Materials Research Proceedings **15** (2020) 42-47 https://doi.org/10.21741/9781644900574-7

First Neutron Computed Tomography with Digital Neutron Imaging Systems in a High-Radiation Environment at the 250 kW Neutron Radiography Reactor at Idaho National Laboratory

Aaron Craft[1,a *], Burkhard Schillinger[2,b], William Chuirazzi[1,c], Glen Papaioannou[1,d], Andrew Smolinski[1,e] and Nicholas Boutlon[1,f]

[1]Idaho National Laboratory, PO Box 1625, MS 2211, Idaho Falls, ID 83415, USA

[2]Heinz Maier-Leibnitz Center, Technische Universität München; Lichtenbergstr. 1, 85748 Garching, Germany

[a]Aaron.Craft@inl.gov, [b]Burkhard.Schillinger@frm2.tum.de, [c]William.Chuirazzi@inl.gov, [d]Glen.Papaioannou@inl.gov, [e]Andrew.Smolinski@inl.gov, [f]Nicholas.Boulton@inl.gov

Keywords: Neutron Tomography, Neutron Radiography, Computed Tomography

Abstract. The Neutron Radiography Reactor (NRAD) at Idaho National Laboratory (INL) was designed for thermal and epithermal neutron radiography for examination of highly-radioactive irradiated nuclear fuel elements. Radioactive samples are remotely lowered into the East and North Radiography Stations (ERS and NRS, respectively), and a rail transfer system remotely positions radiography cassettes into the detector position for indirect radiography. The indirect transfer method with film has been used at NRAD for around forty years, but recent efforts seek to develop digital camera-based neutron imaging systems. Two initial camera detector systems were built using an inexpensive but high-quality scientific CMOS camera with robust shielding, and tests were performed in collaboration with Heinz Maier-Leibnitz Institut of Technische Universität München. The first measurements in the ERS provided valuable experience that informed the design of an improved neutron imaging system that was tested in the NRS. The first successful digital neutron computed tomography at INL was acquired, consisting of 421 neutron radiographs acquired in 4 hours. These first tests with camera-based neutron imaging systems have demonstrated the potential to both increase the throughput of radiography by two orders of magnitude and provide higher quality spatial information with three-dimensional tomographic reconstructions compared to two-dimensional radiographic projections, which represent a significant improvement compared to current film radiography capabilities.

Introduction

Neutron radiography provides more comprehensive information about the internal geometry of irradiated nuclear fuel than any other nondestructive examination technique and has demonstrated its importance to the nuclear industry for many decades [1]. The first neutron radiography experiments at INL were first conducted in 1964, with the first dedicated neutron radiography beamline being built in 1967 at the Transient Reactor Test (TREAT) facility [2]. The construction of the NRAD reactor in 1978 included two neutron beamlines specifically designed for neutron radiography of irradiated nuclear fuels [3]. All three neutron radiography beamlines (two at NRAD and one at TREAT) use the indirect radiography methods, where a cassette of different foils is placed in the beamline and activated, then removed and placed next to either film or image plates to render an image [2,4]. The indirect method is not sensitive to gamma rays but is time-consuming. The production rate at NRAD is limited to 14 film radiographs per day, which precludes use of neutron computed tomography (nCT) for routine examination because nCT required hundreds of radiographs to produce a quality reconstruction. Modifications to the existing radiography set-up must be made to capture the number of projections necessary for tomography in a timely manner [5]. Implementing tomography as a routine examination technique thus requires a digital neutron radiography system, but such digital systems have traditionally had problems operating in high-radiation environments. This paper discusses the first efforts to build such digital systems and the initial nCT results that were obtained.

NRAD Facilities

The NRAD reactor is a pool-type, water-moderated, 250 kW_{th} TRIGA reactor. It sits below a hot cell, allowing radioactive materials to be transported directly into either of the two neutron radiography beamlines [3]. Both the East Radiography Station (ERS) and the North Radiography Station (NRS) have radial beamlines directly aligned with the core. Not only does this provide a high neutron flux, but it also creates a high amount of gamma contamination in the beam. The ERS is equipped with an elevator that allows samples to be remotely placed for neutron radiography, as the ERS is directly below the hot cell. With a distance from the beam aperture to the imaging plane of 444.5 cm, the field of view at the imaging plane is 17.8 cm wide by 43.2 cm tall. The beamline is primarily operated at a length-to-diameter ratio (L/D) of 125, yielding a thermal neutron flux of 6.0×10^6 n/cm^{2}s [6]. The NRS utilizes a cask system to transport fuel samples to an elevator which remotely positions the fuel for neutron imaging because the NRS is not straight underneath the hot cell. The NRS has a longer beamline than the ERS, with 1603.8 cm between the beamline aperture and the image plane. The beam is ~60 cm diameter at the image plane, but a beam limiter reduces the field of view to 17.8 cm wide by 43.2 cm tall for traditional neutron radiography. The NRS beam is most often operated at L/D=185 with a neutron flux of ~4.5×10^6 n/cm^{2}s [3].

Imaging Equipment

The first iteration of the digital imaging system was designed to be low-cost because the high radiation background of the beamline chamber could easily damage the camera. An inexpensive ZWO 178MM Cool CMOS camera was used in conjunction with the SharpCapture 2.9 freeware to capture images. Camera hardware and motor stages were controlled through a combination of a Gertbot and a Raspberry Pi [7,8]. In addition to 10 cm of lead, borated polyethylene plates were also used to shield the camera and Raspberry Pi from the radiation field. The camera in the imaging box, with the assorted wiring to the Raspberry Pi and rotational stage can be seen in Figure 2. The object for these tests was a microwave horn.

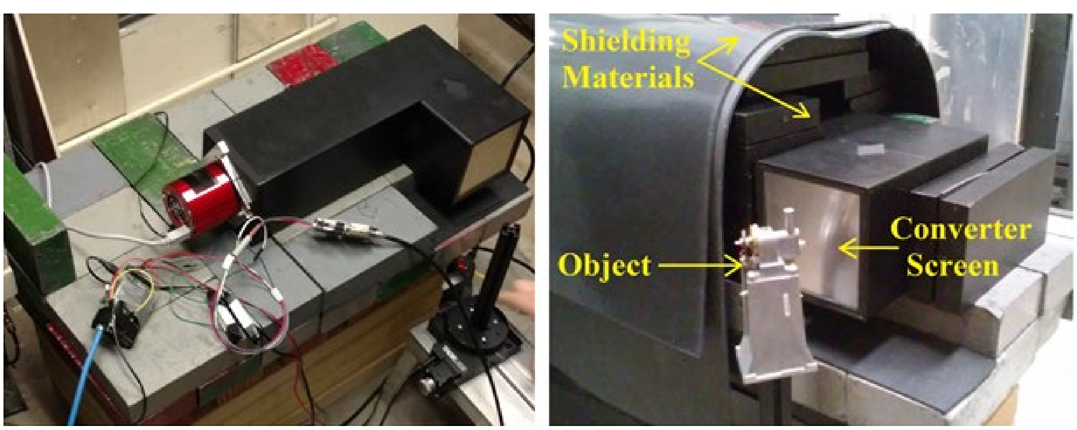

Figure 2. Left, CMOS camera in the imaging apparatus with the connections between the camera, rotating stage and Raspberry Pi controller. Right, Shielding surrounding camera, electronics and imaging box with the microwave horn positioned in front of the converter screen.

A radiograph microwave horn acquired in the ERS is shown in Figure 5a next to a radiograph that was acquired in the NRS with the newer system. A gamma dose rate of 2.0 Sv/hr was measured with an ion chamber dose rate meter placed at the image plane near the scintillator screen. A surrogate prismatic fuel element was also imaged, which was prepared with a gadolinium-dopant liquid penetrant to enhance the visibility of an engineered crack defect inside a coolant channel. The imaging system was able to acquire 32 neutron radiographs in under 12 minutes, which is much more efficient than current daily output of approximately 14 film radiographs. Unfortunately, the Raspberry Pi computer crashed after 44 acquisitions due to the harsh radiation environment. The results obtained before the crash are shown in Figure 3.

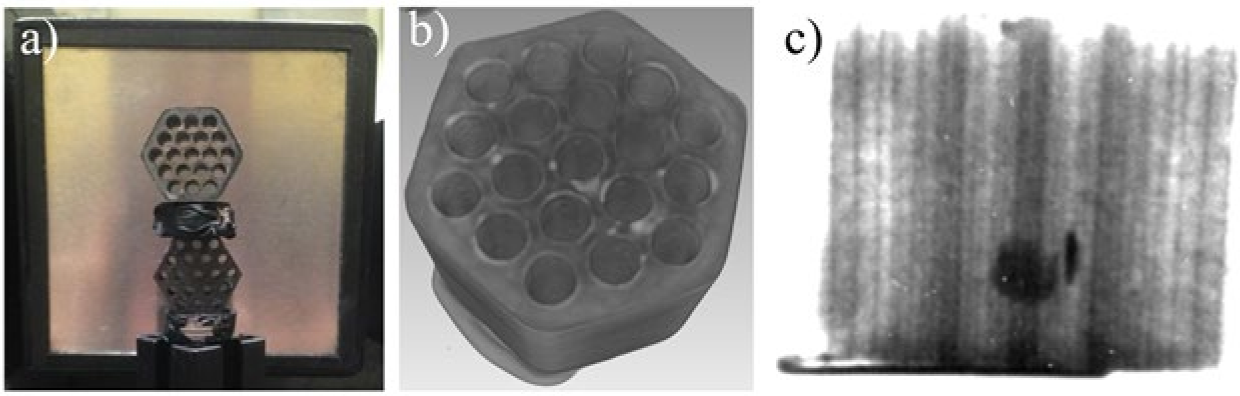

Figure 3. a) Picture of the surrogate fuel element pisitioned in front of the imaging system in the ERS beamline. b) The 3D tomographic reconstruction obtained from only 32 images. c) The 3D rendering emphasizing the gadolinium-penetrant treated crack defect shown as a dark spot in the middle of the image.

The initial success of the first design led to the construction of a second imaging system. The second system was improved by implementing a two-mirror architecture with a longer optical path which helped to reduce the radiation dose delivered to the camera. The camera box was also designed to allow for more robust shielding. The camera was mounted on a translational stage to allow for remote focusing. A simplified version of the ANTARES instrument control at MLZ was used to control the imaging system with the help of a laptop and three Raspberry Pi computers [8]. The field of view was doubled to 20 cm. Vents were also added to the box for cooling the camera the camera. Figure 4 shows the second imaging system design.

A radiograph of the microwave horn were acquired with the newer imaging system in the NRS beamline. Figure 5 shows a side-by-side comparison of radiographs of the microwave horn captured with the first and second imaging systems. A gamma dose rate of 900 mSv/hr was measured at the image plane, less than half the gamma dose rate present for the first measurements in the ERS. The reduced gamma radiation environment, along with the remote focusing and thermal noise reduction, contributed to the capture of an image with significantly improved contrast, signal-to-noise ratio, and resolution. This imaging system allowed for 421 neutron radiographs to be captured in only four hours. Using film and the indirect transfer method, it would take roughly a month of reactor time to acquire the same number of radiographs. This imaging system is able to acquire radiographs more than two orders of magnitude faster than before, which enables nCT at these beamlines despite the high gamma content of the neutron beams.

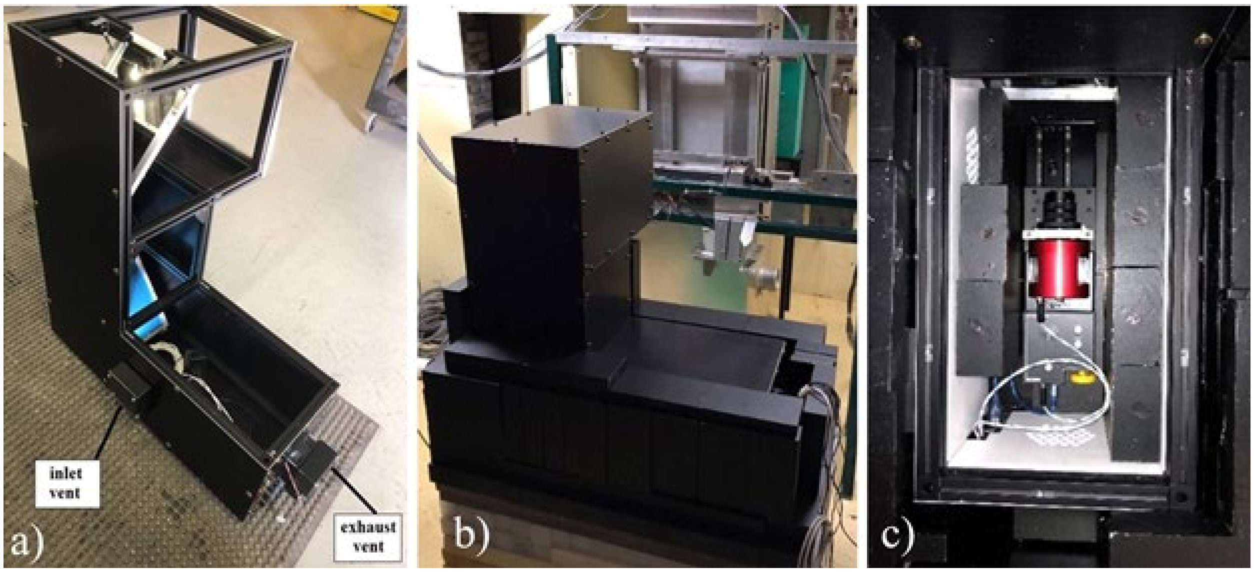

Figure 4. Set-up of the improved imaging system. a) The new box utilizes two mirrors to remove the camera further from the beam's radiation. Vents are also added to reduce thermal noise. b) The box is upgraded to allow for better shielding of the camera and associated electronics. c) The camera is mounted on a linear stage with room for additional shielding inside of the box.

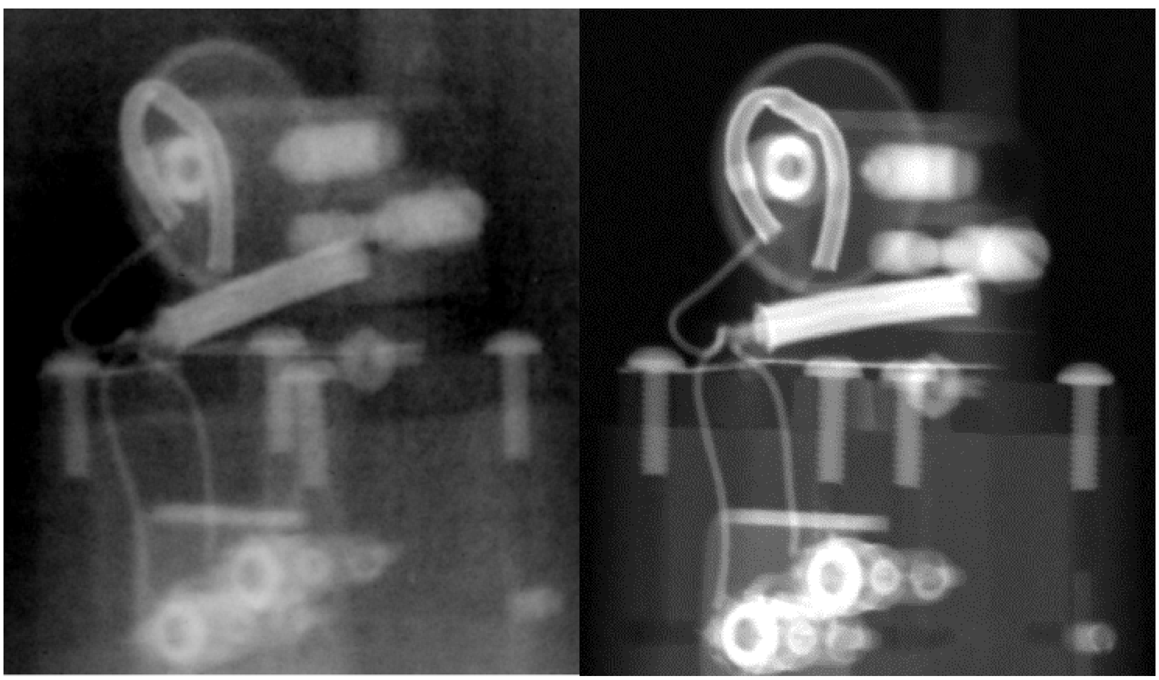

Figure 5. Radiographs of the microwave horn taken with (a) the initial neutron imaging apparatus in the ERS and (b) the improved imaging system in the NRS.

Once 421 the radiographs were obtained, tomographic reconstruction was performed. The resulting reconstruction is shown in Figure 6. The resolution was good enough to distinguish individual internal components of the microwave horn such as screws, wires, coils. The quality of the resulting reconstruction demonstrates that the redesign of the box to accommodate more shielding and the change of controller software and hardware was highly successful in both reducing noise and preventing the controller system from crashing. The improved thermal ventilation and the linear stage to allow for camera focusing both contributed to obtaining a sharper, higher quality images. The ability to run long enough to obtain hundreds of radiographs allows for production of higher quality computed tomography reconstructions than the first system was able to produce.

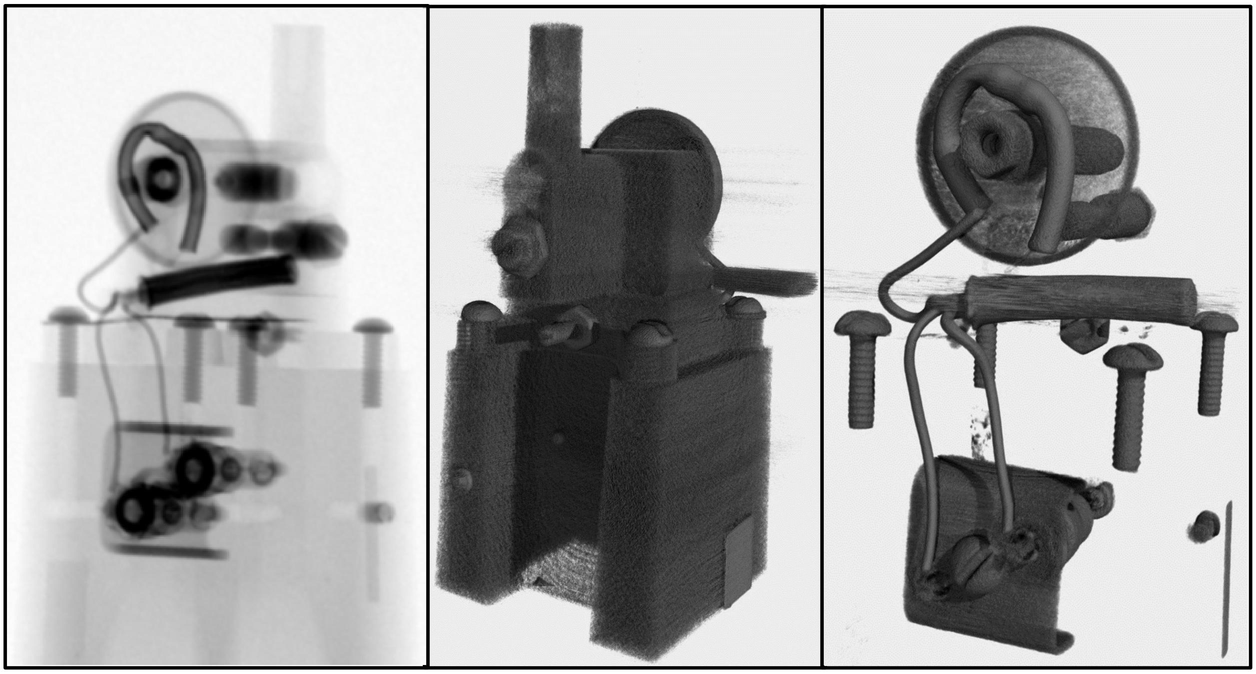

Fig. 6. One of the neutron radiographs (left) used to produce the tomographic reconstruction (middle). Adjusting the visualization threshold levels for the reconstructed object reveals (left) various features such as screws, wires, coils, etc.

Conclusion

The goal of this work was to develop the instrumentation necessary to perform digital nCT. This was accomplished as a collaborative project that built an initial imaging system that led to an improved imaging system that was able to perform quality nCT. Both systems successfully obtained digital neutron radiographs with sufficient image quality to be used in tomographic reconstructions. The improvements made during the construction of the second imaging system allowed stable, quick, and reliable digital neutron radiography. This led to both improved radiographs and higher-quality tomographic reconstructions. Realizing digital neutron radiography capabilities at INL's NRAD facility is an important first step towards implementing digital nCT as a routine examination technique.

References

[1] A.E. Craft and J.D. Barton, "Applications of neutron radiography for the nuclear power industry," Physics Procedia 88 (2017) 73-80. https://doi.org/10.1016/j.phpro.2017.06.009

[2] S.R. Jensen, A.E. Craft, G.C. Papaioannou, W.W. Empie and B.R. Ward, "Reactivation of the Transient Reactor Test (TREAT) Facility neutron radiography program," in this Proceeding.

[3] A.E. Craft, D.M. Wachs, M.A. Okuniewski, D.L. Chichester, W.J. Williams, G.C. Papaioannou, & A.T. Smolinski, "Neutron radiography of irradiated nuclear fuel at Idaho National Laboratory," Physics Procedia, 69 (2015) 483-490. https://doi.org/10.1016/j.phpro.2015.07.068

[4] A.E. Craft, G.C. Papaioannou, D.L. Chichester, and W.J. Williams, “Conversion from film to image plates for transfer method neutron radiography of nuclear fuel,” Physics Procedia 88 (2017b) 81-88. https://doi.org/10.1016/j.phpro.2017.06.010

[5] B. Schillinger, E. Lehmann, and P. Vontobel, “3D neutron computed tomography: requirements and applications,” Physica B: Condensed Matter 276 (2000) 59-62. https://doi.org/10.1016/S0921-4526(99)01254-5

[6] A.E. Craft, B.A. Hilton, and G.C. Papaioannou, “Characterization of a neutron beam following reconfiguration of the Neutron Radiography Reactor (NRAD) core and addition of new fuel elements,” Nuc. Eng. & Tech. 48 (2016) 200-210. https://doi.org/10.1016/j.net.2015.10.006

[7] B. Schillinger and A.E. Craft, "A freeware path to neutron computed tomography," Physics Procedia 88 (2017) 348-353. https://doi.org/10.1016/j.phpro.2017.06.047

[8] B. Schillinger, A. Craft and J. Krüger, "The ANTARES instrument control system for neutron imaging with NICOS/TANGO/LiMA converted to a mobile system used at Idaho National Laboratory," in this Proceeding.