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Aaron E. Craft, Glen C. Papaioannou,
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Conversion from film to image plates for transfer method neutron radiography of nuclear fuel

Aaron E. Craft*, Glen C. Papaioannou, David L. Chichester, Walter J. Williams

[a]*Idaho National Laboratory, PO Box 1625, Idaho Falls, ID 83415, USA, aaron.craft@inl.gov*

Abstract

This paper summarizes efforts to characterize and qualify a computed radiography (CR) system for neutron radiography of irradiated nuclear fuel at Idaho National Laboratory (INL). INL has multiple programs that are actively developing, testing, and evaluating new nuclear fuels. Irradiated fuel experiments are subjected to a number of sequential post-irradiation examination techniques that provide insight into the overall behavior and performance of the fuel. One of the first and most important of these exams is neutron radiography, which provides more comprehensive information about the internal condition of irradiated nuclear fuel than any other non-destructive technique to date. Results from neutron radiography are often the driver for subsequent examinations of the PIE program. Features of interest that can be evaluated using neutron radiography include irradiation-induced swelling, isotopic and fuel-fragment redistribution, plate deformations, and fuel fracturing. The NRAD currently uses the foil-film transfer technique with film for imaging fuel. INL is pursuing multiple efforts to advance its neutron imaging capabilities for evaluating irradiated fuel and other applications, including conversion from film to CR image plates. Neutron CR is the current state-of-the-art for neutron imaging of highly-radioactive objects. Initial neutron radiographs of various types of nuclear fuel indicate that radiographs can be obtained of comparable image quality currently obtained using film. This paper provides neutron radiographs of representative irradiated fuel pins along with neutron radiographs of standards that informed the qualification of the neutron CR system for routine use. Additionally, this paper includes evaluations of some of the CR scanner parameters and their effects on image quality.

Peer-review under responsibility of the organizing committee of ITMNR-8.

Keywords: neutron radiography; neutron imaging; computed radiography; intirect radiography; transfer method; image plate

* Corresponding author. Tel.: (208) 201-4242; fax: (208) 533-7863.
E-mail address: aaron.craft@inl.gov

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1. Introduction

This paper summarizes efforts to characterize and qualify a computed radiography (CR) system for neutron radiography of irradiated nuclear fuel at Idaho National Laboratory (INL). INL has multiple programs that are actively developing, testing, and evaluating new nuclear fuels including advanced commercial nuclear fuels, accident tolerant fuels, reduced-enrichment research reactor fuels, transmutation fuels, and advanced reactor fuels. The Neutron Radiography reactor (NRAD) sits beneath a shielded hot cell facility where neutron radiography and other evaluation techniques are performed on these highly radioactive objects (Craft et al., 2015c). Irradiated fuel experiments are subjected to a number of sequential post-irradiation examination (PIE) techniques that provide insight into the overall behaviour and performance of the fuel. One of the first and most important of these exams is neutron radiography. Features of interest that can be evaluated through neutron radiography include irradiation-induced swelling, isotopic and fuel-fragment redistribution, plate deformations, and fuel fracturing. Results from neutron radiography inform subsequent examinations.

Neutron radiography of irradiated nuclear fuel provides more comprehensive information about the internal condition of irradiated nuclear fuel than any other non-destructive technique to date (Domanus, 1983). The NRAD currently uses the foil-film transfer technique for imaging fuel, which is depicted in Figure 1 (Craft et al., 2015a). Conversion foils (dysprosium and indium) are loaded into a cassette and remotely positioned in the neutron beam behind the fuel. The foils absorb unattenuated neutrons and become temporarily radioactive in inverse proportion to neutron absorption in the fuel. The activated foils are then removed from the beam and film is placed in contact with the activated foil in a vacuum-sealed cassette, allowing the film to be exposed to the decay radiation from the foil. After exposure, the film is developed and scanned to produce a digital radiographic image. This transfer technique is time-consuming, but is one of very few techniques that can provide high quality radiographic images of radioactive objects. INL is pursuing multiple efforts to advance its neutron imaging capabilities for evaluating irradiated fuel and other applications, including conversion from film to CR image plates (IP). Neutron CR (*n*CR) is the current state-of-the-art for neutron imaging of highly-radioactive objects (Vontobel et al., 2006). The *n*CR process uses the transfer method but an IP is coupled to the activated foil instead of film (Figure 1).

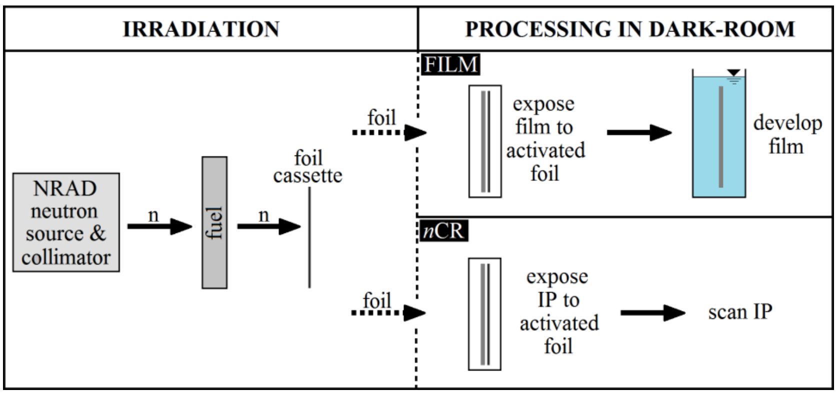

Fig. 1. Transfer method neutron radiography process.

2. Computed Radiography Equipment

A complete CR system includes photostimulable phosphor (PSP) IPs, a CR scanner, and a computer control workstation. CR is based on PSP powder deposited on a substrate to form an IP. The substrate provides structural support for the IP. Information on the composition and structure of the phosphor layer is closely guarded by manufacturers and often proprietary, and thus largely unavailable. The protective layer protects the PSP from damage, and is an abrasion-resistant material that is transparent to the light-spectra of interest. The IPs chosen for this application are the flexible Kodak (Carestream) plates, which were chosen based on their image quality and relatively robust protective layer. Commercial manufacturers typically provide three grades of IP: 1) standard or general purpose (GP), 2) high-resolution (HR), and 3) ultra-sharp or "blue" plate. The GP plates have a thicker PSP layer than the HR and blue plates, and thus they require less exposure dose at the expense of lower spatial resolution. HR and blue plates have a thinner PSP layer than GP plates, and thus require more exposure dose but provide higher resolution. The PSP layer in blue IPs contain a blue dye, which absorbs the red scanner laser, reducing the size of the laser interaction volume from which the blue light is emitted, producing higher sharpness in the resulting image. Different commercial manufacturers of IPs may use different substrate materials, have differing PSP chemistries and thicknesses, and use different concentrations of blue dye in the blue IPs, all generally provide the same three grades of IPs. The GP plates provide adequate spatial resolution for general purpose applications. If higher spatial resolution is required than the GP plates can provide, the HR plates may be desirable. While the HR plates offer improved spatial resolution, they require almost twice the exposure dose compared to GP plates. Blue plates offer higher resolution capabilities than even the HR IPs but require around 60% more exposure dose compared to the HR plates to produce the same output signal. When comparing these plates to decide which type of IP is most appropriate to use, the desired image quality and exposure times, including both the neutron beam exposure and decay exposure times, should be the determining factors.

There are a variety of CR scanners available from commercial manufacturers, and their specific features may vary widely. Two styles of scanners include flat-bed scanners where the IP is flat while scanned and drum-type scanners where the IP is curved, but the fundamental mechanism of acquiring the image signal from an exposed IP is the same regardless of scanner style. A mechanical transport mechanism moved an exposed IP through the scanner. A red laser rasters over the surface of the IP and stimulates the activated PSP, which then releases the stored energy as blue light through photo-stimulated luminescence. The blue light signal is amplified by a photo-multiplier tube into a measureable signal, than converted to a digital signal that is read by a computer. The position of the laser and the output signal are both known, allowing for the formation of an image. Many scanners provide an erasure function that erases the IP using an array of red LEDs positioned after the scanner laser. The laser spot size is often the driving factor for the effective spatial resolution that a scanner can provide. Scanners with 50 µm diameter laser spot size are commonly available, and high-resolution scanners with laser diameters of around 10 µm are also available. The scan resolution is determined by the mechanical transport speed and the laser rastering rate. The PMT voltage may be manipulated to amplify the signal from an IP to utilize the bit-depth provided by the scanner. Manipulation of these and other scanner parameters may be available to the operator depending on the particular software and manufacturer.

By convention, the "fast-scan direction" describes the direction of the laser rastering along an image line and the "slow-scan direction" describes the direction of mechanical transport of the IP through the scanner. Due to a number of physical mechanisms and other phenomena, the effective spatial resolution differs between the "fast scan" (laser spot rastering along an image line) and "slow scan" (mechanical transport of the IP through the scanner) directions. The spatial resolution in the slow-scan direction is typically higher than the fast-scan direction, though the degree of difference will vary for different scanners.

3. Characterization of the CR System

Conversion to *n*CR consists of characterization and qualification of an *n*CR system using the current foil transfer technique with the goal of maintaining similar image quality compared to the current technique with film. Preliminary studies measured the image quality of radiographs acquired using the existing film-based method and determined CR system equipment capable of providing the desired image quality. The hardware selected for this application included a ScanX Discover HR scanner made by AllPro and image plates from Carestream.

Neutron radiography takes significantly more resources (time and cost) than x-ray radiography, and acquisition of multiple radiographs is required to test and characterize the response of the CR system to various input parameters. Therefore, x-ray characterization of the CR system was performed to provide a better understanding of the CR system and inform subsequent image acquisitions using neutrons. Additionally, x-ray CR (*x*CR) was performed to provide a baseline for the performance of the scanner that could be used in the future to test whether the scanner is still performing to its capacity or if maintenance is required.

X-ray CR was performed to evaluate the behaviour of image grayscale intensity as a function of scanner photo-multiplier tube (PMT) voltage. The behaviour of the PMT signal amplification is independent of the IP type, so any IP could be used for these measurements. A GP plate was exposed using constant exposure parameters and scanner settings, varying only the PMT voltage. The plate was placed in a cassette positioned 1.2 m from the source. The source was operated at 130 kV and 62 μA using an 8 μm spot size with no filter for 30 s. The IP was then scanned with a 50 μm pixel pitch and varying PMT voltage ranging between 350-1200 V in 50 V increments. Image grayscale values were plotted with PMT voltage, and exhibited an exponential correlation. An exponential trendline was fit to each data set and the resulting equation used to determine the doubling-voltage (ΔV_{2X}), which is the change in PMT voltage required to change the grayscale intensity by a factor of two. The doubling voltage is not constant, but varies over the range of PMT voltage of the scanner as shown in Figure 2. With information gained from a preliminary radiograph, a user can calculate the difference in PMT voltage (ΔV) required to achieve the desired grayscale intensity ($I_{desired}$) given an initial grayscale value in a ROI ($I_{initial}$) by using the following equation:

$$\Delta V = \frac{\Delta V_{2X}}{\ln(2)} \ln\left(\frac{I_{desired}}{I_{initial}}\right)$$

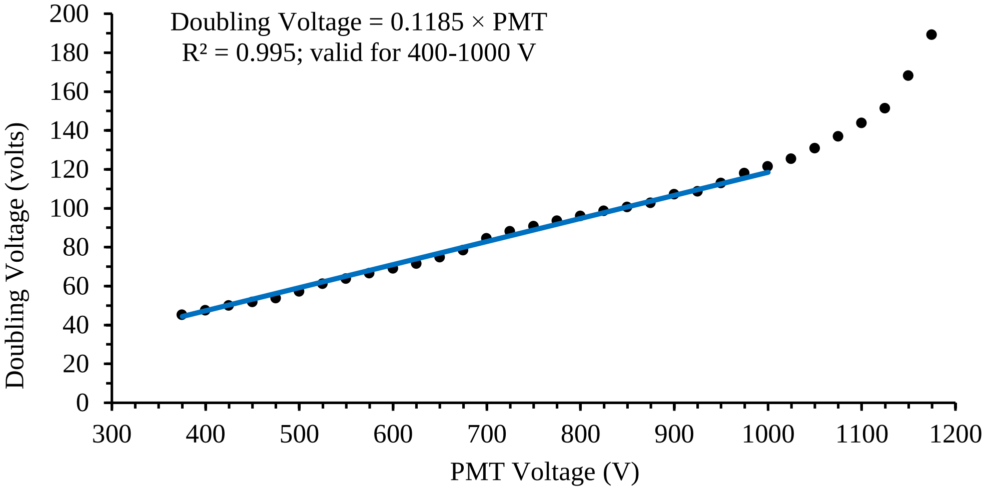

Fig. 2. Doubling voltage as a function of PMT voltage for a ScanX Discover HR.

Additionally, a single exposed IP can be scanned with the eraser function turned off and rescanned using different scan settings to decrease the total number of neutron radiographs required to determine adequate scan settings. However, the signal from the image plate decreases with each scan. If the signal loss with repeated scans were known, it could be compensated for by increasing the PMT voltage. The amount of signal lost with repeated scans was determined to allow high-quality images to be obtained from repeated scans, thus reducing the number of neutron radiographs required. Increasing the PMT voltage beyond 800 V caused an observable degradation of the image signal-to-noise ratio (SNR), and it is recommended to keep the PMT voltage as low as possible to acquire the desired image quality.

4. Neutron Computed Radiography of Irradiated Fuel

The first set of nCR radiographs were taken of a representative irradiated fuel pin, and the IPs were scanned and the grayscale intensities of the resulting images evaluated. From these intensities, the change in PMT voltage required to achieve the desired intensity was calculated. The second set of exposed IPs was scanned using these calculated values provided the expected grayscale values. Thus, x-ray characterization provided the understanding needed to significantly reduce the number of neutron radiographs required to determine the scanner settings for *n*CR.

Figures 3 and 4 show neutron radiographs of an irradiated fuel pin acquired using film and *n*CR with a XL-Blue plate and an HR plate. The exposure parameters for each radiograph are listed in Table 1. Portions of the radiographs showing disrupted fuel pellets are magnified and shown in Figures 5 and 6 for thermal and epithermal radiographs, respectively. The histograms of these images have been adjusted to display a similar grayscale range to allow for a more meaningful comparison between film and *n*CR. From a qualitative perspective, the image quality of *n*CR closely matches that of film, and features such as cracks and relocated fuel fragments can be visualized with similar contrast. Film radiographs exhibit higher sharpness than *n*CR but lower latitude for the thermal-neutron radiographs (Figures 3 and 5). For the epithermal-neutron radiographs, however, *n*CR exhibits higher SNR than film, improving the visibility of the fuel fragments in the *n*CR images (Figures 4 and 6).

Table 1. Image acquisition parameters for neutron radiographs of irradiated fuel pins.

Conversion Foil Material	Imaging Medium	Neutron Beam Exposure Time (min.)	PMT Voltage	Scan Resolution
dysprosium 125 µm thick metal foil (unfiltered neutron beam)	AGFA D3-SC film	22:00	-	25 µm
	*n*CR, XL-Blue plate	22:00	625 V	25 µm
	*n*CR, HR plate	22:00	575 V	25 µm
indium 125 µm thick metal foil (cadmium-filtered beam)	Kodak T200	22:00	-	
	*n*CR, XL-Blue plate	22:00	800 V	25 µm
	*n*CR, HR plate	22:00	850 V	25 µm

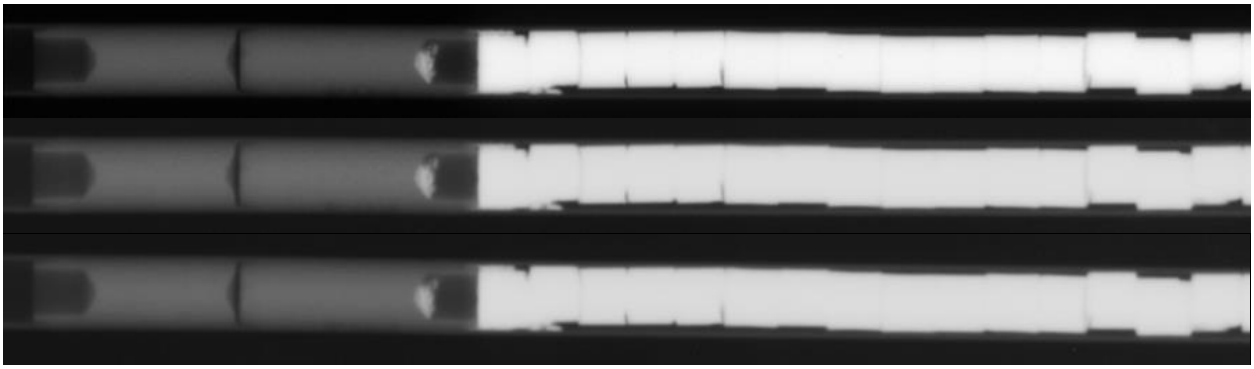

Fig. 3. Thermal neutron radiographs of an irradiated fuel pin acquired using film (top) and *n*CR with XL-Blue (center) and HR (bottom) plates.

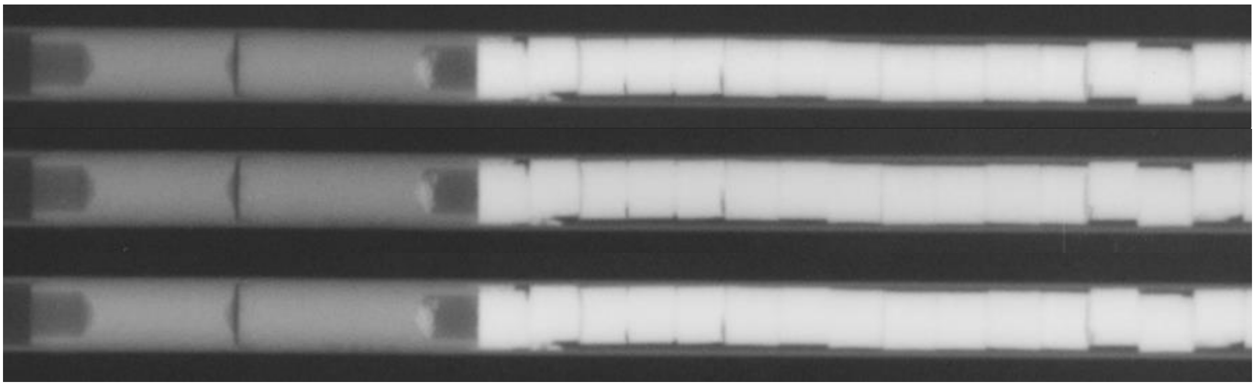

Fig. 4. Epithermal neutron radiographs of an irradiated fuel pin acquired using film (top) and *n*CR with XL-Blue (center) and HR (bottom) plates.

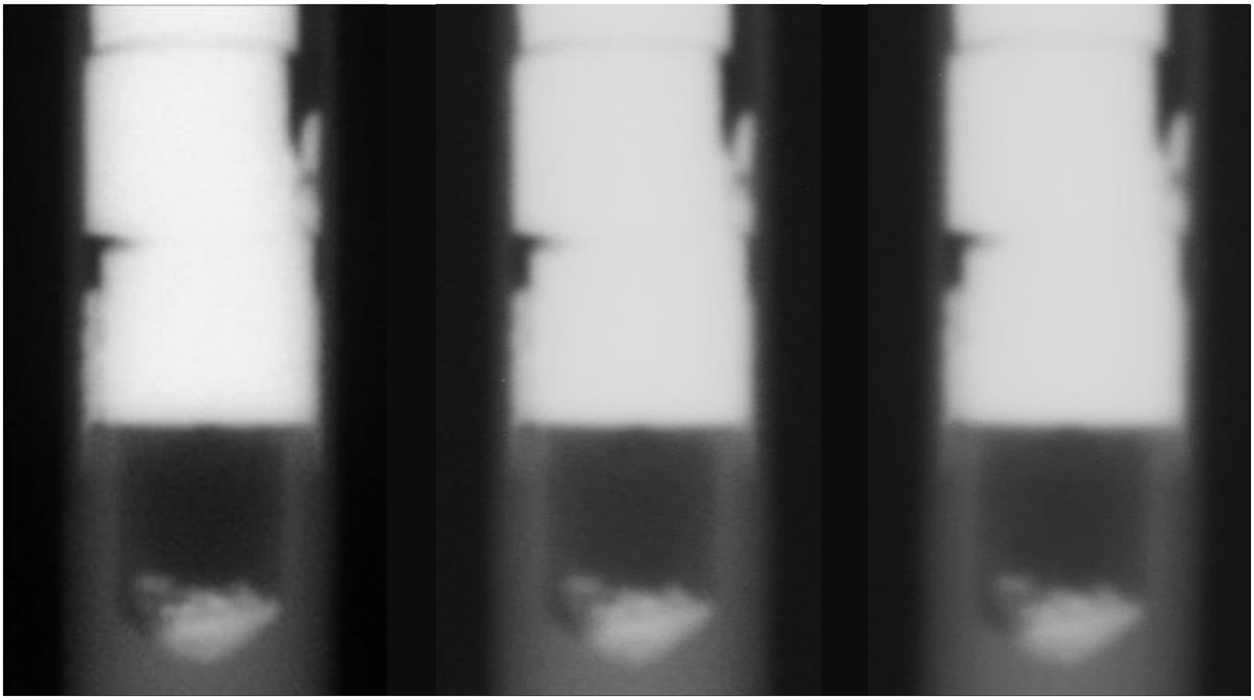

Fig. 5. Thermal neutron radiographs taken using a dysprosium converter foil with film (left) and neutron computed radiography with a XL-Blue plate (center) and an HR plate (right).

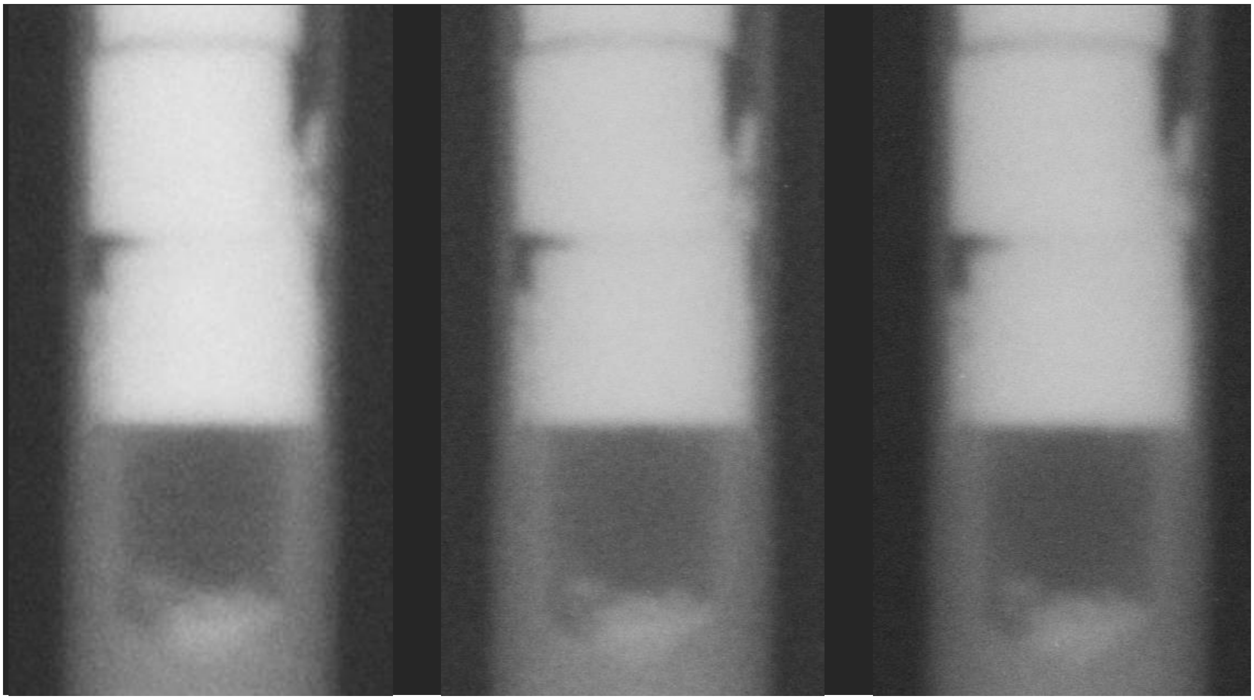

Fig. 6. Epithermal neutron radiographs taken using an indium converter foil with film (left) and neutron computed radiography with a XL-Blue plate (center) and an HR plate (right).

Unfortunately, there are no ASTM or ISO standards for digital neutron imaging systems. ASTM standard E545-05 provides a means of comparing direct-method neutron radiography systems by evaluation of neutron radiographs of two image quality indicators (IQI) determine a facility's radiographic quality category (ASTM International, 2005). While not intended for transfer-method neutron radiography systems, some parts of this standard can be applied for some level of meaningful comparison. Previous characterization efforts performed using film at the East Radiography Station at NRAD determined that the foil-film transfer method was a Category-I neutron imaging facility, the highest quality category according to the ASTM standard (Craft et al., 2015b). For the film radiograph, a dysprosium foil was exposed in the neutron beam for 22 minutes with L/D of 125, then coupled to film and allowed to decay overnight before being scanned at 1200 dpi (21.1 µm/pixel). Likewise, a dysprosium foil was exposed in the neutron beam for 20 minutes and allowed to expose an HR plate overnight before being scanned 25 µm/pixel with the PMT set to 600 V. The resulting radiographs are shown in Figure 7 to provide a side-by-side comparison between film (left) and *n*CR (right). Seven of the holes and all shims in the sensitivity indicator are visible in both film and *n*CR radiographs. Thus, according to ASTM E545-05, both qualify as Category-I radiography facilities. These preliminary results indicate that *n*CR is capable of providing comparable image quality to the existing film technique in a fraction of the time. Further efforts will evaluate foil activation time, decay time, and scanner parameters that provide the highest image quality.

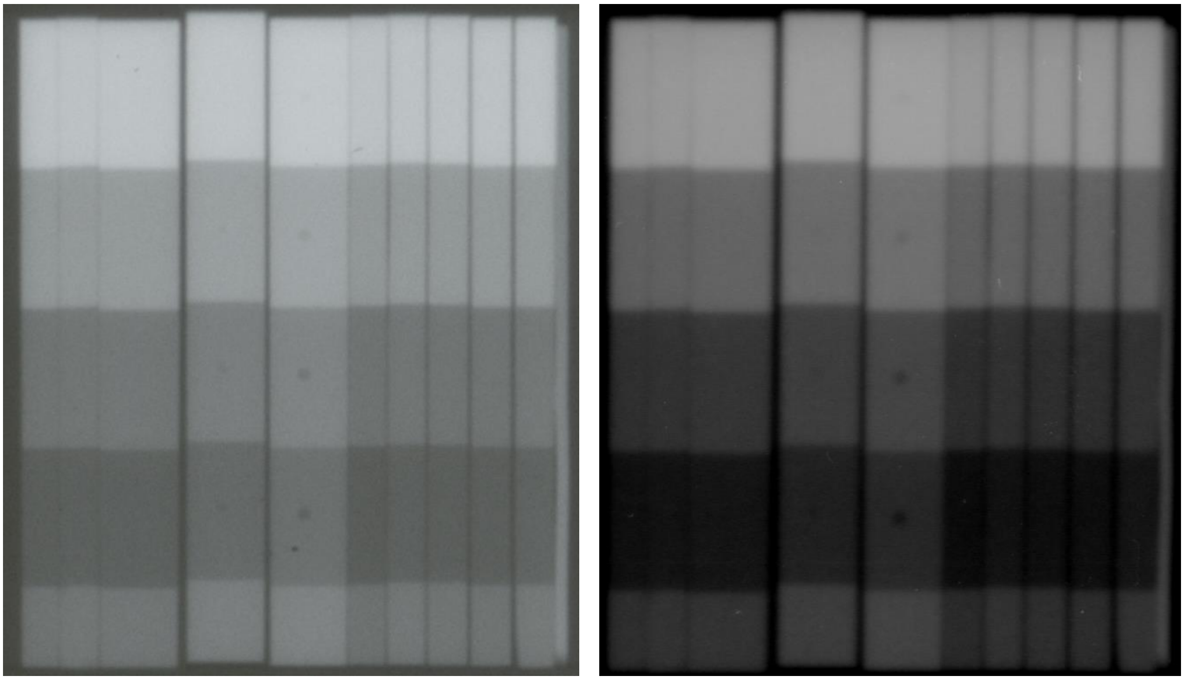

Fig. 7. Neutron radiographs of the ASTM sensitivity indicator made with the transfer method using both film (left) and *n*CR (right).

A gadolinium edge specimen in the neutron radiographs provides an edge spread function suitable for calculating the MTF. Figure 8 shows effective spatial resolution for film neutron radiographs, *n*CR, and *x*CR. The spatial resolution at 10% MTF for film (~11 lp/mm) is twice that of *n*CR (~5.5 lp/mm) using an XL-Blue plate. The emulsion layer of the film is considerably thinner than the PSP layer of an IP, which is the primary reason for the higher resolution of film compared to IPs. The nearly 60% difference in MTF between neutron and x-ray CR images represents a loss in resolution that could be attributed to the foil activation and transfer process. This degradation of spatial resolution from the transfer process can be reduced by using thinner foils and development of IPs with thinner PSP layer.

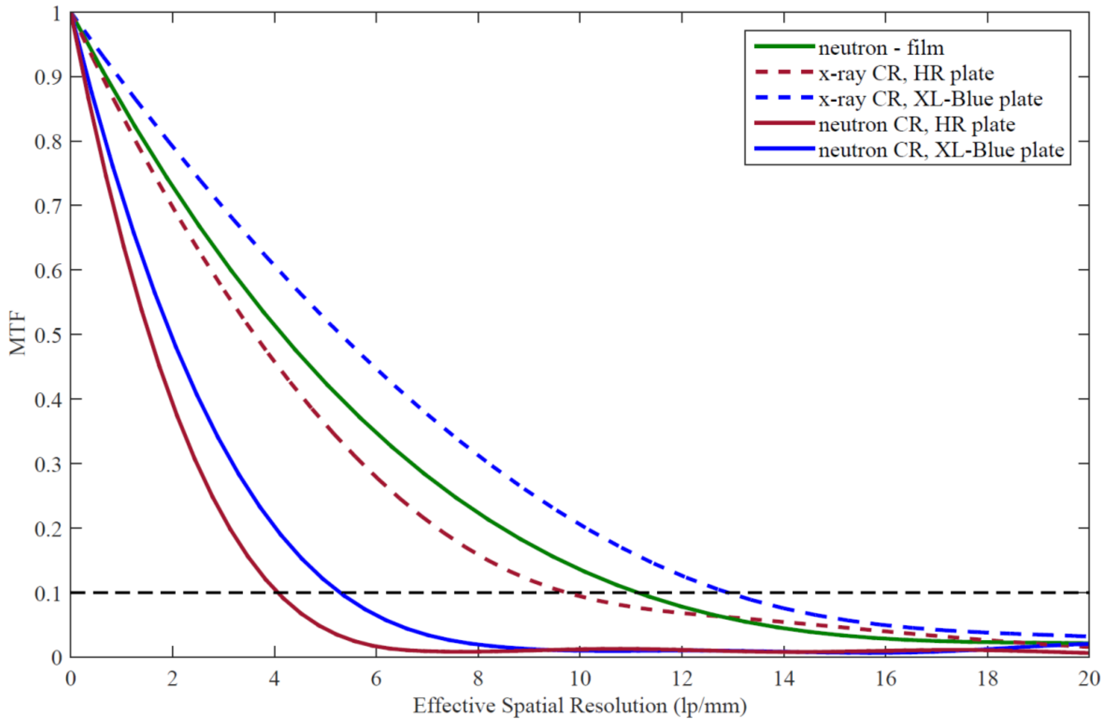

Fig. 8. Comparison of the effective spatial resolution of x-ray CR, neutron film, and nCR systems.

There are many adjustable parameters that affect the neutron radiography system and resulting image quality. Some of these parameters have been evaluated as part of efforts to date, but there are many parameters that should be evaluated further to improve the operational efficiency and data quality of *n*CR images. IPs are more sensitive than film and require less dose, and future efforts will investigate the balance of image quality, neutron beam exposure time and beam L/D ratio. Significant improvements in efficiency should be possible by decreasing beam exposure and/or decay times and increasing the PMT voltage to compensate for the loss of signal, thus shortening the image acquisition time. Another factor that may be degrading the resolution of the *n*CR images is lack of uniform intimate contact with the conversion foils, which is another area for further investigations. Future efforts will include acquisition and evaluation of thinner conversion foils, which would reduce unsharpness from the transfer process at the expense of longer exposure times. Decreasing the thickness of the phosphor layer of IPs and/or directly doping the phosphor with the conversion material (i.e. dysprosium, indium) would likewise improve the spatial resolution. Scanners and image plates from additional manufacturers will also be evaluated in future efforts.

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