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Current and Future Neutron Radiography Standards

Jack S. Brenizer, Jr.

Department of Mechanical and Nuclear Engineering
The Pennsylvania State University
University Park, PA 16802-2301
USA

ABSTRACT - Only two organizations are actively producing standards which are used in neutron radiology (NR): the American Society of Testing and Materials (ASTM) and the International Organization for Standardization (ISO). Six ASTM standards exist that address the neutron radiography method. Two of the ASTM standards have been extensively used world-wide. ISO has a working group which is developing three standards that also address the neutron radiography method. Two of these are currently making their way through the ISO approval system. No ASTM or ISO standards exist for the neutron radioscopic method. Future ASTM standards will address the neutron radioscopic method and neutron radiologic system characterization. It is expected that similar efforts will be undertaken in ISO. Given the relatively small community providing neutron radiologic services, international cooperation and the need for ISO standards will most likely continue to grow.

1. Introduction

Images made with neutrons have been used in a wide variety of nondestructive testing (NDT) industrial and research applications since the early 1960's. There are numerous articles and handbooks reviewing the technique of the making radiographic images using neutrons. [1,2,3,4] While several sources of neutrons are available, the most common source is a non-power research reactor. The limited number of facilities available, coupled with the high cost of reactor operation relative to other nondestructive techniques such as x-ray radiography, has limited the applications and users of neutron radiography. Thus, alternative NDT methods are often used, even when the alterative technique yields less information.

Neutron radiography creates an image which looks like an x-ray radiograph, but the differences between neutron and x-ray interaction mechanisms produce images which may contain completely different information. While x-ray attenuation is directly dependent on atomic number, neutrons are efficiently attenuated by only a few specific elements. This is because x rays interact with the electron cloud of an atom; the more electrons, the greater the attenuation. Neutrons, on the other hand, interact with the nucleus and this interaction is highly dependent on nuclear mass and structure. Boron-10 and gadolinium are good attenuators of thermal neutrons due to their large absorption cross sections whereas hydrogen is a good attenuator by virtue of its large scattering cross section. As a result, organic materials and water are clearly imaged neutron radiographs because of their high hydrogen content, while many structural materials, such as aluminum, are essentially transparent.

By 1969 it was recognized that some standardization was necessary in the neutron radiography field. Since that time more than thirty-seven (37) papers have been presented on neutron radiography system or beam characterization at the six world conferences on neutron radiography. Additionally, twenty-nine (29) papers have been presented on this subject at the first three international topical meetings. Haskins has presented two reviews of neutron radiography standards in the United States and a later paper by Newacheck and Tsukimura updates these earlier papers. [5,6,7] Domanus, Brenizer, and Brenizer and Berger have also presented reviews of neutron radiology standards. [8,9,10] The American Society of Testing and Materials (ASTM) is the principal group within the United States concerned with developing standards concerning the neutron imaging methods. ASTM standards addressing nondestructive testing are in the most current version of [11]. Personnel qualification of neutron radiographers is under the control of the American Society of Nondestructive Testing (ASNT). Work on developing standards for neutron radiography began in 1971 and the first ASTM standard directly dealing with neutron radiography was published in 1975. By 1981, two additional neutron radiography standards had been published. Although these standards have undergone revision, the basic concepts have remained unchanged. Now a total of six ASTM neutron radiography standards have been approved.

The reference to neutron imaging as radiography resulted from its similarity to the x-ray radiographic technique. The development of electronic imaging systems in the mid-1970's began a new field, first referred to as real-time neutron radiography. Most commonly, the neutron attenuation intensity pattern impinges on a scintillating phosphor which after intensification, is viewed with a video camera. The typical frame rates were sufficiently fast to permit observation of dynamic motion without blurring, hence the name real-time.

By the mid-1980's, the ASTM E7.01 Radiology (x and gamma) method and E7.05 Radiology (neutron) method subcommittees recognized the need to more clearly define the term real-time radiography. The terms, radiology, radioscopy, and radiography, have been defined and can be found in the ASTM Standard Terminology for Nondestructive Examinations (E 1316). Radiography is now used to describe techniques which produce a permanent visible image on a recording medium, usually film. Radioscopy is used to refer to techniques which use electronic production of a radiological image that very closely follows the changes in the image with respect to time. Radiology is defined as the science and application of penetrating radiations. Work is now underway to define the method of forming x-ray and neutron imaging with imaging plates.

Neutron imaging methods are a valuable NDT tool. Neutron radiography continues to be used to examine a wide variety of objects ranging from jet engine turbine blades to spent nuclear fuel. Examination of advanced materials, especially composites and detection of corrosion in light metals, such as aluminum and titanium, are two examples of new applications. One area for potential growth of the NR NDT methods is in neutron imaging with non-reactor sources. With new applications and systems, the need for uniform standards for system characterization and NDT radiologic practice will grow.

2. Current Neutron Radiologic Standards

Two groups, ASTM and the International Organization for Standardization, ISO, are active in producing standards which are used in neutron radiologic (NR) NDT activities. In ASTM Committee E-7 Nondestructive Testing, Subcommittee E07.05 Radiology (Neutron

Method) is responsible for six standards, all of which address neutron radiography. This is understandable, since most commercial neutron radiology applications to date have employed either direct or indirect neutron radiography, specifically with thermal neutrons. Neutron radiology standards are also being developed at the international level. In addition, L'Association Française de Normalisation (AFNOR) and the Euratom Neutron Radiography Working Group (NRWG) have produced standards addressing neutron radiography.[12,8] ISO appointed a working group, ISO/TC 135/SC 5/WG 4 "Thermal Neutron Radiography," in April, 1988. Representatives from over fifteen countries have participated in the working group as either members or observers. The working group has met on nine occasions to discuss and draft three work items. At the present time, no ASTM or ISO standards currently exist for neutron radioscopy.

The ASTM Standard Practice for Thermal Neutron Radiography of Materials (E 748) provides a good introduction to the neutron radiographic technique. This document was intended to be somewhat tutorial in nature, describing common thermal neutron radiographic practice and required facilities and equipment. A description of neutron sources, beam filters, and collimators is presented, along with a list of background references. The use of conversion screens and film cassettes for both the direct and indirect imaging methods are discussed in detail. The standard also addresses the materials and general applications for which the neutron radiographic technique is appropriate. ASTM E 748 was submitted by the United States to ISO, and it was accepted as Work Item 5.5 "Non-destructive testing; Thermal neutron radiographic testing; General Principles." After modification, it was balloted under SC 5 in 1991. It is now designated CD 11537.

The ASTM Standard Method for Determining Image Quality in Direct Thermal Neutron Radiographic Testing (E 545) is widely used by neutron radiography practitioners both in the United States and in other countries. This standard is used to determine the relative overall quality of the neutron radiographic images produced. It is not intended to be used for controlling the acceptability of quality of materials and components. The judgement of the radiograph's quality is based upon the evaluation of images obtained from two different indicators that are exposed simultaneously with or under exactly the same conditions as those used to examine a test object. Recent changes to E545 moved the fabrication details for the indicators to separate documents. E 545 now contains only the method for use and analysis of the resulting images of the indicators.

The first device, the beam purity indicator (BPI), is used to obtain a quantitative determination of radiographic quality. Fabrication of the device is straightforward and is detailed in the ASTM Standard Practice for Fabrication of Neutron Radiographic Beam Purity Indicators (E 2003). It consists of a TFE-fluorocarbon block, containing two boron nitride disks, two lead disks, and two cadmium wires. The second device, the sensitivity indicator (SI), is used to qualitatively determine the sensitivity of detail visible on the neutron radiograph. Details of its fabrication are detailed in the ASTM Standard Practice for Fabrication of Neutron Radiographic Sensitivity Indicators (E 2023). The device is made from acrylic, aluminum, and lead components. Solid aluminum shims are used to create low-density gaps in the SI's radiographic image. Holes in acrylic shims also create low-density areas on the film image.

A qualitative determination of a facility's neutron beam can be obtained from a visual inspection of the BPI's radiographic image. Densitometric measurements taken at specified locations on the BPI's image are used to calculate the radiographic contrast, low-energy photon and pair-production contributions to the image, the image unsharpness, and information on the film and processing quality. A specific procedure for the densitometric measurements and calculations is given in the standard. Visual inspection of the SI's image is used to determine the smallest gaps and the number consecutive holes detected. Subjective information regarding the level of detrimental gamma photon exposure is also available. The information obtained from the BPI and SI radiographic image is then used to determine a Neutron Radiographic Category for the facility. The BPI yields quantitative information concerning neutron beam and imaging system parameters. It can also be used as a daily check on consistency of radiographic quality. Likewise, the SI can be used as a check on sensitivity.

The ASTM E 545 was submitted by the United States to ISO and it was adopted as the first draft for Work Item 5.7 "Non-destructive testing; Thermal neutron radiographic testing; Determination of image quality." This draft was not immediately accepted by Working Group (WG) 4 due to disagreements between the round robin test results of the Euratom Neutron Radiography Working Group (NRWG) and those obtained in U.S. round robin tests. [13,14] Discussions between ASTM E 7.05 subcommittee and NRWG (now the European NRWG, ENRWG) representatives led to an understanding of the differences. The different test results were caused by inconsistencies in SI device fabrication. After these were rectified, similar test results were obtained by both groups. Several alternative image quality devices were considered by WG 4. At this time, the members of ISO WG 4 still have numerous questions about the SI device, especially the conversion of the dimensions to SI units, so no draft has been prepared.

The ASTM Standard Method for Determining the L/D Ratio of Neutron Radiography Beams (E 803) is also widely used by neutron radiography practitioners. It provides an experimental technique to determine the ratio of the effective collimator length (L) to effective collimator entrance aperture diameter (D). This is different than the simple ratio of the physical collimator length and aperture diameter, since neutrons scattered off both the collimator and shielding walls affects the L/D ratio.

The E 803 method involves examining the radiographic image of a no umbra device to determine the point where the umbral shadow disappears. The device consists of an U-shaped aluminum channel with a series of parallel V groves at specified intervals along its length. Each grove contains a thin cadmium wire of a known diameter. The device is placed on the film cassette at a 45° angle. A single device will allow determination of L/D ratios up to 150; higher L/D values can be measured by adding a second similar device to the first.

The L/D ratio is evaluated using the following procedure. A radiograph of the no umbra device is made such that the background density is approximately 2.5. The film is then analyzed using one of three alternate methods. In the first, a visual analysis is used to determine where the no umbral shadow disappears. The ratio of the rod position with zero umbral shadow width to the rod diameter is equal to the effective L/D ratio. The second alternate method involves the use of a microdensitometer to determine the zero umbral shadow location. This method should only be used with L/D ratios up to several hundred. A third alternative method requires the use of a microdensitometer to examine the individual umbral shadow waveforms to determine the width of two different umbral shadows. Subsequent calculations using these values yields the L/D ratio. The third method is useful in determining both high and low L/D ratios.

ISO TC 135\SC 5\WG 4 Work Item 5.6 "Non-destructive testing; Thermal neutron radiographic testing; Determination of Beam L/D ratio" has been reviewed and rewritten several times since the original submission of ASTM E 803 by the United States as a working draft. Several alternative L/D measurement methods and devices were considered. [15,16] The general consensus of the working group is that the ASTM E 803 no umbra device and method would be put forward and is being balloted as CD 12721.

ASTM Standard Test Method for Neutron Radiographic Dimensional Measurements (E 1496) provides a technique for extracting quantitative dimensional information on an object from its neutron radiograph. The technique is based on the identification of changes in film density caused by material changes where a discontinuity in film density exists. The standard was based on extremum slope dimensioning method developed by Harms and his colleagues. [17] The test method assumes that the user will have access to a systems that permits measuring film density accurately with high spatial resolution. A typical system will include a traveling-stage microdensitometer. The edge coordinate of a discontinuity is determined to be the location where the slope of the density is at a maximum. This technique is particularly relevant to determining diameters of spent nuclear fuel, gap sizes in contact-circuit mechanisms of shielded components, and prescribed spacings between distinct materials.

3. Future Neutron Radiologic Standards

The ASTM E 545 (with E 2003 and E 2023), E 748 and E 803 standards will continue to be used for the foreseeable future. These standards are under periodic review and are revised to reflect both improvements in the procedures, methods, and devices used, as well as to correct incomplete, inaccurate, or outdated data. New ASTM standards currently being drafted include a standard on neutron radioscopic practice, and several methods for determining parameters used for neutron radiologic system characterization.

A standardized approach for characterizing radiographic and radioscopic systems is desirable and will aid in the interpretation of NR images and will permit an intercomparison of images obtained using different facilities. This concept is not new. For example, an approach for characterization was described by Bayon and Laporte in 1983. [18] The characterization should take into consideration both reactor or other neutron sources. Parameters such as beam divergence, beam uniformity, beam area, beam orientation, neutron energy spectrum, image system performance, dimensional calibration (and uniformity), and contrast sensitivity are all important in understanding and interpreting NR images. Most of these parameters are not addressed in the existing standards. Several characterization devices and parameters, such as the cadmium ratio, modulation transfer functions (MTF), neutron flux, neutron-to-gamma ratio, resolution, and the values measured using the current ASTM BPI and SI devices are often used or referred to when describing an NR facility or system, but they are not determined or used in a standardized manner.

ASTM Subcommittee E07.05 and the ISO TC 135/SC 5/ WG 4 have considered several proposals for system characterization. The general consensus in both groups is that radiographic and radioscopic systems are too complex to adequately characterize with a single parameter or device. The favored approach is one which will involve the establishment of standard methods for the measurement of many of the beam, imaging, and facility parameters mentioned above, coupled with a guide for interpreting each parameter's overall impact on an NR image. Standardization of measurement and interpretation is important since some of the parameters are interrelated. For example, values obtained for the cadmium ratio can be affected by beam filters and neutron energy spectrum.

Many existing standards can be utilized. Standards, such as the ASTM Standard Method for Determining Neutron Flux, Fluence, and Spectra by Radioactivation Techniques (E 261), are well established but are not currently used in describing NR system characteristics.[19] The BPI and SI devices work well for radiography but these need to either be revised or alternatives developed for use with radioscopic systems. Some standard devices and techniques used in gamma and x-ray radiology can possibly be adapted for NR characterization. However, for many of the desirable characterization parameters, relevant or existing standards simply do not exist. A logical approach would be to establish a priority for each of the characterization parameters, develop a method for measuring the parameter, proceed to round robin testing of the method, and then proceed to draft and approve a standard method. After a sufficient number standard methods have been adopted, a overall system characterization document can be established.

New devices are continually being proposed by various NR groups. Both the ASTM E07.05 and ISO/TC 135/SC 5/WG 4 try to evaluate the proposed method or device. For example, at recent ISO/TC 135/SC 5/WG 4 and ASTM E7.05 meetings, several new standard methods and devices for measuring characterization parameters were discussed.[20,21] Those with strong technical documentation or experimental support or those endorsed by national or international groups should be evaluated by round robin testing. Some proposals have been accepted in E07.05 for consensus review and approval, some have been rejected, and several are still under investigation. Many will eventually become ASTM or ISO standards.

4. Conclusions

The international demand for NR NDT services is already in place and will most likely continue to grow. Given the relatively small number of facilities providing neutron radiologic NDT services, comparison of services offered and the quality of services delivered will become increasingly competitive. Standardization of the terms and parameters used to specify the characteristics and capabilities of a facility's NR system is important for several reasons:

1. Standardization provides a basis for prospective customers to make a judgement of which facility is best suited to their particular NDT needs. Using the facility best suited to the project's needs yields success and increases the number of future applications for NR methods.

2. Standardization provides a common language among the customers and practitioners of the NR method. This is very important as it serves to provide a clear picture of the NR NDT method to potential customers and also aids in the establishment of agreements for international NR services.

3. Standardization provides a method to monitor the performance of an NR system over time and provides a means to evaluate changes made in system components and their effect of the change on an NR image.

The development of standards for neutron radiography is well underway. However, additional standards are needed for characterizing the components in the entire imaging system. As new methods using devices, such as radioscopy and imaging plates, mature and are adopted for commercial quality control and inspection, new standards will be needed to identify standard methods and practices.

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