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Simulation of neutron radiograph images at the Neutron Radiography Reactor

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ABSTRACT

The ability to accurately simulate potential radiographic images produced by a radiographic facility can improve the facility's ability to design experiments and evaluate images. The image simulation methods detailed in this paper predict the radiographic image of an object based on the foil reaction rate data obtained by placing a model of the object in front of the image plane in a Monte Carlo beamline model. The image simulation method utilizes a characteristic curve relating foil activity to optical density for the film and foil combination in use at the Neutron Radiography Reactor. The simulation validation compared a radiograph of a polyethylene step block to a simulated radiograph of the same step block. The simulation accurately predicts the optical density in each region of a radiograph of the step block. The simulated radiograph predicts the average optical density of the actual radiograph more accurately for the thinner steps, resulting in step averaged optical density differences between the actual and simulated images of −11.6% for the thinnest step versus a difference of −34.7% for the thickest step, possibly due to the greater accuracy of the higher optical density region of the characteristic curve. Applying the scanner calibration curve to the calculated optical density values decreases the difference between the actual radiograph pixel values and the simulated pixel values for each step except the thinnest step. The step averaged differences between the corrected and actual images increase from −11.6% to −17.0% for the thinnest step and decrease from −34.7% to +7.7% for the thickest step after the calibration curve is applied.

1. Introduction

Neutron imaging is a complementary technique to X-ray imaging (Berger and Iddings, 1998). While X-rays pass through light material and are attenuated by dense materials like metals, neutrons are attenuated by materials containing hydrogen and boron, and pass easily though most metals (Berger and Iddings, 1998).

A neutron radiograph is formed when an object is placed in a neutron beam in front of an image plane (see Fig. 1) (Berger and Iddings, 1998). Neutrons from the neutron source are attenuated by the object being imaged and produce an image at the image plane as a representation of the neutron flux at that point (Nemec et al., 1995).

The image plane, also called the detector, is a combination of a material which interacts with neutrons to produce light or electrons and a material which records the emitted radiation as an image (Heller and Brenizer, 2010). These materials can include gadolinium-doped screens, dysprosium or indium foils, and neutron sensitive micro-channel plates (Crow, 2010; Craft and King, 2011). The image plane can produce either a digital or analog (film) image, depending on the type of conversion. A micro-channel plate contains many small, neutron-sensitive, channels which can provide a direct readout of the neutron image (Crow, 2010). A conversion foil and film provide an image after irradiation of the foil, mating the foil with the film, and developing the film (Heller and Brenizer, 2010).

The neutron source shown in Fig. 1 can be a nuclear reactor, accelerator, or radioisotope source (Arai and Crawford, 2010). All of these source types have been used to perform neutron radiography, but accelerators and reactors provide the highest neutron fluxes and highest quality images. Radioisotope sources are generally more portable than reactors or accelerators (Arai and Crawford, 2010).

The capability to accurately simulate an expected neutron radiograph can improve a radiographic facility's ability to design experiments and would allow the measurement of properties such as density or thickness by comparing simulations with actual radiographs. Modeling a film's response to exposure from an activated metal foil is necessary in order to accurately simulate the radiographic process. A new film characteristic curve developed for this project relates foil activity to film optical density and pro-

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Nomenclature

Latin symbol	Description
A	activity
OD	optical density
p	MCNP reaction rate data
p_{min}	minimum MCNP reaction rate value
p_{max}	maximum MCNP reaction rate value
R	volumetric reaction rate
t	irradiation time
t_{travel}	total time between end of shot and beginning of exposure
t_{shot}	total shot time
SPR	source particle rate
vol	voxel volume

Greek symbol

λ	decay constant
σ	microscopic absorption cross section

vides the necessary data for a film response model. The film response model creates an image simulation based on results from an MCNP model of the neutron beamline.

This image simulation project resulted from a recent project to characterize the Neutron Radiography Reactor's (NRAD) east neutron radiography beamline (Morgan et al., 2013). The characterized beamline allowed for the development of a better image simulation using data from the MCNP model of the beamline. The film response data gathered through this project coupled with the MCNP model expands the simulation capability of the NRAD. The more accurate the image simulation, the more information each radiograph can provide.

The next section explains the concepts necessary to understand the image simulation method, followed by a description of the experimental procedures and results. Then, the paper describes the results of a simulation validation experiment.

The present work developed an image simulation methodology for neutron radiographs produced at the Neutron Radiography Reactor, detailed in the following section.

1.1. Neutron Radiography Reactor

The NRAD is a Mark II, 250 kW Testing, Research, Isotopes General Atomic (TRIGA)-Fuel Life Improvement Program (FLIP) conversion reactor (Stephens, 1978) located in the Idaho National Laboratory's Materials and Fuels Complex. The neutron beamline exits the core on the east side of the reactor through an aperture and collimator and enters the imaging station (see Fig. 2) (Stephens, 1978). The aperture consists of a combat grade boron nitride sheet with a circular opening (Fig. 3). The sheet can be raised and lowered to allow for three different aperture sizes (corresponding to Length to Diameter (L/D) ratios of 50, 125, and 300) (Stephens, 1978). The L/D of 125 is the most commonly used setting at the NRAD. The collimator is a simple tube made of boral lined concrete with an inner diameter of 46 cm (18 in.) (Stephens, 1978).

The NRAD is located below the main hot cell in the Hot Fuel Examination Facility (HFEF) (see Fig. 2). The HFEF contains a large argon atmosphere hot cell which stores and manipulates irradiated material and spent fuel from various reactors. This location allows for the radiography of fuel elements and other highly radioactive material lowered from within the cell. An elevator (Figs. 2 and 4)

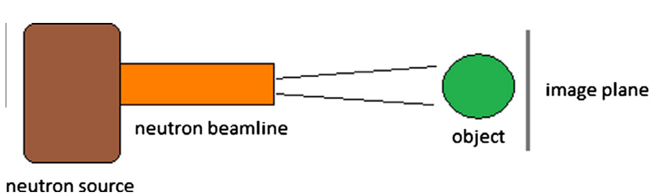

Fig. 1. Neutron radiography block diagram.

positions samples in the neutron beam and raises them back into the cell when the neutron exposure is complete. The cross section of the elevator tube at the point that it intersects the neutron beam is D-shaped and is known as the "D-section" (see Fig. 4). This allows the foil cassette to be pressed against the elevator tube, as close as possible to the object being imaged (Stephens, 1978). The platen presses the cassette against the flat part of the D-section and holds it in place during radiography. The NRAD produces neutron radiographs using the transfer method of radiographic conversion, explained in detail in the following subsection.

1.2. Neutron radiography conversion processes

In neutron radiography, conversion refers to the method of generating the radiographic image (Heller and Brenizer, 2010) and can be direct or indirect (Heller and Brenizer, 2010). Direct conversion utilizes a scintillation material which immediately produces light or other radiation each time a neutron interacts with it (Heller and Brenizer, 2010). The light from these interactions exposes a film, placed in contact with the scintillator (Heller and Brenizer, 2010). In direct digital conversion, a micro-channel plate reads neutron interactions and produces an image in real time (Heller and Brenizer, 2010).

Indirect conversion, also known as the transfer method, uses a foil of material such as dysprosium or indium, which interacts with neutrons through a neutron absorption reaction (Nemec et al., 1995). Exposing the foil to the neutron beam activates the foil. After the foil has been activated, film is placed in contact with the foil in a light tight container. The beta particles and gamma rays from the decay of the activated foil expose the film. The rate of activation is proportional to the neutron flux, and thus the film exposure from the decay radiation is proportional to the amount of attenuation produced by the object being imaged, producing a radiograph of the object (Heller and Brenizer, 2010).

The direct method is typically faster than the indirect method, making it possible to obtain real time images (Crow, 2010). One advantage of the indirect method is that foil activation is insensitive to gamma radiation in the neutron beam (Heller and Brenizer, 2010). While a beam with high gamma flux may fog a direct conversion image, it will have very little effect on an indirect conversion image (Heller and Brenizer, 2010). For this reason, indirect method radiography can image radioactive materials with resolutions on par with the direct technique (Heller and Brenizer, 2010).

1.3. Film processing and optical density

Kodak Industrex T-200 film and AGFA Structurix D3 s.c. film are the films of choice at the NRAD and can be developed using the standard Kodak developers and fixers (Quinn and Sigl, 1980). At the NRAD, T-200 film is mated with indium foils, and D3 s.c. film is mated with dysprosium foils. The developer and fixer chemicals are temperature sensitive and any variation in temperature pro-