Reactivation of the Transient Reactor Test (TREAT) Facility Neutron Radiography Program

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Abstract. The TREAT radiography system is used to perform neutron radiography of fuels, experiments, and other specimens before and after irradiation within the TREAT reactor. The TREAT neutron radiography facility performed approximately 5,000 radiographs by the spring of 1977. Originally built in 1958, the TREAT Facility was in operation until it was placed in a shutdown status in 1994. Following the Fukushima incident and seeing a need for enhanced accident tolerant fuels, the United States Department of Energy decided to restart the TREAT facility and resume transient operations. In November 2017, the TREAT reactor was successfully restarted and is currently performing operational testing in preparation for initial experiment irradiations and transient testing. This paper discusses efforts to reactivate the TREAT neutron radiography facility. To characterize the neutron beam, gold foil activation measurements were made to determine an average neutron flux and flux profile. An open beam image provides the information about variations in the beam profile. A series of system qualification radiographs have been acquired to determine the effective image acquisition parameters, resulting image quality, and the relationships between the two.

TREAT Neutron Radiography Program and Facility Description

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. Neutron radiography has seen significant use for nuclear applications since the capability was first developed, and continues to prove its value still today [1]. The TREAT radiography system is used to perform neutron radiography of fuels, experiments, and other specimens before and after irradiation at the TREAT reactor [2]. Neutron radiographs are acquired using transfer method with dysprosium conversion foils and image plates [3], similar to the process used at INL’s Neutron Radiography (NRAD) Reactor [4]. The system includes the radiography facility where radiography cassettes are exposed to the neutron beam and a Radiography Room where radiographs are subsequently processed. Figure 1 shows a schematic of the TREAT Neutron Radiography Facility. The neutron beam originates in the graphite reflector of the reactor. A collimator routes the neutron beam from the reflector to the radiography stand, and consists of inner and outer collimators and a beam shutter. A carriage system remotely positions a radiography cassette behind the sample position. Highly-radioactive objects can be moved to the radiography stand using a cask. The radiography stand contains radiation shielding materials to protect personnel from harmful amounts of radiation. A Radiography Room provides a location for processing the radiographs. Activated foils are coupled to an image plate in a special cassette, which are then placed in a shielded cabinet during the decay process. The radiography room includes environmental and dust control systems for a clean and consistent image processing environment.
Figure 1. A side-view depiction of the TREAT neutron radiography facility.

**Purpose of Neutron Radiography at TREAT**

Neutron radiography at TREAT has three main purposes. The first purpose is for operational safety. Often, specimens are complex assemblies and/or are highly radioactive which makes looking inside of an experiment not a valid option. Numerous safety barriers and containments are designed into the experiments and must be intact prior to irradiation. Radiographs are taken to provide visual indication the specimen is constructed as designed and that the components remained in position during shipment, which ensure that the reactor and experiment remain safe in all conditions and testing situations.

The second purpose is for post-irradiation test. Transients are frequently designed to cause intentional failure of the specimen. What happened during a transient? Did the specimen remain intact? What is the condition of the containment vessel? The ability to quickly obtain a preliminary answer to those questions is important. This information can then be transferred to the experimenters and to the facility that will be performing subsequent detailed analyses and examinations.

The third purpose is related to non-irradiated items. The industry is seeing uses for neutron radiography in fields such as archeology, historical artifacts, biology, etc. Since neutron radiography is complimentary to x-ray radiography, additional information can be obtained that could not otherwise be seen in a traditional x-ray radiograph. Taking neutron radiographs of these types of items will most likely be a minor activity, but the capability is available.

**History of the TREAT Neutron Radiography Program**

Initial experiments using the TREAT reactor for neutron radiography were conducted in 1964 [5]. The original radiography facility was installed in the mid-1960s with the first production radiograph being generated in 1967. By 1977, over 5,000 radiographs had been acquired [6]. This system worked well but had some deficiencies, namely: insufficient structural support for larger handling vessels, poor alignment mechanism, manual operation of the shield door and foil carriage, and lack of precise specimen positioning. The system was upgraded in 1975-76 with a new stand designed to remedy the aforementioned deficiencies. The manual functions of
opening/closing the shield door and inserting/removing the foil carriage was replaced with remotely-operated motorized actuators. The remote system substantially reduced the radiation dose to personnel working around the stand. The new stand also provided additional internal shielding to further reduce the exposure. In 1984 and in 1986 additional upgrades enhanced the load capacity of the stand and installed an aperture upgrade.

**Restart and Status of the TREAT Neutron Radiography Facilities**

System Readiness. Since the radiography facility had not been used for 20 plus years and normal maintenance was not performed during that time, it was essential to perform a detailed inspection of the system prior to operating. The system readiness plan included activities to establish configuration management, baseline the current condition of the equipment, ensure system operability, repair identified defects, identify and procure critical spare parts, and establish a preventative maintenance program. For components that could not be readily accessed, a borescope was used to inspect and observe the operating components. In spite of sitting idle for over 20 years and the overall age of the components, the radiography facility functioned remarkably well. Additional system enhancements have been installed over the past few years. The shielding inside the stand is composed of lead shot and mineral oil. Due to the original design of the stand, oil leakage has occurred. A new oil reclamation system was recently installed to capture any leaking oil and return it to the stand along with visual confirmation of the oil level. A picture of the radiography facility is shown in Figure 2. External shielding consisting of borated-poly and concrete has also been installed around the exterior of the radiography facility along with additional structural bracing.

*Figure 2. Picture of the TREAT neutron radiography facility layout.*
New exposure cassettes were fabricated to provide consistent foil placement while still allowing for easy transfer of foils into decay cassettes. The original electro-mechanical exposure timer has also been replaced with a digital timer which has increased repeatability and accuracy for shot exposures. A neutron radiography room was constructed to provide a dust, climate, and lighting controlled workspace for equipment storage, radiography operations, image processing, and a shielded decay safe. A vacuum system for handling activated foils significantly reduces radiation dose to radiographers while transferring irradiated foils from exposure cassettes to decay cassettes.

Upgrade from Film to Computed Radiography
Traditionally, all radiographs taken at TREAT were based on film. This required substantial time for decay and film processing. Radiographs were not available for viewing until the following day. Film is becoming more difficult to procure and the chemicals have environmental concerns. TREAT has elected to produce radiographs via the CR process, which utilizes PSP image plates and a digital scanner [1]. Image plates are more sensitive than film, and thus require less exposure time than previous operations with film. CR uses no chemicals, can be much quicker than film, and can achieve similar resolution to film. CR images also have a linear dose response, compared to the S-curve for film, along with greater latitude, allowing for simpler image processing and interpretation. Another benefit of CR is that it directly produces a digital image.

Beam Characterization
The neutron beam flux was measured using foil activation methods [7]. An array of 21 gold foils was activated in the TREAT neutron beam for 3 hours with the reactor power of 80 kW. The resulting activity was measured using a calibrated high-purity germanium detector, then the activity at the end of exposure in the neutron beam was calculated based on this measurement, the decay constant, and the time between the measurement and end of exposure [7][8]. The measured average thermal equivalent neutron flux at the image plane is $8.25 \times 10^6 \pm 1.89 \times 10^5$ $n/cm^2/s$ with the reactor power at 80 kW. The neutron beam uniformity was measured using a neutron radiograph of the open beam with no sample. The resulting peak-to-average ratio is 1.006 in the horizontal direction and 1.011 in the vertical direction.

System Qualification
The purposes of TREAT radiography include pre-transient operational safety shots and post-transient detail shots. The shot types can vary based on the information requested and the image quality desired. As such, it was necessary to determine exposure times and decay times for the various shot types. The first shot type is an information-only quick-shot which has lower resolution but a very short turnaround time. Higher-quality radiographs for programmatic use need to be of higher image quality (resolution and signal-to-noise ratio, SNR) to provide greater detail and clarity. A system qualification plan was implemented to determine the required settings for each shot type. A newly designed Resolution Test Piece (RTP) was utilized as the specimen, containing an American Society for Testing and Materials (ASTM) Sensitivity Indicator and Beam Purity Indicator [9], a 2.5 cm square foil of gadolinium, and a 2.5 cm square foil of hafnium. These ASTM indicators and foils provided the necessary data for image resolution calculation to be performed.

Three radiography campaigns were performed using a range of exposure times and decay times to determine the optimum settings for each shot type. The first campaign varied exposure times to establish this value for further tests. The second campaign varied decay time to establish this value for programmatic-quality radiography. The third campaign also varied decay time, but for much shorter times, to establish the decay time needed for quick shots. All shots were taken
with the reactor operating at 80 kW steady state and using dysprosium converter foils. All image plates were scanned using a Carestream HPX-1 scanner.

The first campaign contained eleven radiographs. Seven radiographs were acquired with nominal exposure times of 20, 12, 10, 8, 6, 4, and 2 minutes. The foils were then placed on Carestream general purpose (GP) image plates in individual decay cassettes and left to decay overnight. Four additional radiographs were acquired with nominal exposure times of 20, 14, 12, and 10 minutes. The foils were then placed on Carestream high resolution (HR) image plates in individual decay cassettes and also left to decay overnight. The intent was to determine exposure times and scanner settings that produced the highest quality images based on signal (i.e. pixel value), SNR, and spatial resolution. The effective spatial resolution seems unaffected by exposure time. The data from the SNR and peak pixel values show diminishing returns beyond 10 minute exposure time, which is the basis for choosing 10 minutes as the exposure time for further tests.

A second set contained five radiographs with an exposure time of 10 minutes and varying decay times, including: 240, 180, 120, 60, and 30 minutes. Following exposure, the foils were placed on GP image plates in decay cassettes and left to decay. This campaign with longer decay times sought to identify the decay time required for high quality radiographs for programmatic use.

A third radiography campaign contained six radiographs with varying decay times, including: 60, 50, 40, 30, 20, and 10 minutes. This campaign was designed to identify parameters for information-only quick-shot radiographs. The exposure time was set at 10 minutes each based on the data obtained from the first set. A decay time of only 20 minutes provided 60% the SNR of a radiograph with 240 minute decay time, and thus was chosen as a reasonable decay time for information-only quick-shots. It is notable that the SNR for radiographs with 240 minute and overnight decay times are both 194, indicating that decay times beyond 240 minutes may not provide additional benefit for SNR. A decay time of 120 minutes provided 94% of the peak SNR, and thus was chosen as the decay time for high-quality radiography for programmatic use. The effective spatial resolution was also measured as a function of decay time and shows that spatial resolution is unaffected by decay time.

**Results of Initial System Demonstration Shots**

Based on the data, current settings for high-quality radiography for programmatic use are 10 minute exposure time and 120 minute decay time using a GP image plate. The HR plates provided higher SNR and effective spatial resolution, which may lead to their eventual use for radiography operations, but additional measurements are needed first to verify their performance. Figure 3 shows a neutron radiograph of an ASTM sensitivity indicator acquired using a GP plate (left) with 10 minute exposure time and overnight decay time, and a corresponding line profile (right). The smallest shim in the sensitivity indicator is visible in both the GP and HR radiographs.

**Future of TREAT Neutron Radiography**

As part of a 5-year improvement plan, upgrades are in the early design stages that will support enhanced capability for the TREAT radiography program. The primary focus is to design and install a new radiography stand and control panel to support installation of camera-based digital neutron imaging systems and subsequent development of neutron computed tomography (CT). CT involves taking multiple shots from various angles along the entire length of the specimen and then mathematically combining them into a reconstructed 3-dimensional image. Neutron CT is an active area of development at NRAD, where novel equipment and techniques are being
evaluated for neutron CT of highly-radioactive objects. This is an ongoing effort in collaboration with partners from universities, industry, and national and international research centers.

Another area for potential new research is flash neutron radiography, which would take advantage of the exceptionally bright neutron beam produced during transients. The peak transient power at TREAT is 19,000 MW, which produces a calculated neutron beam flux of \(1.95 \times 10^{12} \text{n/cm}^2\text{s}\) for \(\sim 100\text{ ms}\), which is \(\sim 1,000\) times brighter than the current brightest neutron beams in the world. The total energy available in a transient is limited to \(\sim 2,500\text{ MJ}\), but the intensity and duration of transient are highly customizable with TREAT’s advanced reactivity control system.

TREAT neutron radiography is prepared to accept and radiograph the newest generation of experiments and specimens. The first of such experiments is scheduled to begin irradiations in September 2018. As new experiments are designed, new radiography support equipment may be required to accommodate these experiments. The TREAT radiography program is poised to remain a valuable asset to the TREAT irradiation program for many years to come.

Figure 3. A neutron radiograph of an ASTM sensitivity indicator acquired using a GP plate (left) with 10 minute exposure time and overnight decay time, and a corresponding line profile (right).

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