Performance and Calibration of a Neutron Image Intensifier Tube Based Real-Time Radiography System


Abstract—Image calibration is central to extending the capabilities of neutron radiography beyond mere visualization. However, the effects of scattered neutrons and variations in background image intensity adversely affect quantitative radiography. We describe the calibration of a real-time neutron radiography system that limits these effects and which is applicable to systems with variable digitizer gain and offset. A neutron image intensifier tube coupled to a vidicon camera with a capture rate of 30 frames/s was used. The system could account for 10 ml of water entering the field of view to within 2% and could measure the variation in thickness of a graphite wedge to within 2.3%. The spatial resolution was 450 μm for a field of view of 410 cm². The image persistence half life was ∼0.3 s and the system was functional for quantitative radiography with neutron fluxes above ∼5 × 10^6 n/cm²/s.

Index Terms—Area detector, image calibration, quantitative imaging, quantitative neutron radiography, real-time neutron radiography.

I. INTRODUCTION

NONINVASIVE techniques for determining the internal structure of objects have existed since at least the late 19th century when Roentgen made the first X-ray radiographs. Much attention in recent years has been given to the use of noninvasive imaging as a scientific tool, e.g. [1], and several techniques including Magnetic Resonance Imaging (MRI), Computed Tomography (CT), X-ray, and neutron radiography are commonly used.

The ideal noninvasive imaging technique would combine a broad field of view with high spatial/temporal resolution and quantifiable sensitivity to variations in the presence of a material. However, current technologies make tradeoffs among these requirements. Neutron radiography provides information complimentary to that obtainable with standard X-ray radiography, CT, or MRI but with benefits for particular applications. The basic physics is well described, e.g. [2], and its use in tomography and specific applications of quantitative imaging has been discussed by a number of authors, e.g. [3]–[7].

Image calibration is central to extending the capabilities of neutron radiography beyond mere visualization and a number of methods with varying degrees of accuracy have been described. By far, the simplest of these is done by measuring the transmittance of a neutron beam through an object and relating it to an exponential attenuation law. However, previous work suggested that this method yields poor results and can be improved upon if the effect of variations in background image intensity and object scattered neutrons are taken into account [8], [10]. The present contribution describes a calibration method that considers these effects and that is applicable to a real-time radiography system with variable digitizer gain and offset.

The development of methods for capturing digital neutron radiographs is an active area of research, e.g. [11]–[13]. The imaging system used for this work is a neutron image intensifier tube coupled to a vidicon camera and an eight bit digitizer. Image intensifier tubes first found application in neutron imaging during the mid 1960s [14] and modern versions, because of their high signal amplification, are well suited for quantitative real-time radiography with low and medium flux beam lines. The characteristics of this system, as they apply to quantitative radiography, are described.

II. MATERIALS AND METHODS

A. Overview

A neutron source, image intensifier tube, closed circuit television camera (vidicon), computer and digitization board comprised the real-time radiography system [Fig. 1(a)]. Calibration was done using a polystyrene step standard, where the linear attenuation coefficient was determined via neutron transmission using a BF-3 detector. The calibrated imaging system was tested by measuring both water volumes entering a porous media as well the thickness of a graphite wedge. The results were compared with the known values.

B. Neutron Source

A TRIGA Mark II research reactor at Cornell University, Ithaca, NY, was used for this work. The reactor was licensed for 500 kW steady state operation and pulsed to 1000 MW. A thermal flux of 1.2 ± 0.2 × 10^13 n/cm²·s has been measured at 500 kW in the core center [15].

The beam port for the radiography facility is comprised of a 10.16 cm diameter tube passing through the TRIGA’s graphite reflector tangent to the core. A beam tube with 15.25 cm diameter, connected to the 10.16 cm section, passes through the
biological shield and into the experiment bay. A graphite plug is located opposite the core center to scatter neutrons and acts to enhance the beam. The position of the plug was manually adjusted to maximize the flux. Downstream of the graphite plug an 18 cm long sapphire crystal, 2.54 cm in diameter and contained within a collimator sleeve, acts as a filter for gamma rays and fast neutrons; see Fig. 1(a).

C. Neutron Beam Characteristics

The L/D ratio for the real-time radiography system, as defined in [16], is variable from 70.0 to 130. In this range, the beam intensity was found to closely follow a linear relation. The thermal neutron flux was determined by gold foil activation and found to be \((6.0 \pm 0.3) \times 10^6 \text{ n/cm}^2 \cdot \text{s}^{-1}\) at 300 kW with a beam diameter of 19 cm. For an L/D ratio of 70, the thermal neutron flux was found to be \((1.2 \pm 0.2) \times 10^7 \text{ n/cm}^2 \cdot \text{s}^{-1}\) at 480 kW with a beam diameter of 16.51 cm. The L/D for this work was 110 \(\pm\) 1.0 and the cadmium ratio was 21.0. A reactor power of 300 kW was used for the real-time radiography in this work.

Neutron intensity increased linearly with reactor power between 10 kW and 480 kW, as measured with a BF-3 neutron detector connected to an Ortec counting system. The beam profile was determined by film radiography with 20-min exposures of both Kodak SR type and DuPont 35 films in a vacuum cassette at 200 kW with a Gd converter, both of which produced comparable results. The films were processed in a Kodak Industrex film processor and scanned with a UMAX Astra 2400 scanner at 300 dpi.

D. Neutron Imaging System

The neutron image intensifier, here a Precise Optics PS93NX, uses a gadolinium oxy-sulfide screen to absorb thermal and sub-thermal neutrons, which results in emission of an internal conversion electron (IC) and subsequent scintillation light when the vacancy in the K-shell, left by the IC, is filled. The scintillation light in turn strikes a photo cathode that emits an electron which is then focused onto an output screen that converts the electron back into visible light which is itself sent to the vidicon camera. The focusing of electrons from the photocathode onto the output screen intensifies the radiographic image. The image intensifier can be operated in standard view with an image area of 410 \(\times\) 410 mm, as well as \(\times 1.5\) and \(\times 2.0\) magnifications with resolutions of 55, 65, and 75 lp/cm [17]. The camera used for this work was a Precise Optics Vidicon, PVC525V, set at \(f = 1.4\).

Video images were digitized using a Scion LG-3 frame grabber connected to a G3 Macintosh computer running NIH Image 1.61. This version of NIH Image limited digitization to an 8 bit gray scale (1 to 256 values, low black and high white) with a resolution of 640 \(\times\) 480 pixels. The system was shown to respond linearly to increases in neutron flux over the range of gain and offset used in this study.

The beam profile, as seen by the real-time radiography system, was measured by averaging 1000 individual image frames. The beam profile on that image was determined by measuring pixel intensity values horizontally and vertically across the image using the above software. Image noise was assessed by dividing a single image frame taken of the neutron beam by a 1000 frame average of the beam. The variation in pixel intensity value within a 1000 pixel area at the center of the resulting image was measured. In order to determine whether an attenuator would have an effect on image noise, a single image frame of the calibration standard was divided by a 1000 frame average of the unattenuated beam. The variation in pixel value within a 1000 pixel area was measured for each thickness of the calibration standard.

E. Calibration for Linear Response of Pixel Intensity Value Versus Neutron Flux

Following the general analysis of image brightness given by Habiki and Mishima [9] it can be shown, and confirmed empir-
Fig. 2. Schematic of the radiographed object and image plane.

The response of the imaging system can be expressed as

\[ \frac{I(x,y)}{I_0(x,y)} = a \frac{\Delta \phi(x,y)}{\phi_0(x,y)} + 1. \]  

(1)

Here, \( I_0(x,y) \) is the image brightness (in pixel intensity values) at the point \((x, y)\) when nothing attenuates the neutron beam and \( I(x, y) \) is the image brightness at the same location when something is attenuating the neutron beam. \( \Delta \phi(x,y)/\phi_0(x,y) \) is the fractional change in neutron flux at a point on the image plane (0 when nothing is placed between the neutron source and the image plane), and “\( a \)” is the system response constant.

The attenuation of a neutron beam can be described using

\[ \frac{\phi(x,y)}{\phi_0(x,y)} = B(\Sigma_t, z, R) e^{-\int \Sigma_a(x,y) dx}. \]  

(2)

Here, \( \phi_0(x,y) \) and \( \phi(x,y) \) \{\( 1/\text{cm}^2/\text{s} \}\), are the measured intensity of the neutron beam at location \((x, y)\) with and without an attenuating object. \( \Sigma_a(z) \{1/\text{cm} \}\) is the object’s total linear attenuation coefficient, \( z \) \{cm\} is its total thickness at location \((x',y')\), and \( R \) is the distance from the point \((x',y')\) to the point \((x,y)\) (Fig. 2).

The factor \( B(\Sigma_a, R, z) \) \{dimensionless\} accounts for scattered neutrons that fall on a detector at the location where the neutron intensity is being measured (see Fig. 2). Two main sources of scattered neutrons are typical: those from the object being imaged and those coming from the shielding that surrounds that object. The sum of the scattered and unattenuated fluxes equals the total neutron flux that falls on the detector at any position

\[ \phi(x,y) = \phi_{\text{sc}}(x,y) + \phi_{\text{ss}}(x,y) + \phi_{\text{un}}(x,y). \]  

(3)

Here, \( \phi_{\text{sc}}(x,y) \) and \( \phi_{\text{ss}}(x,y) \) are the fluxes at the image plane, resulting from scattering by the radiographed object and the surrounding shielding respectively and \( \phi_{\text{un}}(x,y) \) results from neutrons that passed through the object without interaction.

Limiting the effect of scattered neutrons is key to quantitative radiography [8]. The collimator aperture and L/D were chosen to ensure that the beam fell only on the gadolinium covered image plate, which has an absorbency of >90% for thermal neutrons. The interior of the beam catcher was lined with borated polyethylene in order to absorb scattered neutrons that might otherwise be reflected off of the walls and onto the face plate of the image intensifier. The effect of neutrons scattered by the object under study was limited by dispersion, e.g. [8], and an object to image plane separation of 5 cm was used for this work.

Neglecting the effect of \( \phi_{\text{sc}}(x,y) \) and \( \phi_{\text{ss}}(x,y) \) on the neutron flux at the image plane, i.e. \( B(\Sigma_a, z, R) \sim 1.0 \), we can write

\[ \Delta \phi(x,y) = (e^{-\Sigma_a z(x,y)} - 1) \phi_0(x,y) \]  

(4)

where \( \Sigma_a \) is the total neutron linear attenuation coefficient of the material \{1/cm\}, \( z(x,y) \) is its thickness \{cm\} and all other terms are as previously defined. Inserting (4) into (1) and rearranging yields

\[ \frac{I(x,y)}{I_0(x,y)} = a e^{-\Sigma_a z(x,y)} + (1 - a) \]  

(5)

where “\( a \)” is a system response coefficient determined using a polystyrene calibration standard, 2.54 cm wide and ranging in thickness from 0.079–0.635 cm in 0.079 cm steps (see Fig. 3). The linear attenuation coefficient of the polystyrene, 2.45 \{1/cm\}, was determined via neutron transmission.

\( F. \) Volume and Thickness Measurements

If \( \Sigma_a(z) \) is constant in “\( z \)” then (5) can be rearranged to give

\[ z(x,y) = \frac{\ln \left( \frac{I_{\text{in}}(x,y)}{I_{\text{out}}(x,y)} - 1 \right)}{\Sigma_a} + 1 \]  

(6)

which allows measurement of \( z(x,y) \) from knowledge of \( \Sigma_a \) and data on \( I(x,z)/I_0(x,z) \). Because the images used in this study...

Fig. 3. System calibration using a polystyrene standard. Calibration curve using \( I/I_0 \) values versus \( \exp(-2.45 z) \), where \( z \) is the thickness of the polystyrene standard and its linear attenuation coefficient is 2.45 \{1/cm\}. 

Gd coated face plate of the neutron image intensifier 

Image of object generated by \( \phi(x,z) \)
were digital, they can be viewed as two-dimensional data arrays, where a location \((x, y)\) corresponds to the point \((i, j)\) in the array and the image brightness corresponds to the pixel value at that location (integer values ranging from 1 to 256). The volume of a material present at a location \((i, j)\) in an image is then given by multiplying (6) by the area of a pixel. The total volume of material present can be determined by summing (6) over \(i\) and \(j\) (which correspond to locations \(x, y\) on digital images)

\[
\text{volume} = \sum_{i=k}^{l} \sum_{j=m}^{n} z(i,j)w
\]  

(7)

where \(k, l\) and \(n, m\) are the values of “\(i\)” and “\(l\)” which correspond to the perimeters of the object when it is digitized and \(w\) is the area of a pixel.

Equations (6) and (7) were used to measure the thickness of a graphite wedge, placed 5 cm from the image plane, and the volume of water injected into a porous media using a peristaltic pump. The method by which the later measurements were performed has been described previously [7].

G. Image Persistence

The persistence of an image after removal of an object was measured by first placing the calibration standard 5 cm from the face plate of the image intensifier for 600 s. The standard was then pulled away and \(I(x,y)/I_0(x,y)\) versus time was measured for each thickness of the calibration standard.

III. RESULTS AND DISCUSSION

The beam profile as determined by film and real-time radiography is given in Fig. 4 and a clear difference is apparent between the two. Pixel values on the real-time radiograph also show a variation of as much as 10% from one location to another and this needs be taken into consideration if quantitative measurements are to be made using \(I(x, y)\) data. By contrast, it is found that \(I(x,y)/I_0(x,y) = 1.00 \pm 0.008\) across the image field, where \(I_0(x,y)\) is a 1000 frame average of the beam and \(I(x,y)\) is a single image frame. This ratio eliminates the effects of both beam and imaging system introduced profile and is a better choice for quantitative measurements based on beam attenuation. Interestingly, the standard deviation in \(I(x,y)/I_0(x,y)\) is the same for beam attenuations up to 85%, as determined with the calibration standard. The signal to noise ratio (S/N) of the system can be gauged by dividing two separate image frames taken of the neutron beam. Here \(I(x,y)/I_0(x,y) = 1.00 \pm 0.014\), and if the standard deviation is taken to represent the rms value of noise in the voltage signal being digitized, then the definition of S/N would give \(S/N = 20 \log(1.00/0.014) \sim 37\). This would likely improve if a high S/N CCD camera were employed instead of the vidicon that was used.

The persistence of an image was gauged by measuring intensity versus time as shown in Fig. 5. The initial \(I(x,y)/I_0(x,y)\) for different locations on the calibration standard can be seen on the graph at time \(t = 0\). The half life of the persistence is \(\sim 0.3\) s regardless. While the minimum \(I(x,y)/I_0(x,y)\) shown on the graph is \(\sim 0.84\), this actually corresponds to an 85% attenuation of the neutron beam. The persistence decay time sets a limit on the ability of the imaging system to quantify rapid variations that result in an established image. No attempt was made to measure image afterglow.

The L/D for the system as tested would predict a spatial resolution of \(\sim 200 \mu\text{m}\) for an object placed 1.0 cm from the image plane [2]. In practice resolution was limited by the pixel density, here \(640 \times 480\) for the full image. The vidicon camera was operable in both standard view as well as \(\times 1.5\) and \(\times 2.0\) magnifications. In standard view digitization limited resolution to \(450 \mu\text{m}\) for an object 1 cm from the image plane and times two resolution was limited to \(125 \mu\text{m}\) for an object placed closer than 1 cm from the image plane. A comparison of film and real-time radio-

Fig. 4. Comparison of beam profiles as determined by film and real-time radiography. The images were normalized to the same scale. (a) Horizontal and vertical beam profile as determined by film radiography using a Kodak SR film exposed by the neutron beam for 10 min. at 200 kW. (b) Horizontal and vertical beam profiles (500 image frame averages) obtained using the neutron image intensifier and vidicon camera. “I” is image intensity in pixel values.
Fig. 5. Variation in image persistence versus time. The figure shows how the persistence of an image decays with time after the object has been removed. The calibration standard was used to generate the data and the various curves correspond to different thickness’ of the standard. The smaller the initial value of $I/I_0$, the longer it takes for $I/I_0$ to return to 1.0.

Fig. 6. Comparison of real-time and film radiographs of ASTM standards. The film and real time images were normalized to the same scale. (a) 500 frame average of an ASTM standard taken with the real-time imaging system. The $L/D = 110$ and the pixel value is plotted versus position along the scan line shown. (b) Static radiograph taken with a 20 min. exposure of Kodak SR type film. The $L/D = 130$ and pixel value is plotted versus position along the scan line shown. (c) and (d) 500 frame average of a second ASTM standard and static radiograph, taken as above.

graphs of American Society for Testing and Materials (ASTM) standards are shown in Fig. 6. In both cases the standards were placed in contact with the respective image plates. The real-time image is a 500 frame average. The film image was scanned using a UMAX scanner at 3000 dpi. The images were normalized to give the same background pixel value. A graph of pixel value versus position is shown for both real-time and static radiographs and indicates a greater similarity than is apparent to the eye.

Equations (6) and (7) were used to measure the variation in thickness of a graphite block and the volume of water pumped into a porous medium respectively. In both cases, this was done to gauge the precision of the calibration method. The results are shown in Figs. 7 and 8. The standard deviation in the measurements can be determined by applying the error propagation formula [18] to (6) and (7) along with the standard deviation for the $I(x,y)/I_0(x,y)$ measurements described above. Fig. 8 shows error bars representing the standard deviations for the ra-
for example, to a maximum resolution for the graphite measurements of $0.11 \pm 0.07$ cm. Radiographic measurements were able to account for 10 ml of water entering the field of view to within better than 2.0% and thickness measurements made on a graphite wedge were within 2.27% of actual values.

It should be emphasized that in order for the calibration to work as described care must be taken to ensure that $(X_1, Z, R) \sim 1.0$. As a result, calibration done with a given standard is not applicable to all other applications in which the sample geometry and sample to image plane separation might be different.

IV. CONCLUSION

The use of a calibration standard yielded satisfactory results for quantitative neutron radiography. Care must be taken to minimize the effects of object scattered neutrons and an accurate attenuation coefficient for the material under study must be determined. It is also important that the background intensity profile, measured by the imaging system, be taken into consideration or neglected. The neutron image intensifier used for this work provides accurate quantitative real-time radiography applicable to use at a low flux research reactor.

Note: The Cornell University TRIGA was shut down on June 30, 2002. It is scheduled to be decommissioned.

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REFERENCES


