and record keeping, refer to Guide E94, which covers these aspects for X-ray radiography. (See Section 2.)

TEST METHODS

5. Background

5.1 Neutron radiography in industry has been performed predominately using single emulsion X-ray film and gadolinium conversion screens using the direct method. The development of standards may allow applications to move to digital neutron imaging methods. There are some drawbacks to using digital neutron imaging, such as the typically smaller field of view, high cost per detector, and the difficulty to simultaneously achieve a high spatial resolution and a large field of view. However, digital neutron imaging offers many advantages over film methods. These include:

5.1.1 Shorter exposure times,

5.1.2 Expanded bit-depth (increased contrast and latitude),

5.1.3 Post processing (artifact correction, normalization, and filtering),

5.1.4 Digital files (transport, duplication, and storage),

5.1.5 Possibility for higher spatial resolution (neutron microscopes, single-event imaging),

5.1.6 Dynamic (time-resolved) imaging,

5.1.7 Ability to obtain 3D information via tomography, and

5.1.8 Advanced techniques such as phase contrast imaging, spin-polarized imaging, time-of-flight imaging, and Bragg-edge imaging.

5.2 Neutrons are neutral particles that are challenging to detect. As a result, to image with thermal neutrons, the neutrons are absorbed (or scattered) to produce some other form of radiation that is more easily detected. With film imaging, a thin layer of a strong neutron absorber (such as gadolinium, boron, or indium) is generally employed to convert neutrons into radiation that can expose the film (such as electrons and photons). Similarly, most approaches used for digital X-ray imaging can be used to produce images from neutrons with the use of a suitable material to convert neutrons into a more detectable radiation. After this neutron conversion process, the image recording, advantages, and disadvantages for producing images will be similar to those of X-ray imaging with the same method. However, the neutron conversion process and the presence of multiple types of radiation add other factors that will affect the image.

5.3 Neutron imaging setups always have some gamma content as a result of neutron production and subsequent neutron interactions, as is discussed in Guide E748. The effect of this gamma radiation should be considered specifically with relation to the image acquisition method. In some cases, it may be possible for a digital imaging system to establish which detections are the result of gamma radiation and which are from neutrons, and so ignore the gamma detections. These systems, however, have too slow of count rates for practical imaging applications currently.

5.4 Though there are numerous methods that can be used to produce digital neutron images, two methods are used commonly; these are Computed Radiography and Camera-Based systems.

5.5 *Computed Radiography (CR) Systems:*

5.5.1 For general information on CR systems, refer to Guide E2007. Only elements unique to neutron CR (nCR) are discussed here.

5.5.2 X-ray CR (XCR) and nCR are fundamentally the same process, except that nCR includes the use of a neutron converter. Neutrons are not directly detectable by any reaction, and therefore must be converted to some other particle that is detectable, such as ionizing radiation (for example, beta particles, gamma-rays). The storage phosphor and scanner are the same for both XCR and nCR.

5.5.3 X-ray CR imaging plates (IP) are not efficient at detecting neutrons since they do not usually contain a significant amount of a strong neutron absorber. To overcome this, two approaches are utilized: (*1*) embedding a neutron converter in an imaging plate built specifically for neutron imaging, and (*2*) pressing a neutron converter against the surface of an X-ray imaging plate.

5.5.4 A strong neutron absorber (for example, gadolinium oxide, Gd_2O_3) can be mixed into the imaging plate's storage phosphor. By mixing the neutron absorber into the phosphor layer, radiation emitted in any direction from the conversion material can be recorded in the phosphor layer, which can improve efficiency, shorten exposure times, and potentially increase spatial resolution. The disadvantage of using imaging plates with embedded conversion materials is they are not widely available, have high cost, and generally lack durability compared to standard high-resolution X-ray imaging plates. Since the imaging plate is flexible, a flexible cassette can be used to allow imaging on a curved surface with reduced geometric unsharpness.

5.5.5 The second approach that can be utilized is to press a thin layer of a neutron converter (often 25 µm of gadolinium on an aluminum back plate) to the surface of an X-ray imaging plate, just like film neutron radiography. This approach allows the use of X-ray imaging plates and potentially the conversion screens and cassettes utilized for film neutron radiography. This approach has several limitations. Firstly, with the conversion screen on the surface, not more than half of the emissions from the conversion screen will be traveling towards the IP, limiting conversion efficiency. Secondly, the conversion screen is normally placed behind the CR IP. As a result, the neutrons pass through the IP before reaching the conversion screen. Since the IP is reasonably thick and hydrogenous this results in some neutron scattering.

5.5.6 Spatial resolution of nCR is limited by several factors, including:

(1) The laser spot size, laser power, pixel pitch, and raster rate of the scanner,

(2) Light diffusion in the imaging plate phosphor layer, and

(3) Thickness of the phosphor layer, and other factors that affect spatial resolution in all CR systems. If a neutron absorber is added to the phosphor layer it may affect the light spread.

Additionally, there is lost spatial resolution in the neutron conversion process as the neutron's original position is not recorded by the imaging plate but rather the detection location of the conversion radiation emitted by the neutron absorber as the radiation traverses the phosphor layer. Generally, a basic spatial resolution of around 100 µm is obtainable by using a high-resolution IP with a thin conversion screen (for example, 25 µm gadolinium on an aluminum substrate).

5.5.7 Contrast in nCR is driven by the attenuation characteristics of neutrons in the object, for which behavior can be very different and complementary compared to X-rays.

5.5.8 Field of View, imaging plates and scanners for XCR are widely available in the common film sizes, allowing a reasonably large field of view compared to other digital methods. Smaller formats are also widely available.

5.5.9 Counting statistics are affected by the flux and exposure time as with other digital methods. Film generally requires a fluence of around 10^9 neutrons per cm^2 when using a gadolinium conversion screen. nCR could produce an image with similar contrast sensitivity in nearly half the fluence. Generally, the exposure time would be of the same order of magnitude as for film imaging. Typically, the longer the exposure the better the image until the IP becomes saturated.

5.5.10 X-ray CR imaging plate phosphors are designed for X-ray imaging, and thus contain high-Z materials for high X-ray attenuation. As a result, gamma-rays typically represent a significant portion of the recorded image, reducing contrast, and complicating the interpretation of the image.

5.5.11 The lifetime of imaging plates is generally limited by physical damage to the phosphor surface of the plate. Some damage occurs during the scanning process from imaging plate feeding as well as from physical handling of the imaging plate. Damage usually takes the form of scratches which are visible on the resulting digital images. Generally, plates are expected to last hundreds of uses, and potentially thousands for X-ray imaging plates.

5.5.12 Plastic (X-ray) cassettes are readily available for imaging plates, but plastic will scatter a large number of neutrons and significantly reduce the spatial resolution. Aluminum or magnesium alloy film cassettes should be utilized. If using a conversion screen with an X-ray imaging plate, the cassette needs to ensure intimate contact with the conversion screen.

5.5.13 While direct nCR uses a converter material (for example, gadolinium) that emits radiation promptly upon absorption of a neutron, the indirect, or transfer, method uses a converter material (for example, indium or dysprosium) that absorbs a neutron, becomes radioactive, and emits its conversion radiation over a period of time. The transfer method can be employed by activating a separate conversion screen or embedded material in the neutron beam before producing the image on the plate. If using an embedded neutron converter, the screen should be cleared using the CR scanner following activation and prior to recording the transfer image. If using a separate conversion screen, the imaging plate is not exposed to the neutron beam line and instead the activated transfer screen is placed in contact with the imaging plate in a cassette outside of the beam to record the image on the imaging plate over a period of time as the converter decays. Imaging plates are more sensitive than film, so shorter transfer times are often employed compared to transfer method with film.

5.6 *Camera-Based System (CBS):*

5.6.1 For general information on DDA systems refer to Guide E2736. Only elements unique to neutron imaging with such systems are discussed here. A CBS consists of a neutron-sensitive scintillator screen, a digital camera, and optics that couple the camera to the scintillator screen. The scintillator screen contains a neutron converter material that absorbs incident neutrons and releases ionizing radiation. The secondary radiation interacts with the surrounding scintillator material to emit visible light, which is then recorded by the digital camera. Fig. 1 depicts a typical system. The resulting image quality is affected by numerous factors including the material absorbing the neutron, the thickness of the scintillation screen, the optics between the scintillation screen and the camera, and the camera system.

5.6.2 The scintillation screens utilized need to have a sufficiently high probability of detecting neutrons, produce a suitable quantity of light, and adequately maintain the position of the incident neutron. Several suitable materials are commonly used: gadolinium oxysulfide $Gd_2O_2S(Tb)$ (Gadox), lithium-6 fluoride zinc sulfide ($ZnS/^6LiF$), and boron-10 oxide zinc sulfide ($^{10}B_2O_3/ZnS$).

5.6.3 These neutron scintillator screens contain a conversion material to absorb neutrons and subsequently emit secondary decay radiation which can be detected more easily. The secondary radiation (usually electrons or alpha particles) then interacts with the scintillator that emits visible light. The higher the neutron absorption cross section for the converter material, the more efficient the detector will be, which allows for shorter exposure times, improved counting statistics, and can indirectly improve spatial resolution by allowing the use of thinner scintillation screens. Having a thicker scintillation screen can increase the neutron detection efficiency and the light output. However, as the light travels through the scintillation screen, it diffuses in the scintillator, diminishing spatial resolution. Additionally, some light will be attenuated as it passes through the scintillation screen. As a general guideline, the scintillation screen thickness should not vastly exceed the imaging system's target basic spatial resolution, with scintillation screens between 20 µm and 100 µm in thickness being common.

5.6.4 Gadox can be used in higher spatial resolution imaging setups as a result of gadolinium's large neutron absorption cross section for thermal neutrons and to a lesser extent, the range of the electrons emitted on neutron absorption, which is about 5 µm to 10 µm. A basic spatial resolution of around 30 µm is achievable with a 20 µm thick scintillator.

5.6.5 In scintillation screens containing lithium, neutron absorption in the lithium-6 isotope results in the emission of an alpha and a triton of relatively high energy (4.78 MeV total). As a result, these particles can travel further and so can emit light at a greater distance from the incident neutron. Basic spatial resolution around 50 µm can be achieved with a 100 µm thick scintillator. These $ZnS/^6LiF$ scintillator screens typically emit substantially more light than Gadox scintillator screens.

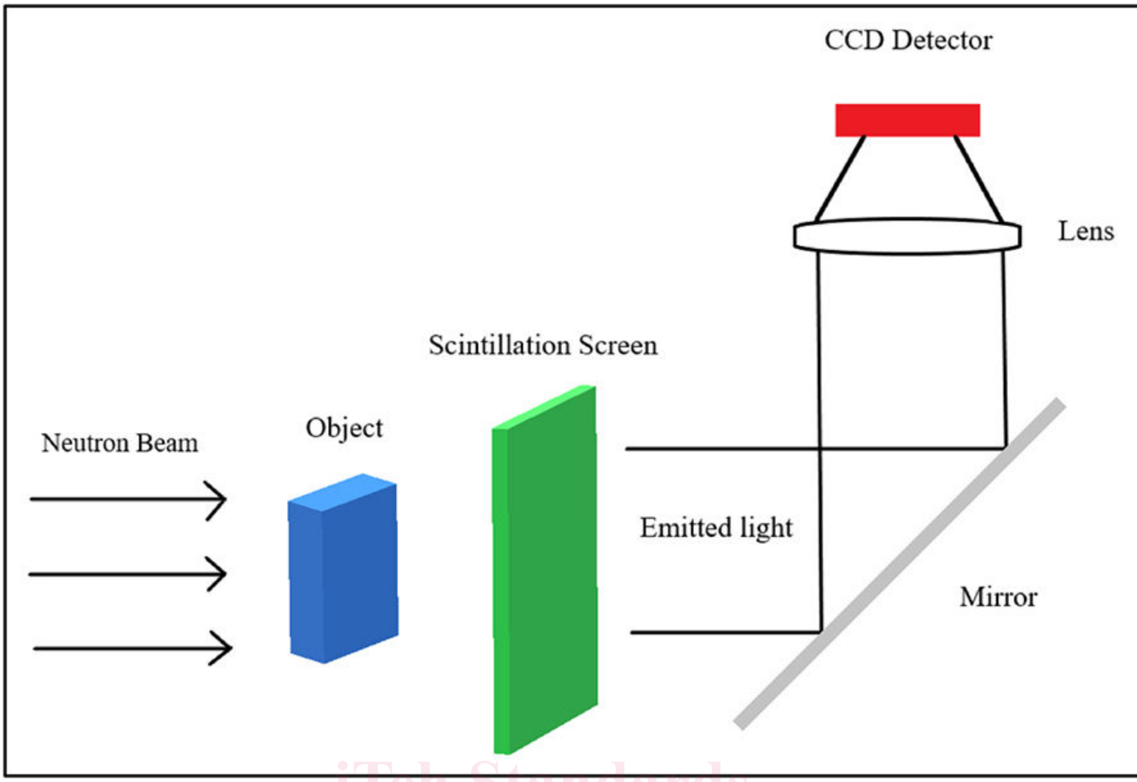

FIG. 1 General Layout for a CBS

5.6.6 Scintillator screens are also sensitive to gamma exposure, which will similarly produce light that will be included in the image. In many cases the signal produced by these gamma interactions may locally significantly exceed that of the neutrons. Reducing the gamma content in the beam line (through beam design or filtering as detailed in Guide E748) and post processing can be used to address this.

5.6.7 After the neutrons have been converted into light, the light needs to be directed towards the camera system. The simplest approach would be to directly aim the camera at the scintillation screen. This approach is not used because the digital cameras are sensitive to the ionizing radiation (both gamma and neutron), which affects the image as it is being recorded in the image as bright spots (that is, gamma spots) and damages the camera system causing bad pixels. (Practice E2597 provides additional coverage of bad pixels.) Instead, the camera is optically coupled to keep it out of the direct radiation beam. The most common approach is the use of a first-surface mirror at a 45° angle. A lens is used to focus the light onto the camera system. Fiber optically coupling the scintillator to the camera is also a viable approach, improving light collection but limiting the spatial resolution of the system. Image intensifiers can also be used to multiply the produced light for lower resolution work. One factor that needs to be considered is the matching of the camera's sensitivity to light with the wavelengths emitted by the scintillation screens. There are numerous variations of the scintillator materials that can be used which will shift the light emissions to other colors in the visible spectrum, an approach that can be used to better match the light emissions to the camera's sensitivity.

5.6.8 The cameras used are most commonly black and white CCD or CMOS digital cameras. These are usually either produced for astronomy or other scientific applications. The resulting image is limited to the number of pixels present in the camera chip. As a result, the larger the field of view is, the larger the area being recorded by a single pixel, which can be the limiting factor on image spatial resolution in some situations. Another factor of significance is the size of the imaging chip in the camera, as a larger chip can capture more light. Noise in the camera will limit the image quality, so most suitable cameras employ cooling to reduce noise during the exposure, which can be minutes long depending on the flux and spatial resolution. To reduce imaging artifacts and damage to the camera, the camera is positioned to reduce its exposure to radiation and typically shielded against radiation, often with multiple centimeters of lead.

5.6.9 A light tight box (often called a camera box) is used to contain the scintillator and the optics and is coupled to or includes the camera. This avoids issues with dust on the optical components and ensures alignment of the components. If the camera is located inside the camera box, cooling the camera may be more challenging.

5.6.10 Exposure time in a CBS will scale with the basic spatial resolution of the detector. A scintillator-camera system that is 25 % efficient at detecting neutrons with each pixel having a region 20 µm by 20 µm of the field of view focused onto it, at a thermal neutron flux of 1×10^6 n/cm^2/s, would record just one neutron per second at full beam intensity and so require tens of minutes to produce an image. Focusing a 100 µm by 100 µm image area onto each pixel would reduce