A neutron fluence map of the Los Alamos National Laboratory Godiva IV critical assembly

Jesse M. Roebuck[1,*] , *Danielle* R. Redhouse[1], *Joetta* M. Goda[2], *Melissa* Moreno[1], and *Curtis* Peters[1]

[1] Sandia National Laboratories, Albuquerque, New Mexico, USA
[2] Los Alamos National Laboratories, Los Alamos, New Mexico, USA

Abstract. A neutron fluence map and a total ionizing dose map of the Los Alamos National Laboratory Godiva IV fast burst critical assembly was generated using passive reactor dosimetry, comprised of sulfur pellets and thermoluminescent dosimeters. Godiva IV is an unmoderated, fast burst, critical assembly constructed of approximately 65 kg of highly enriched uranium fuel alloyed with 1.5 % molybdenum for strength. [1] The mapping was performed during a single 75.6 ºC temperature rise burst operation, with the top and sides of the cylindrical Godiva-IV Top Hat covered in passive dosimetry. Dosimetry was placed in a symmetric pattern around the Top Hat, with higher concentrations near the control rods and burst rod. A specific portion of the lower quadrant of the burst rod was mapped to confirm a testing region where the neutron fluence varied by no more than ± 5%. The results will be used to assess the neutron, gamma, and total ionizing dose environment in three-dimensional space around the assembly for higher fidelity experiment placement, active dosimetry positioning, and radiation field characterization.

---

[*] Corresponding author: jroebuc@sandia.gov

1 Introduction

Godiva IV, seen below in Figure 1, is a fast burst critical assembly constructed of approximately 65 kg of highly enriched uranium (HEU) fuel alloyed with 1.5 % molybdenum for strength [1]. Godiva is used to perform criticality and benchmark experiments for the Department of Energy's Nuclear Criticality Safety Program (NCSP) and other sponsors. The main mission of the Godiva and the NCSP is to test the critical worth of materials/items to create benchmarks for safety analysis.

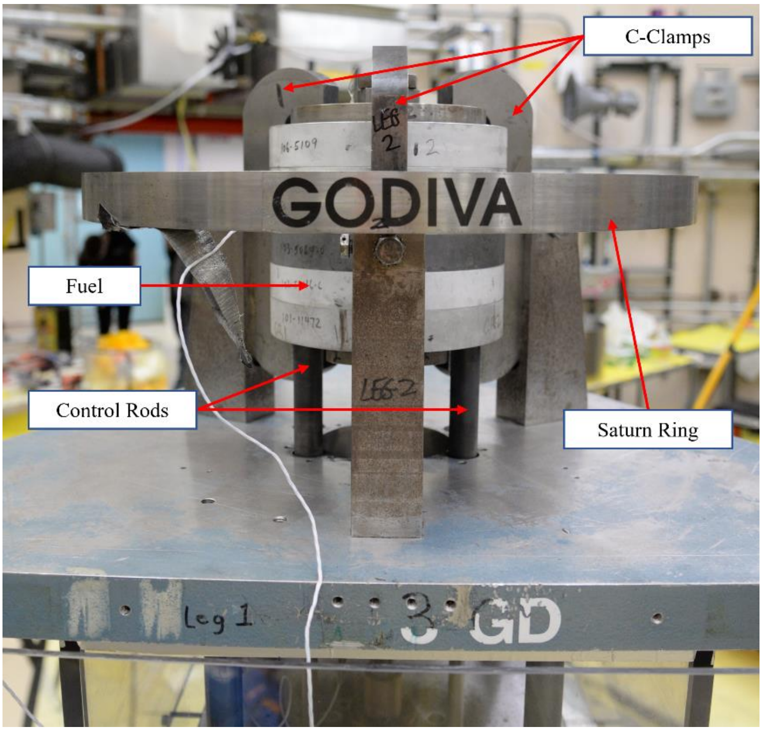

Fig. 1. The Godiva IV critical assembly.

The Top Hat mapping process was designed to provide information pertaining to the leakage fluence characteristics surrounding the Godiva IV fast burst critical assembly, an area commonly used for experimentation, using more than 400 hundred sulfur pellets and 65 TLDs. The Top Hat is used as a physical, passive control to reduce surface contamination and keep airborne levels of HEU well below acceptable levels [1]. Constructed of aluminum and cylindrical in shape, it covers the fuel assembly thus protecting the surrounding area. This mapping process was performed as a preliminary study for the neutron and gamma fluence measurements planned for the *Godiva IV Characterization Experiment*, a collaboration between Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL). The information gained will inform experiment placement according to fluence needs, and the placement of active and passive dosimetry for the characterization measurements.

The mapping of the Top Hat was performed during the *Godiva Pulse Repeatability Experiment*, which had the primary goal of quantifying the relative change in source emission, or repeatability of a Godiva burst, focusing on a standard 70 °C temperature rise burst size [2]. During the test period in May of 2022, twelve bursts were performed at a targeted ΔT of 70 °C. The dosimetry map was installed on the Top Hat during one of the bursts. The measurement produced high fidelity results that can be used by experimenters to inform experimental placement and radiation field metrics.

2 Methodology

The process to create a fluence map and a total ionizing dose map involved several steps and presented some unique challenges. The primary challenge was the distance between Godiva IV which is located at the National Critically Experiments Research Center (NCERC) in Nevada, and SNL located in Albuquerque, New Mexico, about 1 110 km apart. Access to the critical assembly when needed was another challenge. Since the team that operates Godiva is constantly conducting operations for its customers, it is difficult to work with the critical assembly when needed. Another challenge was working near or on a critical assembly for prolonged periods of time, this can be difficult or infeasible due to radiation concerns, including but not limited to, personnel dose or possible actinide contamination. As a result, there was not a practical way to do hands on work with Godiva IV. Additionally, it is not possible to easily locate or identify key components of the critical assembly without direct line of sight on the assembly due to the Top Hat. Given these challenges, some outside-of-the-box solutions were required.

A full-size replica of the Godiva Top Hat, measuring 304.8 mm in height and having a radius of 251.5 mm, was assembled to prepare the dosimetry map without traveling between SNL and NCERC. This also helped avoid any unnecessary exposure. LANL furnished detailed drawings of the Top Hat covering the fuel assembly, which were used to construct the full-size replica consisting of a thin sheet of plastic, rivets, and epoxy. Once completed, the layout and type of dosimetric monitors to be used was planned. It was determined that the dosimetry on the top surface of the Top Hat would be laid out with the use of polar coordinates, with the glory hole acting as the origin of the grid. The glory hole is a hollow region through the center of the core where dosimetry foils and sulfur pellets can be placed for high flux irradiations [1]. The lateral surface of the Top Hat which surrounds the critical assembly, was laid out with a traditional cartesian grid system. Figure 2 below shows the Top Hat replica with the map laid out on the surface. With the parameters of the map determined, the locations of key components were overlayed on to the map. A graphing tool, in conjunction with the Monte Carlo N-Particle Transport (MCNP) model of the assembly, were used to draw each component of the critical assembly. Equation 1 was used to determine the outer circumference of the fuel. For the inner circumference of the fuel, Equation 2 and Equation 3 were used.

$$(x-0)^2 + (y-0)^2 \le \frac{7}{2}, \{|x| > \frac{7}{4}\} \tag{1}$$

$$\sqrt{(\frac{7}{4})^2 - x^2} \le y \le \sqrt{(\frac{7}{2})^2 - x^2} \tag{2}$$

$$-\sqrt{(\tfrac{7}{4})^2 - x^2} \geq y \geq \sqrt{(\tfrac{7}{2})^2 - x^2} \qquad (3)$$

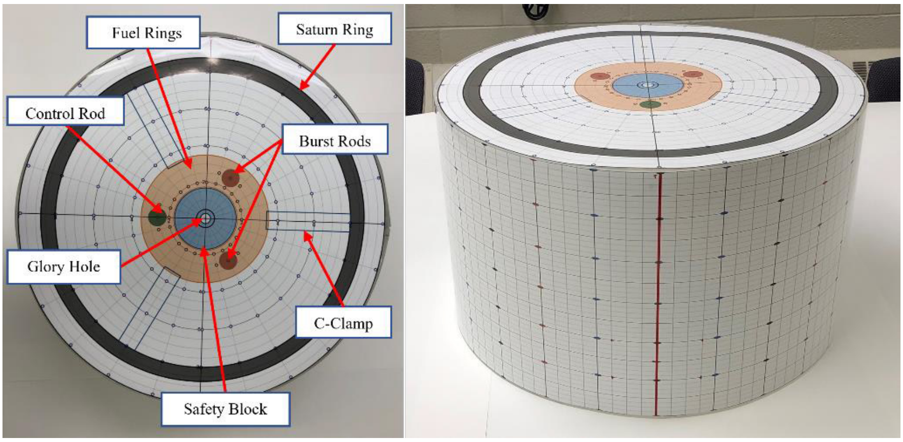

Fig. 2. Replica of the Godiva IV Critical Assembly Top Hat with the map.

Sulfur pellets and calcium fluoride (CaF_2:Mn) thermoluminescent dosimeters (TLD-400s) were selected for their radiation sensitivity in the neutron energy region of interest. Both types of dosimeters, shown in Figure 3, were acquired from the SNL Radiation Metrology Laboratory (RML). RML's standard sulfur pellets measure 4.8 mm in diameter by 6.3 mm thick and are 99.5 % sulfur. The TLDs measure 10.0 mm^2 by 6.0 mm in height. TLDs provide total ionizing dose to cross confirm dose estimates from the MCNP model. Sulfur pellets are used as a fluence monitor in accordance with ASTM E265-15 [3] standard. For this work the sulfur pellets provide the total fluence and the 1-MeV Damage Equivalent Silicon (DES) fluence. Approximately 90 % of the entire Top Hat surface was covered in sulfur pellets with the remaining 10 % in TLDs. In all, the map contained a total of 406 uniformly placed sulfur pellets and 65 TLDs.

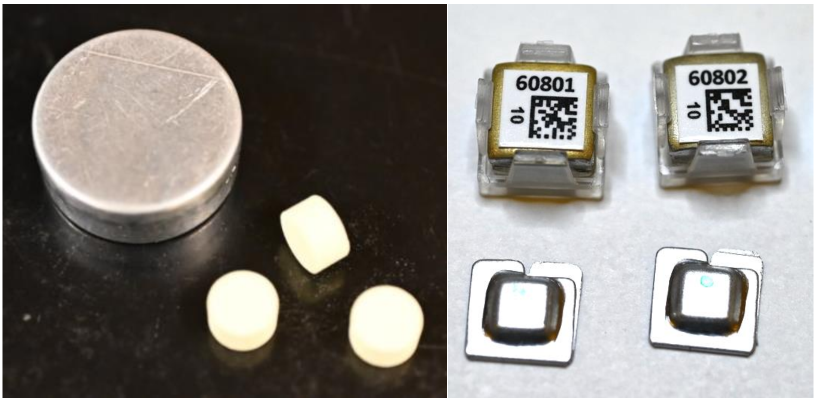

Fig. 3. Sulfur pellets and calcium fluoride (CaF_2:Mn) thermoluminescent dosimeters (TLD-400).

When considering the arrangement and placement of the dosimeters, uniform spacing was ideal due to the size of Godiva and the Top Hat. The spacing of the dosimeters on the lateral surface of the Top Hat was determined to be 66.3 mm by 50.4 mm. The spacing of the dosimeters placed on the top surface was 25.4 mm apart, radiating out from the center in concentric rings. After the general spacing requirements were met, key regions were identified and the dosimeter spacing for those areas were established on a case-by-case basis. Notably, the burst rod and both control rods where key areas of interest during a burst, therefore, a high concentration of sulfur pellets and TLDs were placed in their regions outside of the spacing requirements.

For the top surface, the key regions of interest were the areas above the burst rod, both control rods, and the inner circumference of the fuel plates. Each rod received nine additional sulfur pellets and the inner circumference of the fuel received 24 sulfur pellets. These areas received a greater concentration of dosimeters so that higher fidelity measurements may be achieved, while also confirming uniformity assumptions on rod activity or neutron fluence.

The areas of interest for the lateral surface were the same as the top surface of the Top Hat, the burst rod, and both control rods. Sulfur pellets were placed in front of the lower quadrant of the burst rod, where the burst rod stroke is uniform for bursts. This large region of mapping was done as computational modeling showed a uniform fluence region with a uniform neutron fluence that varied by only ±5 %. This would indicate an ideal location for performing characterization experiments. This consisted of 93 sulfur pellets laid out in an approximately 159.0 mm by 134.0 mm gridded area. Another concentration of sulfur pellets was laid out along the length of one of the control rods, consisting of a single column of 24 pellets spaced 12.7 mm vertically. For the second control rod, TLDs were used to monitor dose. A 135.0 mm by 50.8 mm region consisting of 45 TLD's was placed approximately 50.8mm from the bottom-edge of the Top Hat. A total of 25 TLDs spaced 12.7 mm apart, were placed vertically along the remaining length of the control rod. This area was used to monitor the total ionizing dose in the region around the control rods. Figure 4, below, shows the layout of the dosimeters of the above-mentioned regions. Finally, all the dosimeters were placed onto a paper Top Hat mockup of the map on-site at NCERC. This allowed for precise placement and quick removal of the dosimeters on the Top Hat, before and after the burst. The map was placed on the Godiva IV Top Hat by LANL facility personnel as shown in Figure 5.

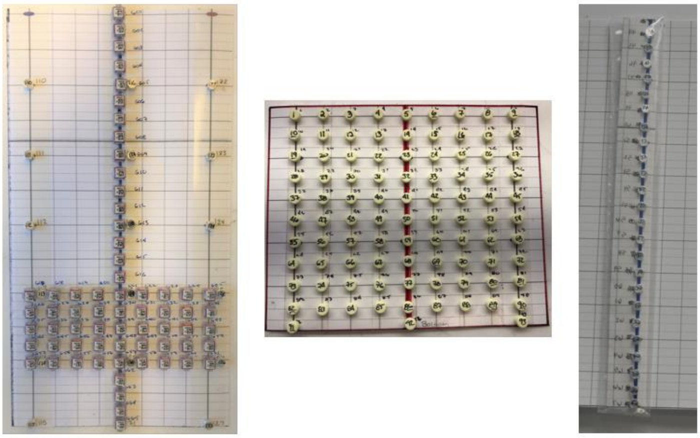

Fig. 4. Dosimeters for the Burst Rod (middle) and both Control Rods with the TLDs on the left.

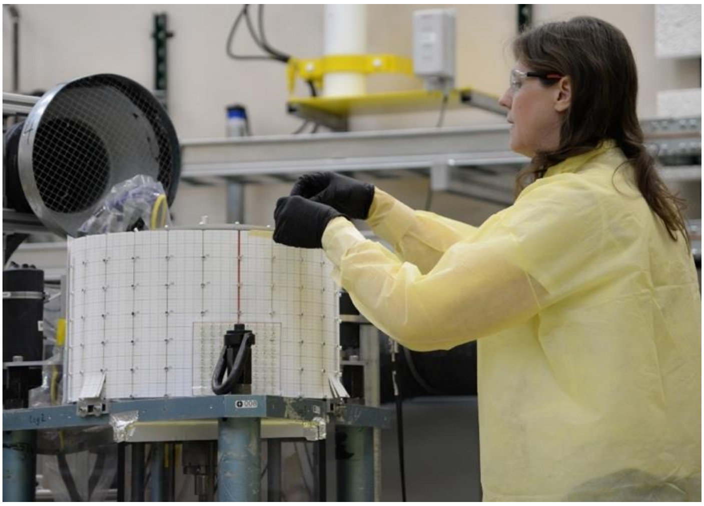

Fig. 5. Joetta Goda (LANL), the principal investigator of the Godiva device, attaching the pre-loaded map to the Godiva IV Top Hat.

Following the burst operation, the dosimetry map was removed from the Top Hat and moved to the NCERC count room for post-processing. All dosimeters were removed from the map and shipped back to SNL RML to be counted. RML's standard counting process involves counting each piece of neutron dosimeter twice on two independent detector systems. TLDs were counted using Harshaw 400 machines, while the sulfur pellets were counted using gas proportional Mirion Series 6 Low-Background Gas Proportional counters. A sulfur pellet is shown being counted at RML in Figure 6. The counts were certified accurate to 1.9 % uncertainty for the sulfurs and 3.4 % uncertainty for the TLDs, both to 1σ.

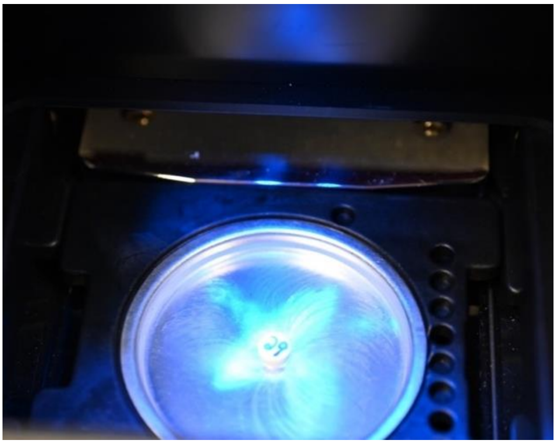

Fig. 6. Sulfur pellet counted on a Mirion Series 6 gas proportional counter.

3 Results

The resulting fluence map shows the highest magnitude fluence regions and the uniform fluence regions that surround Godiva IV. This allows for planning and placement of detector systems and experiment locations outside of the assembly, where a leakage environment exists. Most importantly, it further informs and validates the Godiva IV MCNP model's assumption. Figures 7 and 8, below, compare the data obtained from the dosimeters used during measurement and the MCNP model along the lateral surface of the Top Hat. Figures 9 and 10 compare the top surface of the Top Hat from both the experimental process and MCNP model. In these images, dose is normalized to the largest activation on the map. Lastly, Figure 11 shows the comparison of the TLD data from the mapping process and the MCNP model. For this work MCNP version 6.2.0 was used in conjunction with the ENDF/V-III and the International Reactor Dosimetry and Fusion File (IRDFF-II) nuclear data to produce these results. These results are also normalized to the maximum dose; and, in some instances, the maximum occurs outside the area of interest and therefore is not shown.

For the collected sulfur data, irregularity is expected when comparing real results to MCNP. MCNP modeling is based on ideal geometry and conditions that do not exist in the physical world. In this case, MCNP is used to inform experimental dosimetry mapping placement, but ultimately shows that a gradient across the Top Hat exists for which the model does not account. The comparison of the experimental and computational results shows that the other trends of the two data sets are similar, showing enhancement and reduction in regions associated with assembly features. Note that the model does not account for changing materials inside the room such as test stands, fixtures, and equipment; all of which could affect the leakage radiation field.

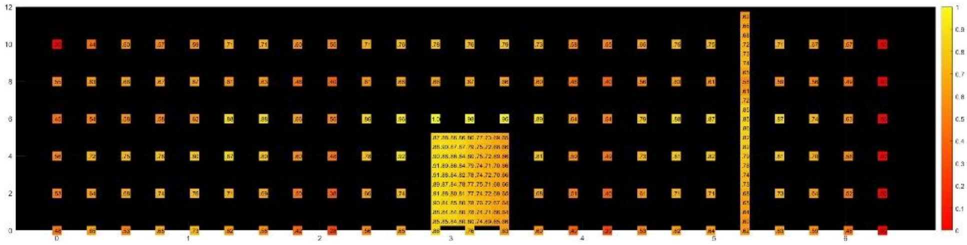

Fig. 7. Neutron fluence data from the sulfur mapping of the lateral surface of the Top Hat. Note**:** the height is measured in inches and the length is radians of rotation. The intensity scale is on the right.

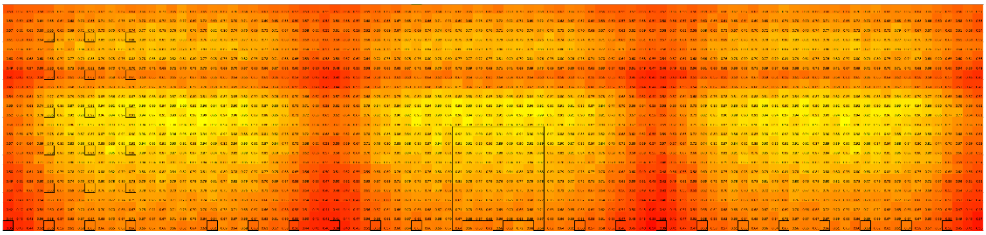

Fig. 8. MCNP model results of the total neutron fluence of the lateral surface of the Top Hat.

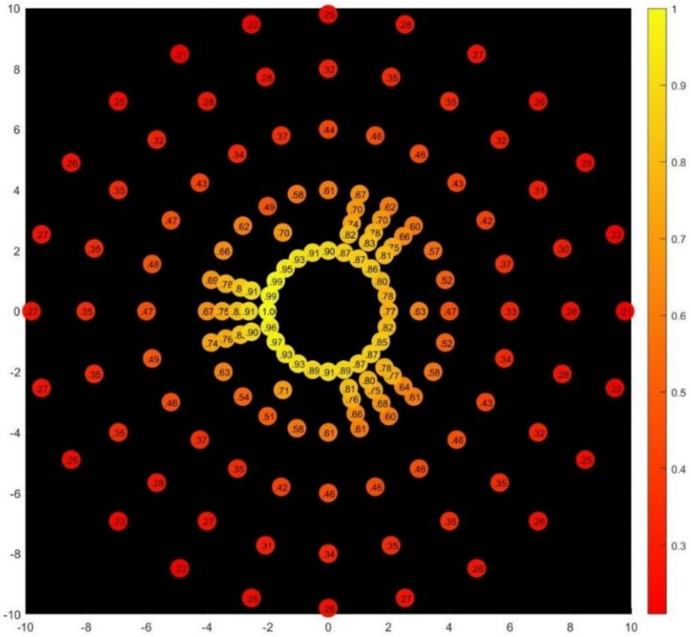

Fig. 9. Neutron fluence map showing sulfur dosimetry data from the mapping process on the top surface of the Top Hat. Note: the x- and y-axes are length measured in inches. Intensity is represented by the scale on the right.

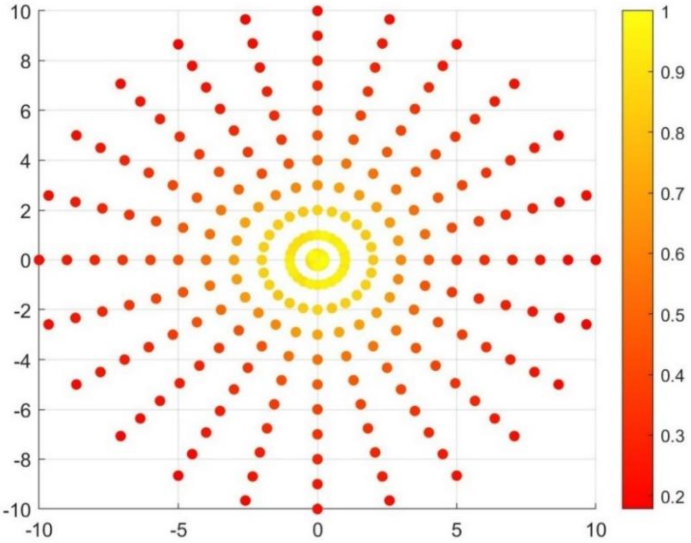

Fig. 10. MCNP model of the top surface of the Top Hat showing neutron fluence. Intensity is represented by the scale on the right.

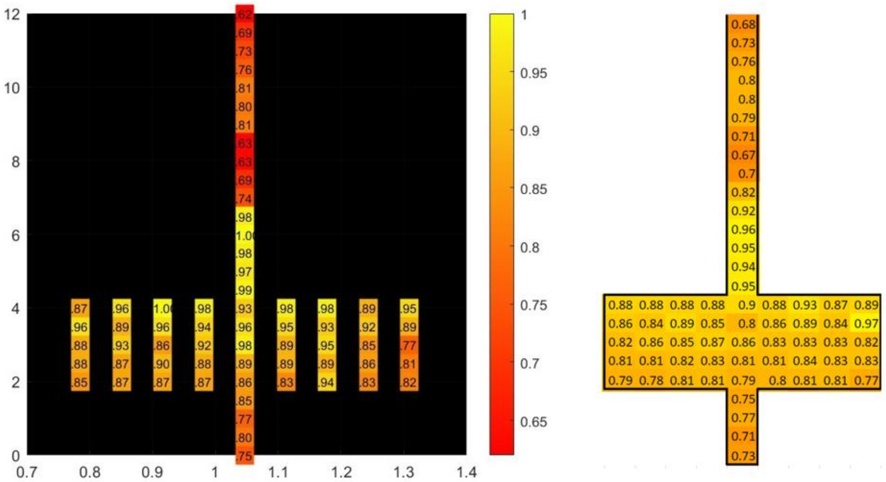

Fig. 11. Comparison of the resulting TLD dose from the mapping process on the left (the height is measured in inches and the length is raiains of rotation with the intensity scale on the right) and MCNP model (right).

When the fluence and dose values are plotted in conjunction with the location of each individual dosimeter, we can get a visual of the inner workings of the critical assembly based on the activation of the TLDs and sulfur dosimeters. Plots show a reduction of total ionizing dose in the vicinity of the Saturn ring or C-clamps, and higher dose in areas around the control and burst rods. This is due to the shielding of gammas by the materials present in these assembly components. Conversely, neutron fluence shows an enhancement or increased scattering around the Saturn ring or C-clamps. This enhanced scattering fluence may also be due to the steel mandrel that the safety block is threaded onto and forms the lower portion of the core. The maximum fluence is seen starting at approximately 76.0 mm from the bottom of the Top Hat and extending to approximately 152.0 mm above, this space encompasses a total area of 76.0 mm by 300 mm between each clamp. This region highlights an area that would be ideal for experiment placement when the maximum amount of fluence is desired.

When compared with a picture of the critical assembly, it is easy to identify from the plot, the location of the Saturn ring and the three clamps that hold the fuel together as seen in Figure 1, above. The presence of these components noticeably lowers the fluence by acting as a shield, absorbing, or scattering gamma and neutron radiation. These regions would not be favorable for experiment and/or detector placement as they represent areas with radiation fields that are distorted by permanent features of the assembly.

4 Conclusion

The map of the Godiva critical assembly has provided insight into the ideal areas of experimental placement and location where active and passive dosimetry could be placed for the best results; depending on fluence needs. The map paints a visual picture of what happens during a burst and how the different components that make up the critical assembly affect the fluence and total dose in the leakage environment surrounding the critical assembly at the Top Hat surface. In plotting normalized total ionizing dose or fluence, areas around the assembly can be used to quickly scale desires fluence metrics or dose metrics when used in conjunction of the characterized metrics of Godiva. With this information, experimenters will be better equipped to field test items at locations external to the critical assembly, enabling efficient use of test time and space on Godiva IV.

This work was supported by the DOE Nuclear Criticality Safety Program, funded, and managed by the National Nuclear Security Administration for the US Department of Energy.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

References

[1] J. GODA, et al., "A New Era of Nuclear Criticality Experiments: The First Ten Years of Godiva IV Operations at NCERC," Nuclear Science and Engineering, Submitted (2021)

[2] J. Goda, T. Grove, B. Pierson, D. Redhouse, R. Weldon, IER 557: Godiva Pulse Repeatability and Characterization CED-3B Final Design Report, LA-UR-22-30192

[3] ASTM E265-15, "Standard Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32," ASTM International, Published July 2020