Detector Noise in X-ray Computed Tomography Examinations of Irradiated Tristructural Isotropic (TRISO) Fuels

William Chuirazzi[1,*], Brian Gross[1], Joshua Kane[1], Swapnil Morankar[1], and Rahul Reddy Kancharla[1]
[1]Idaho National Laboratory, USA
(*) william.chuirazzi@inl.gov

Abstract—**Tristructural isotopic (TRISO) fuel is a promising next-generation fuel form for advanced nuclear reactors. TRISO fuel consists of sub-millimeter diameter uranium-bearing fuel kernels encapsulated in multiple layers of carbon and ceramic materials. As part of the assessment of TRISO fuels, post irradiation examination (PIE) is performed to provide information on changes in microstructure, mechanical properties, and potential degradation. X-ray computed tomography (XCT) is a nondestructive technique that collects a series of two-dimensional radiographs as a function of sample rotation and mathematically reconstructs them into a three-dimensional dataset that provides volumetric information on the sample's internal features. This work focuses on PIE of irradiated TRISO fuels using XCT with a focus on examining the impact of highly radioactive fuels on the images generated with the instrument's CsI detector. Despite examining samples with over 2.00 Sv/hr on contact, techniques such as frame-averaging as well as a lack of interaction of high-energy gamma-rays with the detector ensure there is no noticeable impact on the quality of the CT images due to detector noise.**

Keywords —**X-ray computed tomography, TRISO fuel, post-irradiation examination, nondestructive examination.**

I. Introduction

TRISTRUCTURAL isotropic (TRISO) nuclear fuel is a next-generation fuel form consisting of a fuel kernel (usually a mixture of uranium carbide and oxide, referred to as UCO) surrounded by different carbon based layers. These layers include the porous buffer layer, the inner pyrolytic carbon layer, the SiC layer, and the outer pyrolytic carbon layer [1]. Several thousand individual particles are loaded into a graphite matrix creating a fuel form known as a compact in the United State's Department of Energy's Advanced Gas Reactor (AGR) program. Originally conceived in the 1950's as part of the Dragon Project [2], interest has been renewed in TRISO fuel as it is a fuel type for Hight Temperature Gas Reactors (HTGRs). Some advantages of the HGTR design with TRISO fuel include high peak operating temperatures (up to ~1200 °C and above), effective fission product retention, and enhanced fuel performance [3]. TRISO fuel is also under consideration for a variety of microreactor designs, further motivating the need for further study of TRISO-based fuel. While there are slight variations in layer thickness between different irradiation campaigns, a typical depiction of an individual TRISO particle form the AGR-5/6/7 campaign is shown in *Fig. 1(a)* while *Fig. 1(b)* displays a general TRISO compact from the AGR program.

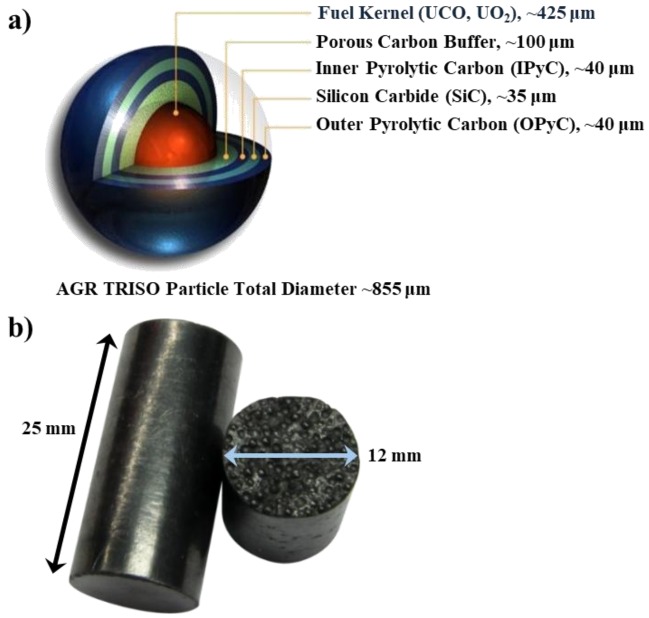

Fig. 1. (a) Depiction of an individual TRISO particle showing all its layers with associated layer thicknesses for AGR TRISO particles. (b) A photo of an AGR compact which consists of several thousand TRISO particles embedded in a graphite matrix. Images courtesy of the U.S. Department of Energy's Advanced Gas Reactor program.

Post-irradiation examination (PIE), the study of material after it has undergone in-core irradiation, is useful for providing a more comprehensive understanding of fuel behavior, including mechanisms of degradation, and the materials' performance under the harsh environmental conditions of a nuclear reactor. PIE helps improve fuel performance, enhance reactor safety, and informs the development of next-generation nuclear fuels by defining a safe range of conditions the fuel can operate within. Traditional destructive PIE exams, such as metallography and electron microscopy, can provide detailed information about microstructural changes and fuel integrity

[4].

X-ray computed tomography (XCT) is a nondestructive examination technique that has recently been incorporated into the PIE process to examine individual particles as well as fuel compacts. X-ray CT is a measurement of X-ray attenuation through a sample. A series of two-dimensional (2D) radiographs are captured as a function of sample rotation. These 2D projections are then reconstructed to produce a three-dimensional (3D) volume of the sample [5]. These data can then inform traditional destructive examination techniques by targeting regions of interest and can also be meshed to create direct input into modeling efforts.

As XCT has been used to examine highly radioactive nuclear fuel, the question arises whether the sample's radioactivity is directly affecting the measurement itself by inducing a signal on the equipment used to detect the X-rays transmitting through the sample. While the ability to examine highly radioactive material directly reduces the timespan from testing to information and ultimately expedites the implementation of new nuclear concepts, it is imperative that the high levels of radioactivity of these samples does not impact the measurement in a meaningful way, as this could compromise the data collected. The goal of this work is therefore to investigate what effect, if any, radioactive samples have on XCT measurements.

II. THEORY

In the AGR program, TRISO compacts were irradiated in the Advanced Test Reactor to determine the performance envelope of the fuel [6,7]. During this irradiation the uranium kernels absorbed neutrons to produce fission as well as activation. Once the compacts were removed from the reactor, the activated fuel continued to undergo radioactive decay, releasing a variety of ionizing radiation, including gamma-rays, alpha- and beta-particles. The source term that was recorded in the as-run physics analysis report for the AGR-5/6/7 Compact 5-3-1 [8] was updated to account for radioactive decay from the time of reactor discharge to the anticipated date of XCT examination using ORIGEN 2.2 [9]. The source term showed some of the most radioactive isotopes to be Cs-137, Pu-241, Sr-90, Pm-147, Ce-144, and Ru-106. A total of 96 emitting isotopes were identified.

The X-ray microscope utilized in this work uses a complementary metal-oxide semiconductor (CMOS) based detector. In this detector type, a semiconductor photodiode is used to create an electrical charge when exposed to incident radiation (light or otherwise). The voltage is proportional to the strength of the initial signal. Transistors are then used to amplify the voltage values and convert them to a digital signal. An analog-to-digital (ADC) converter then transforms these voltage values into a digital number that can be used to create an image. Note that a key feature of CMOS technology is that this entire process occurs directly on the sensor itself [10].

One concern with using CMOS detectors for imaging radioactive samples is that the ionizing radiation emitted from the samples themselves can induce charge directly on the detector. This can add noise to images and may introduce additional imaging artifacts. One process for mitigating this concern is that for each radiograph several images are taken (either 5 or 20 images per projection depending on detector binning) and then a median image is calculated from the set of images. It is unlikely for ionizing radiation emitting from a radioactive sample to impinge on the same pixel of the detector repeatedly due to the stochastic nature of radioactive decay. The median image therefore reduces the impact of the random radiation from the sample on the image produced by the detector.

III. EXPERIMENTAL

All measurements were performed at Idaho National Laboratory's (INL) Irradiated Materials Characterization Laboratory (IMCL).

A. X-ray Computed Tomography Equipment

The X-ray computed tomography measurements were performed using a ZEISS Xradia 620 Versa X-ray Microscope (XRM) [11]. In this work the flat panel detector (Varex 2315, Varex Imaging, Salt Lake City, UT, USA) was used to image the complete volume of the compact. This detector is a CMOS detector utilizing a high efficiency microcolumnar CsI scintillator. *Fig. 2* shows the internals of the ZEISS Xradia 620 Versa as staged for imaging AGR TRISO compacts.

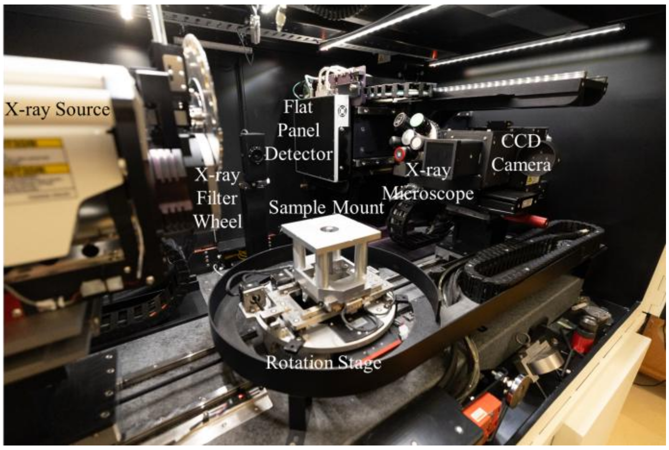

Fig. 2. Labeled photograph showing the setup in the ZEISS Xradia 620 Versa at IMCL for imaging irradiated AGR TRISO compacts.

B. Compacts

During the PIE of irradiated AGR TRISO compacts a total of five individual compacts have been examined- two from the AGR-3/4 irradiation campaign [6] and three from the AGR-5/6/7 irradiation campaign [7]. A graded approach was taken to examining radioactive compacts- first XCT was performed on unirradiated compacts with natural uranium, followed by unirradiated compacts with fresh fuel, before AGR-3/4 compacts and finally AGR-5/6/7 compacts were examined. The radiological dose rates of each compact on their approximate date of examination are shown in Table I.

TABLE I
RADIOLOGICAL DOSE RATES FOR AGR COMPACTS EXAMINED WITH XCT

		Compact ID				
		AGR-3/4 12-4	AGR-3/4 7-1	AGR-5/6/7 5-3-1	AGR-5/6/7 3-6-1	AGR-5/6/7 2-1-3
Dose Rate on Contact (Sv/hr)	βγ	0.24	>0.5	13.18	>2.00	>0.50
	γ	0.03	0.12	1.20	1.40	1.99 (at ~12.7 cm)
Dose Rate @ 30 cm (Sv/hr)	βγ	0.03	0.04	0.10	0.11	0.10
	γ	0.00	0.01	0.02	0.02	0.03

Custom shielding of the compacts was necessary to protect laboratory personnel as well as equipment from the high radiation fields produced by the compacts [12]. The compact was placed in a radiologically clean aluminum container which was then mounted inside a tungsten "push-pop" shield. Operators transferred the shielded configuration into the X-ray microscope using long-reach tools. The shielded compact was placed inside instrument onto a stage which was coupled directly to the vertical stage inside the X-ray microscope. Once the compact was secure inside the X-ray microscope and the lid was removed, the compact could be remotely raised out of the shielding apparatus and into the X-ray beam path. A photograph of a compact and associated shielding is shown in *Fig.* 3. For more details on the design and implementation of the "push-pop" shielding apparatus, the interested reader is referred to [12].

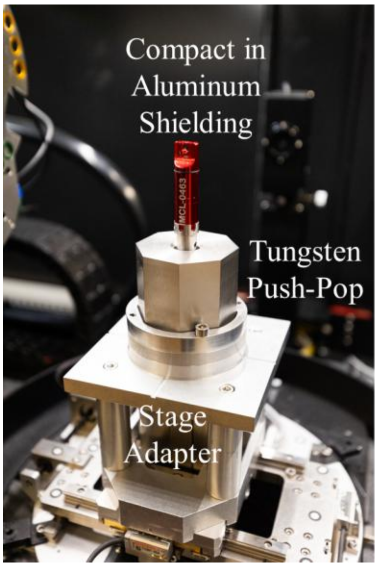

Fig. 3. A photograph displaying a compact mounted with the "push-pop" shielding configuration within the X-ray microscope.

C. *Measurements*

During initial XCT scans of AGR-3/4 Compact 12-4 [6] as well as AGR-5/6/7 Compact 2-1-3 [7], a series of measurements were collected to attempt to quantify the impact the radiation from the compacts had on the XCT images themselves. First a dark image, an image acquired with the X-ray source off, was taken without any sample in the cabinet of the X-ray microscope. Once the compact and push-pop shielding were loaded into the X-ray microscope's cabinet, a dark image was taken of the compact shielded within the push-pop. The compact was then raised out of the shielding and a final dark image was then acquired.

A 100-pixel thick line profile was taken across the center of each image. The mean grayscale values across the line profile were calculated as were the associated error. These values were then compared across the different images to quantify the impact the radioactive compacts had on the resulting images.

Several complete CT acquisitions using different X-ray energies and imaging conditions were also taken over the course of ~3 days on AGR-5/6/7 Compact 3-6-1. Acquisition settings were modified to collect an open beam image (X-rays on but the compact removed from the field-of-view) every 500 radiographs. This evolution first consisted of a scan lasting approximately 18 hours and 45 minutes that utilized a 160 kvP Bremsstrahlung spectrum of X-rays. A total of 4801 radiographs were collected with each radiograph having an acquisition time of six seconds. Next, a scan taking approximately 35 hours and 30 minutes was collected using the same X-ray spectrum, but the count time of the 4801 radiographs was increased to 12 seconds. Finally, a scan using a Bremsstrahlung spectrum of X-rays with a kVp of 60 keV taking a total of approximately 27 hours was conducted. Each radiograph in this scan had an acquisition time of nine seconds and again a total of 4801 radiographs were captured. The different scan parameters were selected to try to get information on different components of the compact (by using different X-ray kVp) and for method develop for reducing the heavy metal artifacts from imaging nuclear fuel (longer exposure time).

A 102-pixel×102-pixel box was taken near the top-left corner of each open beam image as well as near the center of the image. The locations remained the same across each image and the median grayscale value within the box was measured. The goal of this measurement was to ascertain how the compact's radiation dose on the detector was impacting the detector's measurement over time.

IV. RESULTS

The results of dark images taken with the radioactive compacts in different shielding configurations (removed outside the instrument, inside the instrument but within the push-pop shielding, and inside the instrument completely exposed to the detector) are shown in *Fig. 4*. For AGR-3/4 Compact 12-4, the mean difference between the dark image of the compact removed from the X-ray microscope's cabinet and that of the dark image taken of the compact exposed directly to the detector with no shielding was 32.14 ± 0.22 (where the error is the standard deviation from the mean). While the mean value of the dark image when the compact was removed from the X-ray microscope was only 69.95 ± 0.68, it may seem like this ~46% increase from the dark image without a sample is significant. However, the detector has a 16-bit dynamic range, so the addition of ~32 counts to the baseline noise measurement from the compact's radiation represents an increased signal of less than 0.05% across the detector's entire dynamic range. This slight increase does not substantially impact the images produced of the compact. Likewise, the much more radioactive AGR-5/6/7 Compact 2-1-3 saw an increase in the dark image of 29.05 ± 1.21 grayscale counts when the radioactive sample was directly exposed to the detector. However, the initial noise in the detector with the compact removed was 2522.64 ± 22.93. The dark noise increase from the radioactive sample is therefore only ~1% of the initial background reading and represents a change of less than 0.05% across the detector's entire dynamic range. These increased signals are not substantial enough to meaningfully impact the images.

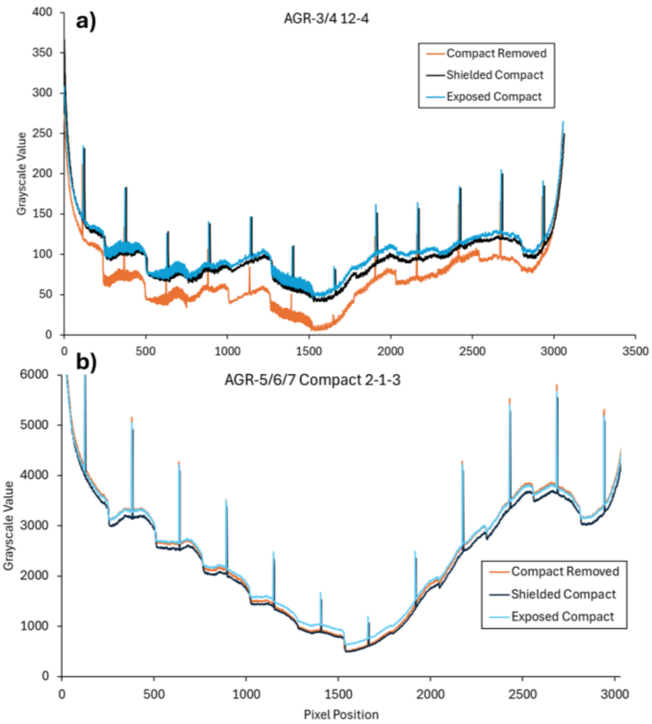

Fig. 4. Charts displaying the median value of a 100-pixel wide line profile across open beam images for (a) AGR-3/4 Compact 12-4 and (b) AGR-5/6/7 Compact 2-1-3.

Median grayscale values on different regions of the detector throughout the duration of the ~72-hour data acquisition for AGR-5/6/7 Compact 3-6-1 are shown in *Fig. 5*. The grayscale values in each region of the open-beam images within each acquisition are relatively consistent, pending minor fluctuations. Note that these fluctuations may be caused by X-ray source drift in the instrument and not by any radiation-induced degradation in the detector itself. One interesting observation is the increase in the signal in the middle of the detector compared to the edge of the detector for the lower energy (60 kVp scan). An explanation for this may be that the lower X-ray energies may get more attenuated in air when traversing the longer path length to the edge of the detector compared to the middle of the detector. More investigation is necessary to provide a more comprehensive explanation for this observation. Regardless, the incident radiation from the compact itself does not seem to significantly impact the open-beam images collected by the detector, implying that the detector performance is not degraded with its prolonged exposure to the radiation field of the compact.

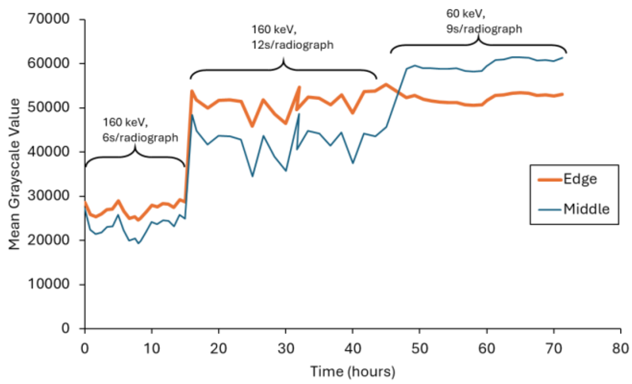

Fig. 5. Plot showing the mean grayscale value of a 102-pixel×102-pixel box at two locations in a series of open beam images as a function of time. The relative grayscale intensity across each exposure does not significantly change, indicating the detector is not experiencing significant effects from the radiation of the sample.

V. CONCLUSIONS

In this work, the impact of radiation fields from AGR TRISO compacts on a solid-state flat panel detector for X-ray computed tomography measurement is evaluated. Even when examining a compact with very high radiation dose (over 2.00 Sv/hr from just γ-rays on contact), these measurements suggest no appreciable level of noise is added to the collected data. The increase in signal on the detector from the radioactive compacts compared to no sample in the instrument was found to be minimal (less than 0.05% of the dynamic range of the detector). Likewise, there was not a noticeable change in the open-beam images generated over time when the detector was subjected to a sustained radiation field.

Frame-averaging multiple radiographs into a single median radiograph for each projection (as was done in this work) helps reduce the impact of incident radiation from the radioactive sample. Additionally, it is suspected that a large portion of the gamma-rays emitted from the samples have higher energy than the detector is optimized through, allowing them to pass through the detector without depositing significant energy into the detector and minimizing their impact of the images. Further simulation studies are underway to explore this hypothesis. In the meantime, this work shows that it is feasible to perform X-ray computed tomography on highly radioactive nuclear fuel specimens without fear of severe radiation induced damage to the detector or degradation of the images. Ultimately, the XCT examination of highly radioactive samples can help expedite the lifecycle from a novel nuclear concept's inception to its study and then commercial implementation.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy's Advanced Gas Reactor (AGR) program. This manuscript has been authored by Battelle Energy Alliance, LLC, under Contract No. DE-AC07–05ID14517 with the U.S. Department of Energy. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

REFERENCES

[1] Demkowicz, Paul A., Bing Liu, and John D. Hunn. "Coated particle fuel: Historical perspectives and current progress." *Journal of Nuclear Materials* 515 (2019): 434-450.
[2] Price, M. S. T. "The Dragon Project origins, achievements and legacies." *Nuclear engineering and design* 251 (2012): 60-68.
[3] Nabielek, Heinz, et al. "The performance of high-temperature reactor fuel particles at extreme temperatures." *Nuclear Technology* 84.1 (1989): 62-81.
[4] Degueldre, Claude, Johannes Bertsch, and Matthias Martin. "Post irradiation examination of nuclear fuel: Toward a complete analysis." *Progress in Nuclear Energy* 92 (2016): 242-253.
[5] Withers, Philip J., et al. "X-ray computed tomography." *Nature Reviews Methods Primers* 1.1 (2021): 18.
[6] Collin, Blaise P. *AGR 3/4 irradiation test final as run report*. No. INL/EXT-15-35550. Idaho National Lab. (INL), Idaho Falls, ID (United States), 2015.
[7] T Pham, Cam Binh, et al. *AGR-5/6/7 irradiation test final as-run report*. No. INL/EXT-21-64221-Rev000. Idaho National Lab. (INL), Idaho Falls, ID (United States), 2021.
[8] Werner, Christopher John, et al. *MCNP version 6.2 release notes*. No. LA-UR-18-20808. Los Alamos National Laboratory (LANL), Los Alamos, NM (United States), 2018.
[9] Croff, A. G. *ORIGEN2: a revised and updated version of the Oak ridge isotope generation and depletion code*. No. ORNL-5621. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 1980.
[10] El Gamal, Abbas, and Helmy Eltoukhy. "CMOS image sensors." *IEEE Circuits and Devices Magazine* 21.3 (2005): 6-20.
[11] Chuirazzi, William, Rahul Reddy Kancharla, and Swapnil Morankar. "Laboratory-Based Micro-X-ray Computed Tomography of Energy Materials at Idaho National Laboratory." *JOM* 77.3 (2025): 1337-1353.
[12] Chuirazzi, William, et al. "Strategy to safely enable X-ray computed tomography examination of highly radioactive tristructural isotropic nuclear fuel." *Nuclear Engineering and Technology* (2025): 103726.