Designation: E2861 – 16

Standard Test Method for Measurement of Beam Divergence and Alignment in Neutron Radiologic Beams[1]

This standard is issued under the fixed designation E2861; 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 test method covers the design, materials, manufacture, and use of a divergence and alignment indicator (DAI) for measuring the effective divergence of a thermal neutron beam used for neutron imaging as well as determining the alignment of the imaging plane relative (usually normal) to the centerline of the beam. This test method is applicable to thermal neutron imaging.

1.2 The values stated in SI units are to be regarded as the standard.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E543 Specification for Agencies Performing Nondestructive Testing

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

2.2 *Other Documents:*

ANSI Y14.5M Dimensioning and Tolerances[3]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this guide other than those defined in this section, refer to Terminology E1316.

3.2 *Definitions:*

3.2.1 *neutron image*—record in two dimensions of the intensity of neutron radiation. Examples include radiographs, radioscopic images, computed radiography (CR) images, and track etch images produced from a neutron source.

3.2.2 *neutron imaging*—process of making a neutron image.

4. Summary of Test Method

4.1 The DAI allows the user to determine the alignment of the imaging plane with the beam centerline and the beam divergence for a thermal neutron beam. The user can determine if the imaging system is aligned, aligned only in one direction or completely misaligned and the angle of misalignment, as well as the divergence angle for the imaging system. The DAI is made using aluminum plate and rods, and incorporates cadmium wires for contrast. Circular symmetry is utilized to simplify manufacture. An important feature of the DAI is flexibility to adapt the "as-built" dimensions into the analysis. The DAI is placed with the five stand off posts against the film cassette or radioscopic imaging device in the physical center of the beam. The DAI is perpendicular to the selected beam radius when the center S1 and center S4 cadmium wire images overlap (see Figs. 1 and 2). The degree of misalignment can be measured by the cadmium wire image positions. After the DAI is aligned, analysis of the cadmium wire "+" image spacing yields the beam divergence.

5. Significance and Use

5.1 As discussed in Practice E748, traditional neutron radiography typically employs a high flux reactor source with a well defined collimation system to produce an image on film. The alignment of the imaging plane and the divergence angle are generally well defined and a small degree of misalignment or uncertainty in divergence angle makes little difference in the final image. These systems are well characterized by their physical dimension, the L/D ratio, and image quality indicators (Beam Purity Indicator and Sensitivity Indicator) described in Test Method E545. Neutron computed tomography is an

[1] This test method is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.05 on Radiology (Neutron) Method.

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

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

***A Summary of Changes section appears at the end of this standard**

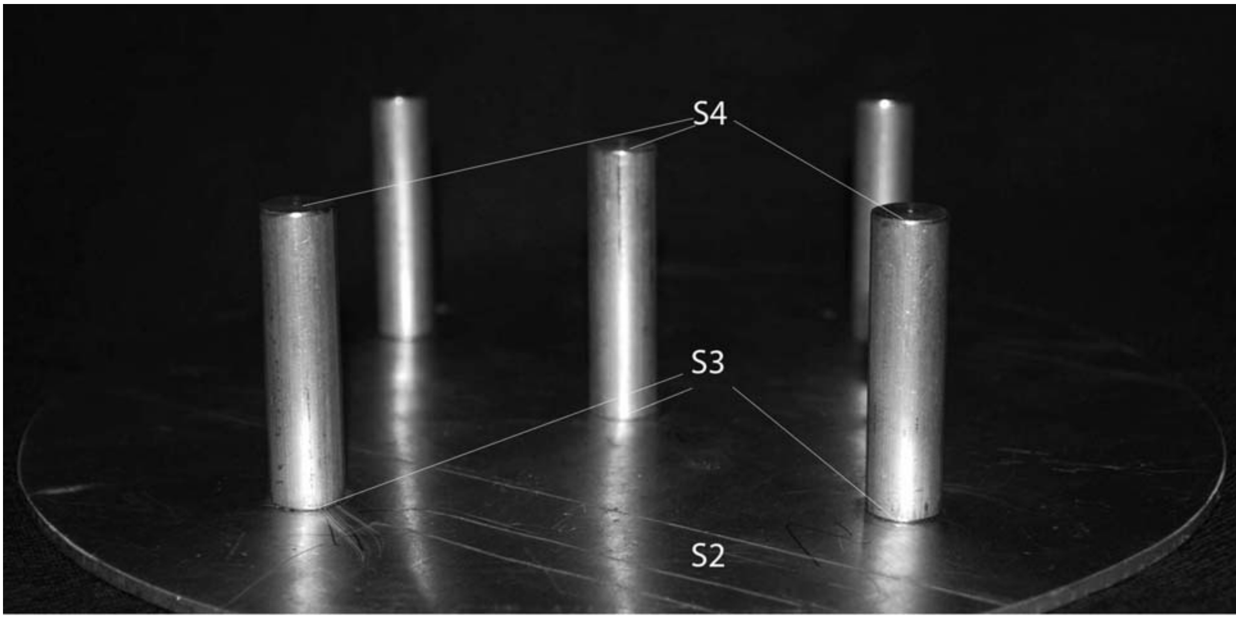

FIG. 1 Image of the DAI device with added labels to label the S2 surface as the un-grooved side of the plate, the S3 surface as the end of the stand off post that is mounted to surface S2, and S4, the end of the stand off post to be positioned at the imaging plane.

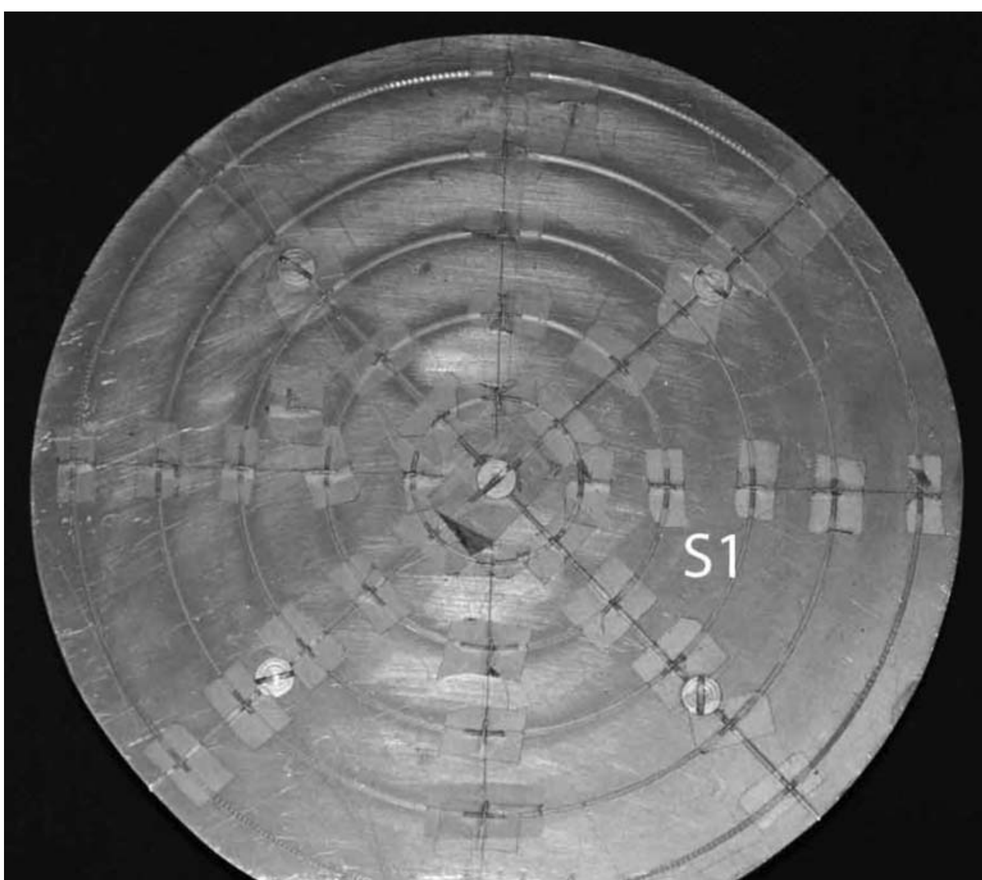

FIG. 2 Image of the S1 surface of a DAI device (with added S1 label), showing grooves, cadmium crosses, and aluminum screw heads. This device used tape to hold the cadmium wire crosses in place. The surfaces S1, S2, S3, and S4 shown in Figs. 1 and 2 are all parallel.

example where it is important to know with some precision both the beam's centerline and the degree of beam divergence, especially if the beam does not closely approximate a parallel beam. Portable or movable neutron imaging systems often utilize shorter collimation systems, a less precise alignment and poor symmetry in divergence angles, which may affect image analysis. In these example cases, direct measurement of the alignment and the divergence angles is desirable as calculation from system geometry would be less straightforward and accurate. Fabrication of the device is an extension of the Test Method E803 L/D device, providing different information through a similar approach.

6. Basis of Application

6.1 If specified in the contractual agreement, personnel performing examinations to this standard shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT-CP-189, SNT-TC-1A, NAS-410 or a similar document and certified by the employer or certifying agency, as applicable. The practice or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

6.2 *Qualification of Nondestructive Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Specification E543. The applicable edition of Specification E543 shall be specified in the contractual agreement.

6.3 *Procedures and Techniques*—The procedures and techniques to be utilized shall be as specified in this standard.

6.4 *Reporting Criteria*—Reporting criteria for the examination results shall be in accordance with Section 14 unless otherwise specified. Since acceptance criteria are not specified in this standard, they shall be specified in the contractual agreement.

7. Materials

7.1 The DAI is made using aluminum plate, rod, and screws to minimize neutron attenuation and long-lived induced radioactivity. An aluminum alloy such as Al 6061 or Al 1100 is suitable for device construction. Cadmium wire and thin cadmium sheet (0.5 mm is appropriate) are incorporated for contrast, the exact diameter of the cadmium wire is not critical, but all groove dimensions and holes drilled for the cadmium must be adjusted to fit the actual wire diameter. Cadmium wire below 1.0 mm in diameter is suitable for use.

8. Hazards

8.1 Since cadmium can represent a safety concern, the Material Safety Data Sheet (MSDS) for cadmium should be reviewed and safe handling practices followed.

8.2 Radiation hazards exist when operating radiation imaging systems. The activity of the DAI should be measured prior to handling or transporting following use as some activation will occur during imaging.

9. Sampling, Test Specimens, and Test Units

9.1 Distances on the images can best be measured digitally using the "as built" distance between the images of the stand off posts on the S4 surface of the device to determine the distance each pixel represents in the image. For images on film, digitization of the radiographs may allow higher precision measurements, but a vernier caliper can alternately be utilized to take measurements from the radiograph.

NOTE 1—If using a vernier caliper and film, a clear sheet of plastic can be placed between the film and caliper to prevent damage to the film.

9.2 Neutron images of the DAI device must be taken under the conditions of interest (with the same collimation system, image plane distance, etc.) and the DAI positioned as described in Section 12. For film-based images, Practice E748 describes the standard practice for thermal neutron radiography of materials.

10. Preparation of Apparatus

10.1 Circular symmetry is utilized to simplify manufacture and assembly of the device. The DAI is illustrated in Fig. 3 with device dimensions. An important feature of the DAI is flexibility to adapt the "as-built" dimensions into the analysis. Therefore, a high degree of dimensional accuracy is not required in either the cadmium wire or in the fabrication of the machined parts, however, the plate must be straight (a diameter tolerance zone of 1.0 mm), otherwise the minor differences in height will lead to discrepancies in the data. The degree of accuracy in the calculated alignment and divergence angles depends on the accuracy of measurement of the "as-built" dimensions and the features observed in the neutron image of the DAI. Device construction is adapted from Ref. (**1**).

10.2 *DAI Device Construction:*

10.2.1 Machine a disk 22.0-cm in diameter from 0.30-cm thick aluminum plate. See Fig. 3. The maximum variation across the plate must be under 1.0 mm. Any deviation in distance from the imaging device to surface S1 results in an increase in uncertainty in calculated divergence angles.

10.2.2 Cut 44 pieces of 0.5-mm diameter by 1-cm long cadmium wire and 80 pieces of 0.5-mm diameter by 0.5-cm long cadmium wire. Although the exact diameter of the cadmium wire is not critical, all groove's dimensions and holes drilled for cadmium wire must be adjusted to fit the actual wire dimension, for example, depth and radius of the groove should match the radius of the wire to ensure the wire fits tightly in the groove and the grove's widest point is at the S1 surface.

10.2.3 Machine five grooves of 0.25-mm radius, 0.25-mm deep, at 2.0, 4.0, 6.0, 8.0 and 10.0-cm radii in one side of the 22.0-cm disk from 10.2.1. The side with the grooves will now be called the S1 surface of the DAI. See Fig. 3 and Fig. 2.

NOTE 2—The accuracy of the groove positions affects the accuracy of the DAI.

10.2.4 Machine four grooves of 0.25-mm radius, 0.25-mm deep, across the diameter of the 22.0-cm disk from 10.2.1 on the S1 surface. Each groove should be at 45° as shown in Fig. 3.

NOTE 3—The accuracy of the groove positions affects the accuracy of the DAI.

10.2.5 Machine four grooves of 0.25-mm radius, 0.25-mm deep, on surface S1 to fit the cadmium wire from 10.2.2 of appropriate size to hold the "L" and "T" orientation markers as depicted in Fig. 3a. The exact position and size are not important as they are only for reference.

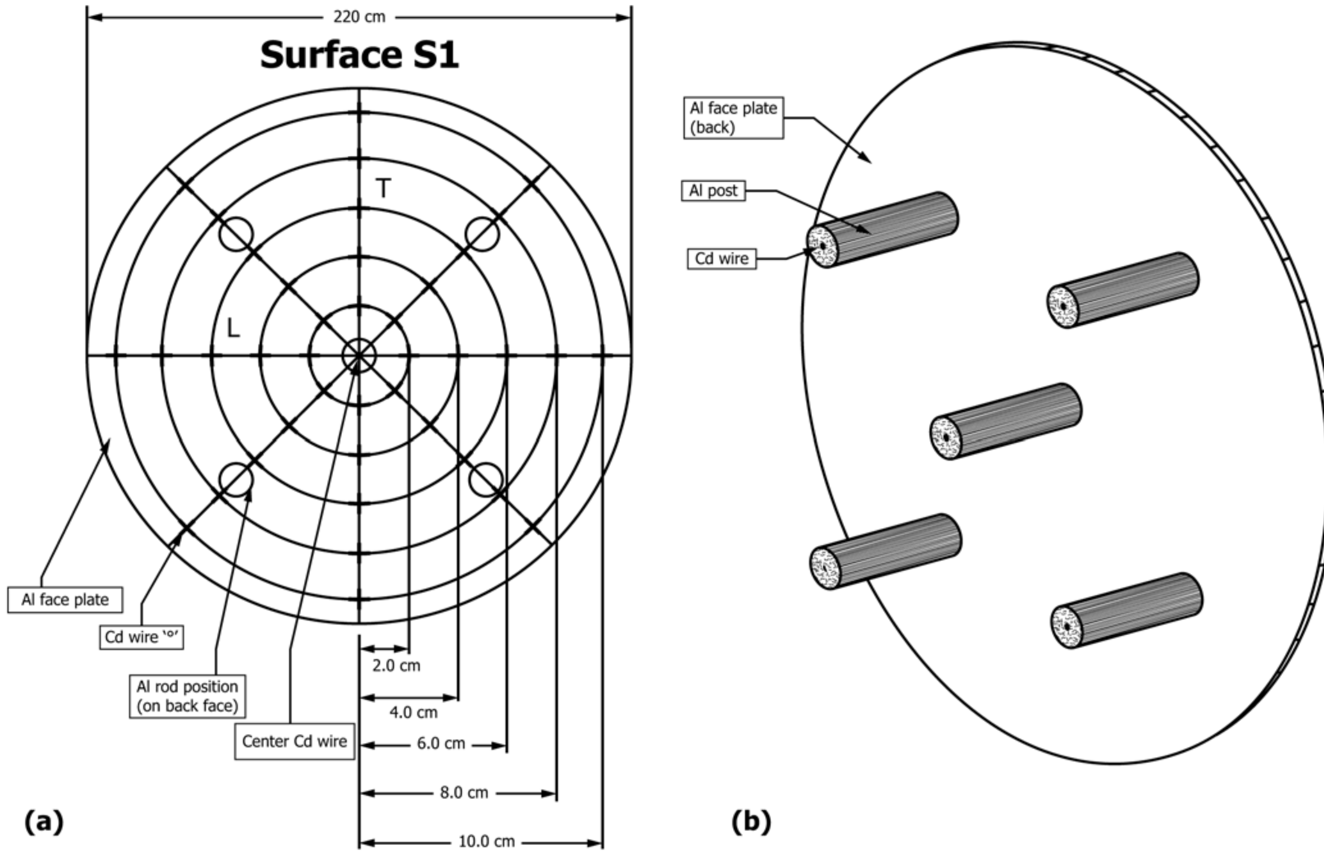

FIG. 3 Diagram of the DAI Device Showing the Cadmium Pieces in Solid Black: (a) the S1 surface with machined grooves and dimensions in centimetres, and (b) different orientation illustrates post positions.

10.2.6 Machine five aluminum posts 1.25 cm in diameter and 5.0 cm in length, making sure the faces of the posts are finished perpendicular to the post length.

10.2.7 Obtain five flat-head aluminum machine screws about 1.3 cm in length. The diameter of the screw is not critical, but should be approximately 0.6 cm in diameter.

10.2.8 Orient the S1 surface of the 22.0-cm diameter plate such that one groove machined in 10.2.4 is vertical relative to your position. The position of the posts and screws are illustrated in Fig. 3 and Fig. 2, respectively. Drill appropriate through holes for the screws of 10.2.7 in the center of the plate and at a radius of 7.07 cm in the 45°, 135°, 225°, and 315° grooves machined in 10.2.4. On surface S1 of the disk, counter sink the holes for the screw heads such that the screw heads are flush with the S1 surface.

10.2.9 Drill and tap one end of each post from 10.2.6 for the screws from 10.2.7, making sure the tapped holes are perpendicular to the post face. This end of the post will be referred to as the S3 surface.

10.2.10 Cut five pieces of 0.5-mm diameter cadmium wire each 0.3 cm long.

10.2.11 Drill a hole for the cadmium wire from 10.2.10 in the center of each post opposite the tapped hole, making sure the holes are perpendicular to the post face. This end of the post will be referred to as the S4 surface.

10.2.12 Mount the S3 surface of the posts to the S2 surface of the 22.0-cm disk (the surface without the grooves) using the flat-head aluminum screws. Check that the posts are perpendicular to the S2 surface.

10.2.13 From the S1 surface of the 22.0-cm disk, drill a hole for a cadmium wire from 10.2.10 in the exact center of the center post mounting screw, making sure the hole is drilled perpendicular to the disk surface.

10.2.14 Insert a piece of cadmium wire from 10.2.10 into the hole drilled into the center post mounting screw in 10.2.13 (S1 surface) and four of the holes in the stand off posts (S4 surface), leaving the center post empty. A small amount of neutron transparent epoxy or glue can be used to secure the cadmium wire if it is loose.

10.2.15 Cut a small piece of cadmium from a 0.5-mm thick sheet. Cut the piece such that its cross section is square and it will fit into the unfilled center post hole from 10.2.11 (S4 surface).

NOTE 4—The square shape of the cadmium piece in the S4 surface will permit differentiation between S1 and S4 cadmium pieces in the radiographic image.

10.2.16 Insert the square cadmium piece from 10.2.15 into the center post hole in the S4 surface left empty in 10.2.14. A small amount of neutron transparent epoxy or glue can be used to secure the cadmium piece if it is loose.

NOTE 5—Be careful not to fill the hole with a neutron attenuating adhesive which would prevent differentiation between S1 and S4 surface cadmium pieces on the DAI image.

10.2.17 At each groove intersection on the S1 surface of the 22.0-cm disk, except at the center, secure a "+" made from one 1.0-cm piece of cadmium wire and two 0.5-cm pieces of cadmium wire from 10.2.2. Use the 1.0-cm piece in the circular groove and two 0.5-cm pieces in the radial grooves as shown in Fig. 4. The wire may be secured with a small amount of neutron transparent epoxy, glue or tape. See Fig. 3 for the cross locations.

10.2.18 Using the remaining four cadmium wires from 10.2.2, make an "L" and "T" at the locations shown in Fig. 3 in the grooves from 10.2.5. Affix the wire with a small amount of neutron transparent epoxy, glue or tape.

11. Calibration and Standardization

11.1 To calibrate the device and ensure no bias exists, precise measurement of the device's "as built" dimensions and use of these measured values in calculations (rather then those specified for device construction) is required. Specifically the distance from the cadmium wire on the S1 surface of the DAI device to the imaging plane, and the radius from each cadmium cross to the center of the device needs to be accurately determined. A vernier caliper can be utilized to determine the "as built" dimensions.

11.2 Radius measurements must be taken from the center of the cadmium wire groove at each cross location to ensure accuracy.

11.3 The separation distance between the wires on the S1 surface of the plate and the image plane also needs to be accurately determined. If the separation distance varies across the device, (possibly the result of warping or poor construction) the accuracy will be significantly degraded.

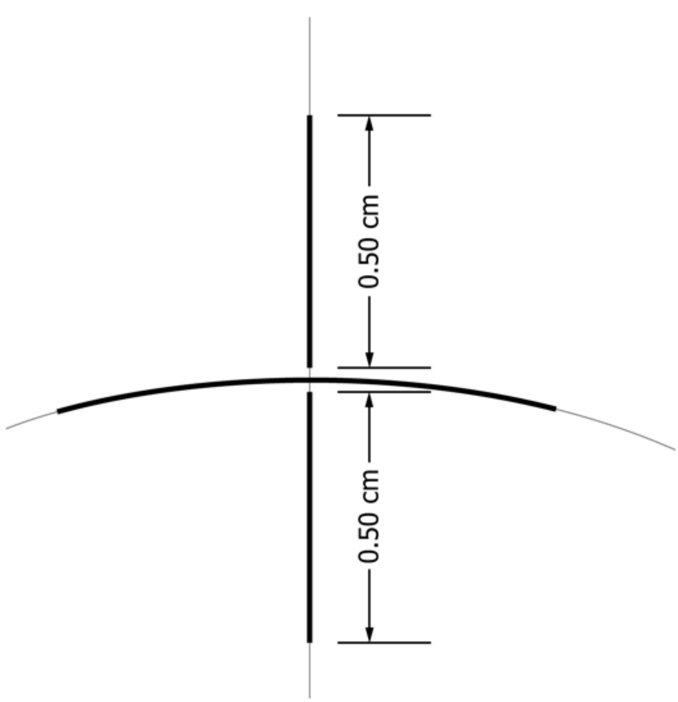

FIG. 4 Cadmium Cross Construction: Insert the 1.0-cm long piece of cadmium wire into the circular groove at each cross location depicted in Fig. 3. Place one of the 0.5-cm long cadmium pieces on either side of it in the radial groove, ensuring that all of the wires remain in the grooves.

12. Procedure

12.1 Mount the DAI so that the S1 surface is oriented towards the neutron source, the S4 surface of the posts are as close to the image plane as possible, and the device is centered in the beamline.

12.2 Make a neutron image of the DAI. Do not change the DAI's orientation to the beam before analyzing the image.

12.3 Analyze the resulting neutron image using the method described in Section 13.

12.4 Use shims, or adjust a rotary table if available, to correct for any misalignment indicated through the image analysis.

12.5 Take another neutron image to confirm alignment.

13. Calculation or Interpretation of Results

13.1 The DAI measures two properties: the degree of misalignment of the imaging plane to the beam (including the direction of misalignment) and the divergence angle of the beam. Fig. 5 shows the orientation of the axes. The piece of cadmium wire in the center of the S1 surface of the plate and the S4 surface of the center post allow for determination of alignment. If only one piece of cadmium can be seen on the film, then the plate is perpendicular to the beam. However, if both cadmium pieces are visible, the plate is misaligned. The piece of cadmium wire on the S4 surface will appear brighter and more square than the piece on the S1 surface, permitting easy discrimination between the two cadmium images. The offset is determined by measuring the distance in both the x and y directions between the images of the wires as shown in Fig. 5. With this value, the DAI and imaging device can be adjusted in order to align the imaging plane perpendicular to the beam, or the measured offsets in the x and y direction can be used to calculate the divergence angles in conjunction with the images of the cadmium crosses. If symmetry is found, calculation of divergence angles along the x and y directions is likely sufficient. To calculate the divergence angles on the diagonals, project or measure the offset to the diagonal axes and use these offset values to determine the angle of misalignment along each diagonal axis. The images of the cadmium wires on surface S4 give a zero-thickness image baseline providing points with a known separation for reference. Mathematical calculatons are based on Refs. (**2**) and (**3**).

13.2 *Alignment of Beam and Imaging Plane:*

13.2.1 Determine the distance from the center cadmium wire at the S1 surface to the neutron imaging device. This distance is termed j.

13.2.2 Examine the neutron image of the DAI obtained in 12.3 to determine the position of the center post's S1 and S4 surface cadmium pieces.

13.2.3 If the center S1 cadmium wire image is blurred due to geometric unsharpness, the center of the blurred image can be used as the wire's position.

13.2.4 If the image of the square S4 cadmium piece does not fall within the image of the round S1 center cadmium piece,

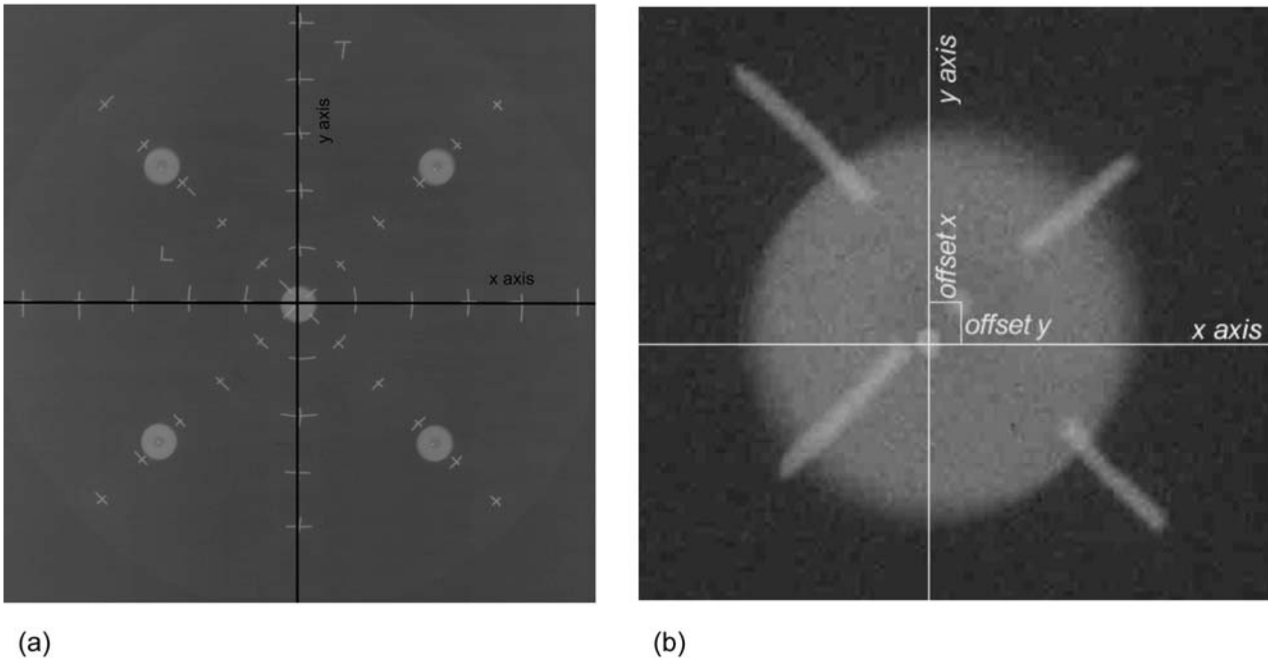

FIG. 5 View a) defines the *x*- and *y*-axes on an image, where the direction with a T is the *y*-axis. View b) shows where to measure the offset in the *x* and *y* directions. Note the square, sharper dot is the origin for the axes.

measure the separation distance, $offset_x$ and $offset_y$ in the *x* and *y* direction as shown in Fig. 5.

13.2.5 The angle of adjustment required to align the DAI to the beam can be determined by trial and error by repeating 12.1 through 12.5, until alignment is achieved. Alternatively, the rotational angle, required to align the DAI in the *x* or *y* direction can be determined by the equation:

$$\beta_{x\ or\ y} = tan^{-1}\left(\frac{offset_{x\ or\ y}}{j}\right) \tag{1}$$

where:

j = the distance separating the S1 center cadmium piece and the imaging plane, and

$offset_{x\ or\ y}$ = the offset along either the *x* or the *y* axis.

13.2.6 If the DAI cannot be aligned by rotation, then verify that the DAI is approximately centered in the neutron beam.

NOTE 6—The DAI must be multiple centimeters from the beam centerline to observe this condition.

13.3 *Beam Divergence:*

13.3.1 The beam divergence angle will change with position so it should be calculated at each cadmium wire cross location independently. Choose a cadmium wire cross location at which the divergence angle is to be determined. On the *x* axis, use the *x* value, on the *y* axis, use the *y* value for the calculations. To calculate a divergence angle on the diagonals, measure the offset in each diagonal direction and use this value to determine the alignment angle, to use in each direction.

13.3.2 Determine the "as-built" radius, r_{act}, by measuring the distance between the cadmium wire cross and the center cadmium wire at the S1 plate surface.

13.3.3 Determine the radius on the image, r_{exp}, by measuring the distance between the image of the cadmium wire cross and the center cadmium wire image (the bright, squarer image representing the S4 center cadmium piece, if the imaging system is misaligned).

13.4 *Aligned Calculations:*

13.4.1 If the imaging system is aligned (the S1 and S4 surface cadmium wire images at the center overlap on the image) the following simplified approach can be used:

$$\alpha = tan^{-1}\left(\frac{r_{exp} - r_{act}}{j}\right) \tag{2}$$

where:

α = the divergence angle at a specific wire cross location.

NOTE 7—Generally alignment will not be perfect and any offset necessitates the use of the misaligned calculations (see 13.5).

13.5 *Misaligned Calculations:*

13.5.1 If the S1 and S4 surface cadmium wire images do not overlap, the imaging system is not perfectly aligned. The result of this is that one side of the DAI will be closer to the beam aperture (denoted with a subscript "c") and the other will be further from the beam aperture (denoted with a subscript "f"). Corrections need to be made to the divergence angles to account for this. Fig. 6 demonstrates this idea and serves to define variables. In the *x* and *y* directions, the position of the bright dot indicates the closer side. For example, if the bright dot is to the left of the dull one then the left side is the close side and the right is the far side.

13.5.2 Calculate the rotational angle needed to align the imaging system using Eq. 1 in the *x* and *y* direction and along the diagonal axes if desired.

13.5.3 Calculate the distance between the S1 center cadmium wire and the location of its image $\left(\overline{OD}\right)$ using Eq 3, where the offset is along the appropriate axis.

$$\left(\overline{OD}\right)^2 = j^2 + (offset)^2 \tag{3}$$

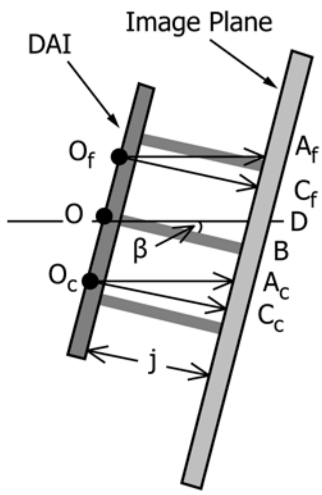

FIG. 6 Illustration of a misaligned DAI. This diagram is the basis for the calculations of the divergence angle while the DAI is not aligned. B is the position of the bright center dot on the neutron image (the image of the S4 center piece of cadmium) and D is the position of the dull center dot on the neutron image (the image of the S1 centerpieces of cadmium).

13.6 *Divergence Angle on the Far Side:*

13.6.1 For the axial directions where the cross location is positioned on the far side in an unaligned imaging system, use the following to determine the divergence angle.

13.6.2 Calculate the distance between the points A_f and C_f $\left(\overline{A_f C_f}\right)$ where the offset is along the appropriate axis.

$$\overline{A_f C_f} = r_{exp} - offset - r_{act} \tag{4}$$

13.6.3 Calculate the distance between the points O_f and C_f $\left(\overline{O_f C_f}\right)$ where β has been determined along the appropriate axis.

$$\left(\overline{O_f C_f}\right)^2 = \left(\overline{A_f C_f}\right)^2 + \left(\overline{OD}\right)^2 - 2\left(\overline{A_f C_f}\right) \times \left(\overline{OD}\right) \times \cos\left(90 + \beta\right) \tag{5}$$

13.6.4 Calculate the divergence angle for the far side using the value for the appropriate axis.

$$\alpha_f = \sin^{-1}\left(\cos\beta \times \frac{\overline{A_f C_f}}{\overline{O_f C_f}}\right) \tag{6}$$

13.7 *Divergence Angle on Close Side:*

13.7.1 For the axial directions where the cross location is positioned on the close side in an unaligned imaging system, use the following to determine the divergence angle.

13.7.2 Calculate the distance between the points A_c and C_c where the offset is along the appropriate axis.

$$\overline{A_c C_c} = r_{exp} + offset - r_{act} \tag{7}$$

13.7.3 Calculate the distance between the points O_c and C_c where β has been determined along the appropriate axis.

$$\left(\overline{O_c C_c}\right)^2 = \left(\overline{A_c C_c}\right)^2 + \left(\overline{OD}\right)^2 - 2\left(\overline{A_c C_c}\right) \times \left(\overline{OD}\right) \times \cos\left(90 - \beta\right) \tag{8}$$

13.7.4 Calculate the divergence angle for the close side using the β value for the appropriate axis.

$$\alpha_c = \sin^{-1}\left(\cos\beta \times \frac{\overline{A_c C_c}}{\overline{O_c C_c}}\right) \tag{9}$$

13.7.5 A plot of the divergence angle, α, as a function of DAI radius can be used as a check on alignment. The plot should be symmetric about zero if circular symmetry exists in the collimator.

14. Report

14.1 The following information shall be reported:

14.1.1 Misalignment in the *x* and *y* directions, and

14.1.2 Calculated divergence angle at each axial and radial location.

15. Precision and Bias

15.1 Precision and bias of the calculated divergence angle is strongly dependent on the accuracy of the position measurements.

15.2 When the values *j*, $offset_x$, $offset_y$, and radial positions are measured with 0.05-cm precision, both alignment and divergence angles were established to have uncertainties of ±0.02 degrees.

16. Keywords

16.1 alignment; beam characterization; divergence angle; neutron radiography

REFERENCES

(1) Brenizer, J. S., Raine, D. A., Gao, J., and Chen, J., “Design of a Divergence and Alignment Indicator,” *Nuclear Instruments and Methods in Physics Research A*, Vol. 377 (1996), pp. 58-62.

(2) Brenizer, J. S., Raine, D. A., Gao, J., Chen, J., “Comparison of Neutron Radiography Beam Divergences with Divergence and Alignment Indicator Measurements,” *Neutron Radiography* (5) Proceedings of the Fifth World Conf. on Neutron Radiography, Berlin, Germany, (June 17-20, 1996), C. O. Fischer, J. Stade, and W. Bock, eds., (Deutsche Glesellschaft für Zerstörungsfreie Prüfung e.V., Germany), 1997 , pp. 183-190.

(3) Chesleigh, M. and Brenizer, J. S., “Analysis and Testing of the Divergence and Alignment Indicator using the Penn State Neutron Radiography Beam,” *J. Radiation Isotopes and Applications*, Vol. 61 # 4, (2004), pp. 591-595.

SUMMARY OF CHANGES

Committee E07 has identified the location of selected changes to this standard since the last issue (E2861-11) that may impact the use of this standard.

(1) Added "computed radiography" within the definition for neutron image in the Terminology.

(2) In Section 9, minor wording changes to ensure film is not interpreted as the only method for acquiring the neutron image.