Oak Ridge National Laboratory

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X-Ray Imaging and Computed Tomography for Nuclear Waste Classification

By:

Bernadette Brezinski, Gomez Wright, and Paul Rose, Jason Hayward

Oak Ridge National Laboratory

University of Tennessee, Knoxville

U.S. DEPARTMENT of ENERGY

Purpose

- Department of Energy (DOE) Legacy Waste
  - Significant volumes of radioactive waste and contaminated materials were left from the Manhattan Project and Cold War weapons production
- Effective nuclear waste characterization is essential to ensure **safe**, **compliant**, and **cost-effective** treatment, storage, and disposal
- Utilization of X-Ray Computed Tomography (CT) enhances waste classification and support informed decision-making

Figure 1: Transuranic (TRU) waste stored primarily in 55-gallon drums.*

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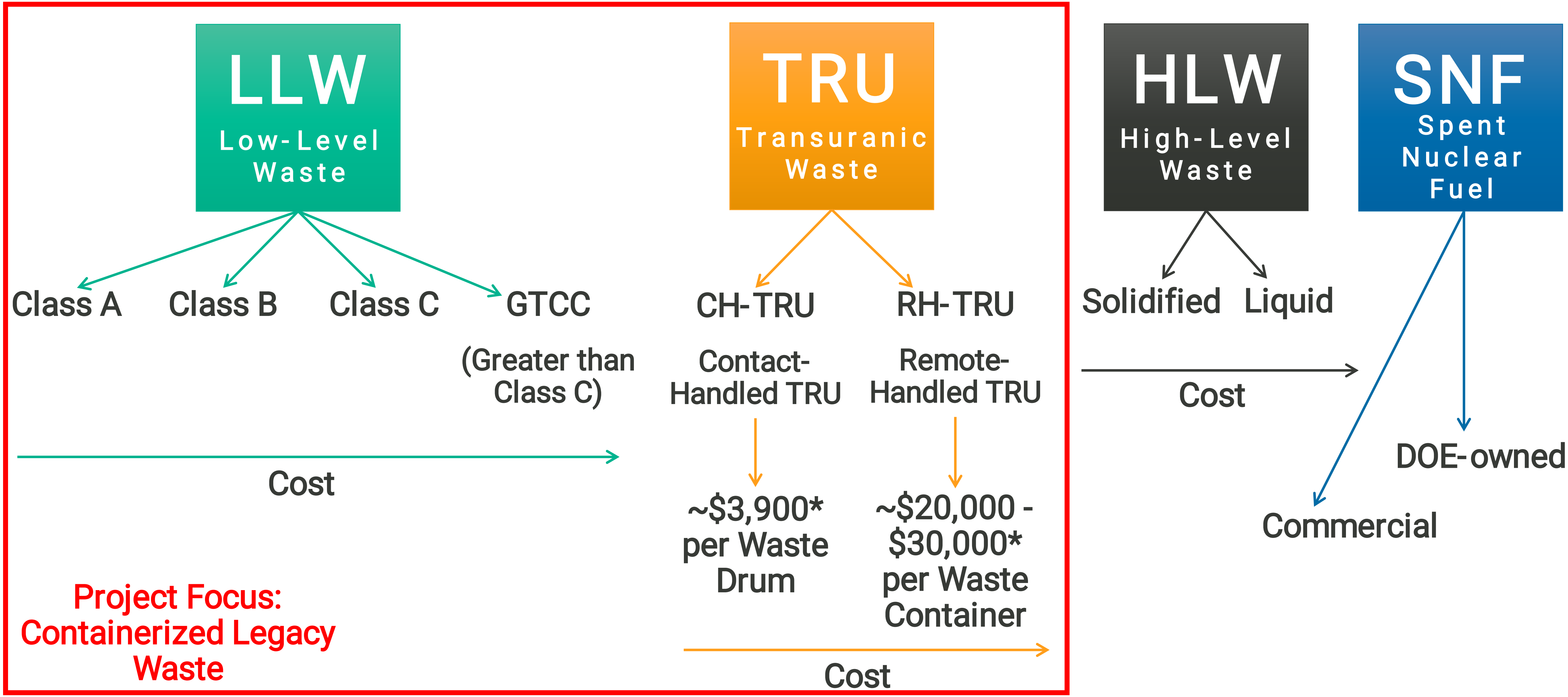
*U.S. Department of Energy, *Environmental Management Los Alamos Field Office: Legacy Waste Management*. Los Alamos, NM: U.S. Department of Energy, n.d.

DOE Nuclear Waste Classification



LLW
Low-Level Waste

Class A
Class B
Class C
GTCC
(Greater than Class C)

Cost

TRU
Transuranic Waste

CH-TRU
Contact-Handled TRU
~$3,900* per Waste Drum

RH-TRU
Remote-Handled TRU
~$20,000 - $30,000* per Waste Container

Cost

Project Focus: Containerized Legacy Waste

HLW
High-Level Waste

Solidified
Liquid

Cost

SNF
Spent Nuclear Fuel

DOE-owned
Commercial

*National Academies of Sciences and Medicine, *Improving the Characterization Program for Contact-Handled Transuranic Waste Bound for the Waste Isolation Pilot Plant*. Washington, DC: The National Academies Press, 2004.

Current Technology for Waste Classification

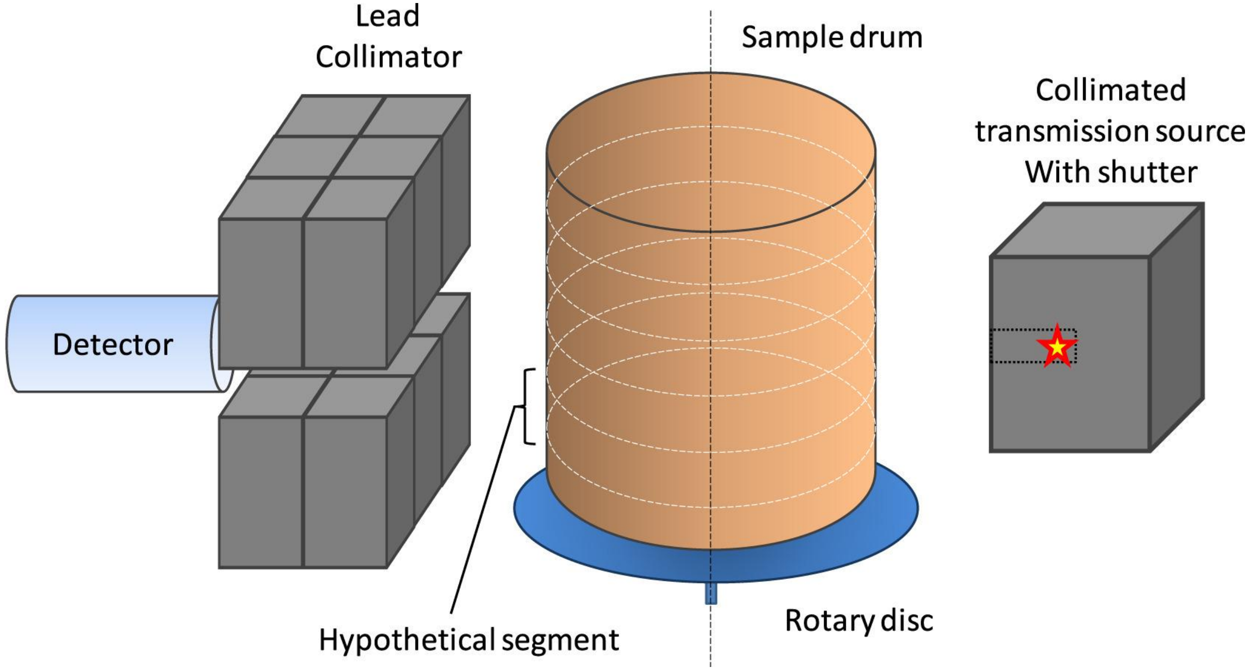


Figure 2: SGS examines multiple vertical segments of a drum to measure the gamma ray emissions. An external source is used for an attenuation correction. Sometimes, a vertical rotation of the barrel is done simultaneously with each vertical segment.*

- Segmented Gamma Scanning (SGS) is a **nondestructive assay technique** that measures gamma ray emission from vertical drum segments to determine radioactive content
- Limitations of Conventional SGS:
    - Assumes uniform material distribution
    - **Underestimates Pu mass** in drums containing lumped Pu due to:
        - Self-attenuation
        - Uneven/isolated distribution of lumps
    - Transmission correction (using an external gamma source) may miss lumps

* S. Patra and C. Agarwal, “Segmented gamma-ray assay of large volume radioactive waste drums containing plutonium lumps,” *Applied Radiation and Isotopes*, vol. 153, p. 108827, 2019.

X-Ray Computed Tomography (CT)

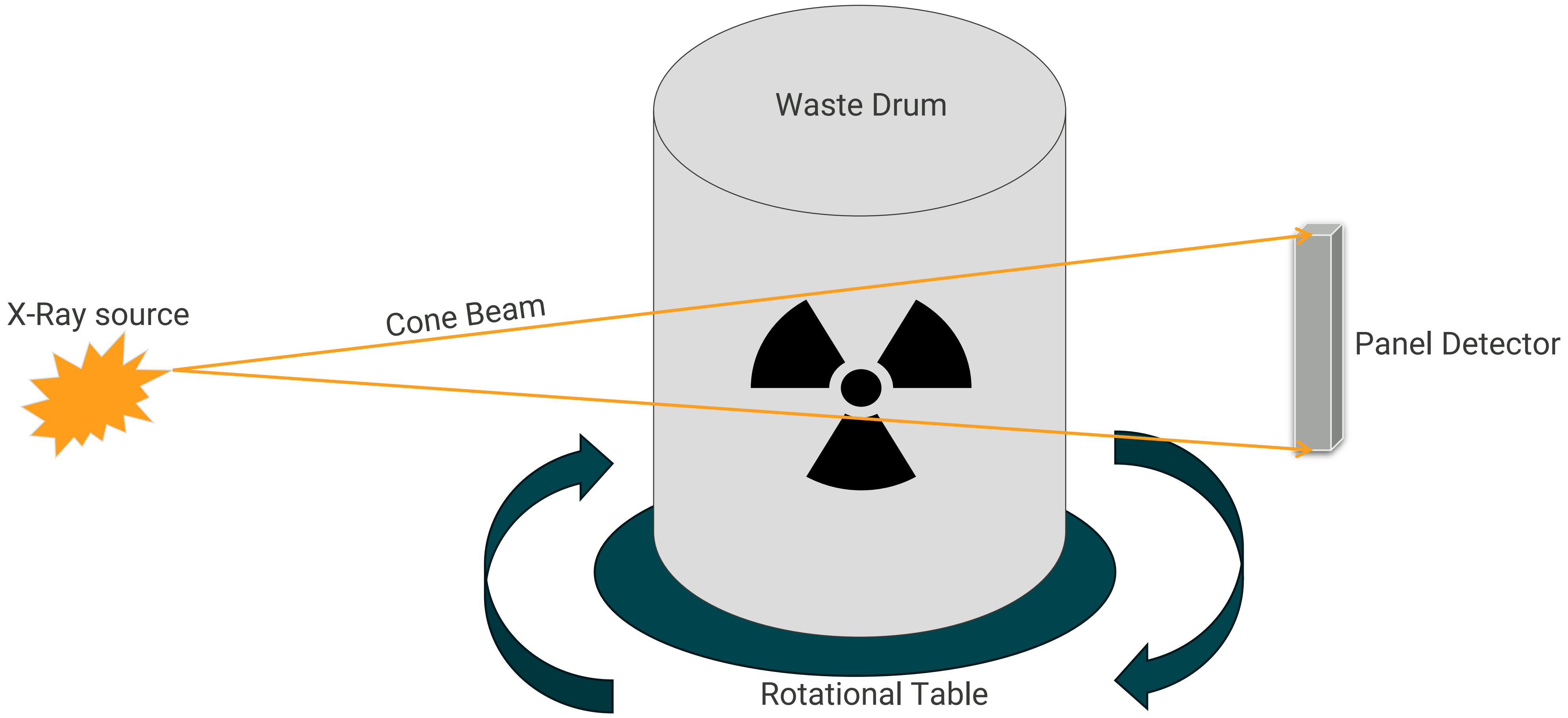


Figure 5: X-ray Computed Tomography setup (not to scale). Generation of 3D images by capturing multiple X-Ray projections over a range of angles and reconstructing them using mathematical algorithms.

Experimental Setup

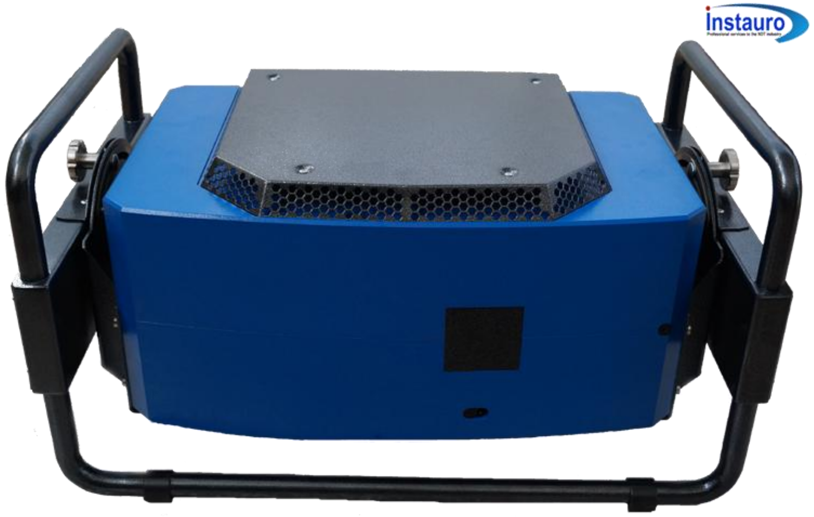


Figure 6: Instauro SEA-7 Betatron System

Figure 8: NOVO Slider System

- 7 MV Instauro Betatron
    - Pulsed with a repetition rate of 400 Hz
    - Spot size: 0.2 mm by 0.2 mm
    - Beam spread angle: 15°
- NOVO-22W (2107A-4) detector
    - Indirect conversion thin-film-transistor
    - Weight: 4.264 kg
    - Dimensions: 42.7 cm tall, 35.6 cm wide
    - Active area: 85%
    - Gadolinium Oxysulfide Gd_2O_2S Scintillator with an amorphous silicon photodetector
    - Pixel Grid: 2350 x 2878
- NOVO Slider System
    - Imaging Area: 2.5 x 1.39 m
- Turntable diameter = 76.2 cm

Figure 7: NOVO 22-W (2107A-4) Flat Panel Detector

Experimental Test Drum Setup

Figure 9: (a) The inside of the test waste drum is shown. The criticality cage holds the inner vessel and is surrounded by a lead blanket. (b) The inner vessel contains three pipe nipples with varying materials, including a bag of tungsten shot, a tungsten rod, a vial of water, and wood screws.

- **85-gallon** test drum
- Criticality cage surrounded by a **lead blanket**
- Materials inside the pipe nipples
    - 0.0762 m **tungsten rod**
        - Simulates solid metal waste
    - 0.4536 kg bag of **tungsten shot**, simulating uranium and TRU waste
        - Simulates oxidized metals
    - 0.0762 m **wood screws**
    - Plastic **vial of water**
        - Pipe Nipple 1: ~25 mL H_2O
        - Pipe Nipple 2: ~40 mL H_2O
        - Pipe Nipple 3: ~10 mL H_2O

X-Ray Imaging Tests Performed

Composite X-Ray Image of Full Test Drum

- The NOVO slider system was used to acquire a full image of the waste drum
    - 4 × 3 detector grid
- Total Acquisition Time: 15 min
- Compared with a commercial real-time radiography system

Full CT of Inner Vessel of the Criticality Cage

- One detector grid is used to examine the full inner containment vessel
- 360 images recorded over an angular range of 0° to 360°
    - Averaged 5 flat field and dark frame images
- Total Acquisition Time: 45 Min
- Source to Detector Distance: 4.1196 m
- Source to Center of Rotation Distance: 3.7349 m
- Reconstruction Algorithms tested:
    - FBP, SART, ASD-POCS

Full Image Acquisition

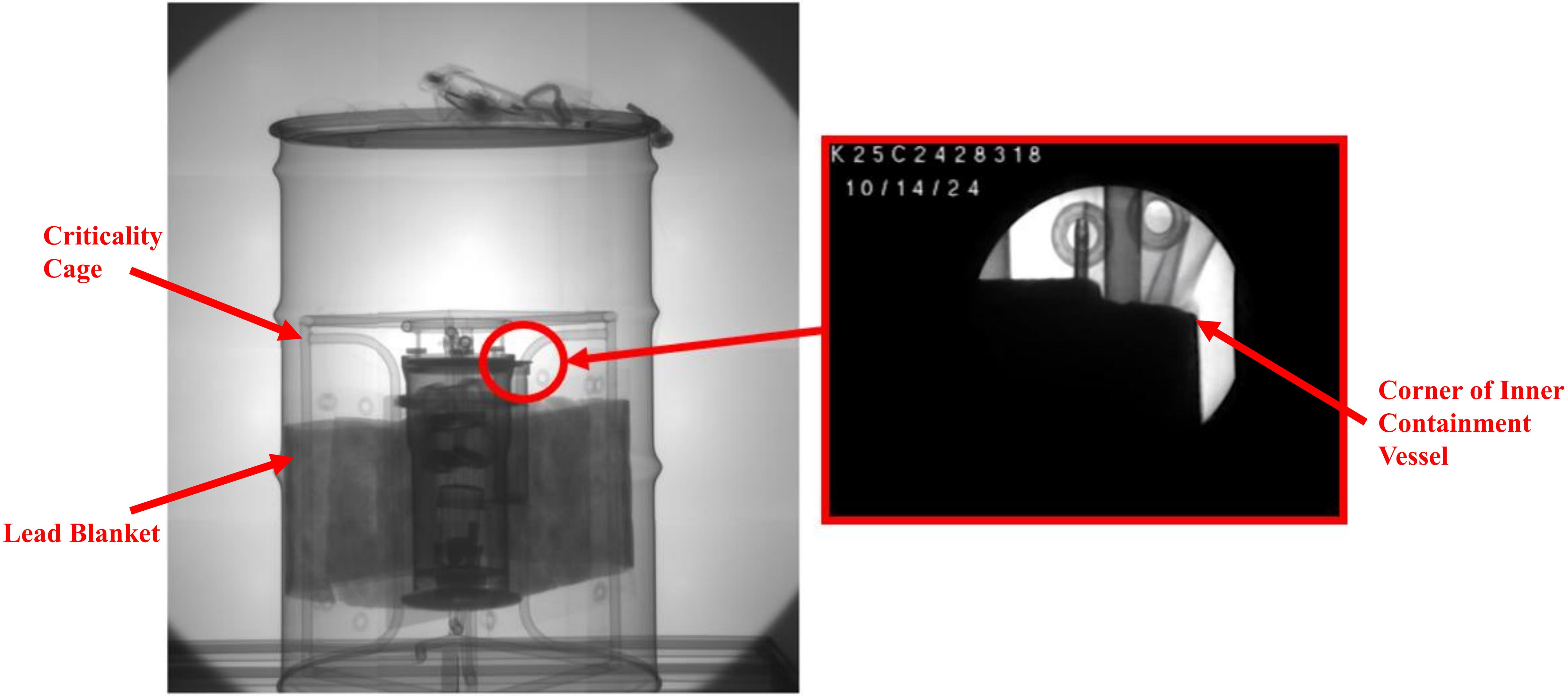


Figure 10: A stitched image of the full test waste drum (criticality cage surrounded by a lead blanket) acquired with the NOVO slider is shown (left) and compared to an X-Ray image taken on Oct. 14, 2024 using a commercial real-time radiography system with a source energy of 300 kV (right).

Visibility of Nuclear Waste Components in Pipe Nipple #1

Visualize Wood Screws / W Rod

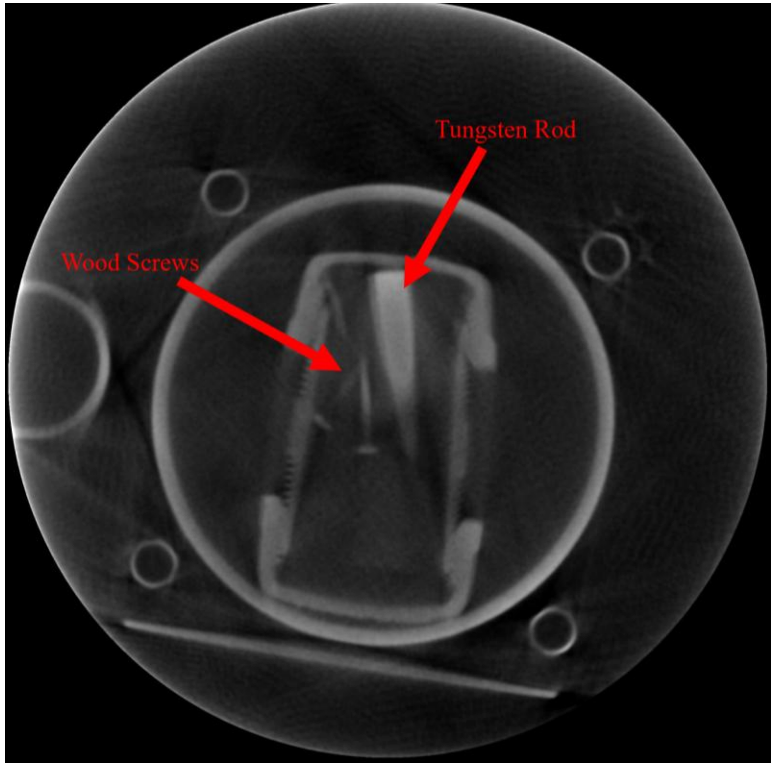


Figure 14: The tungsten rod and wood screws of the upper pipe nipple is visualized from the ASD-POCS reconstruction.

Visualize the Plastic Vial of H_2O

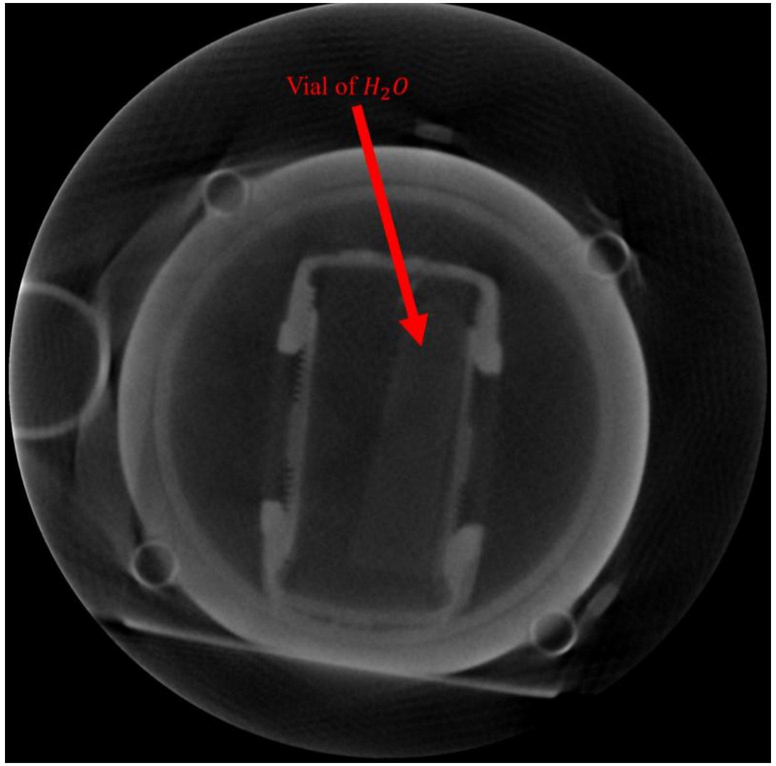


Figure 15: The plastic vial of H_2O can be seen in the upper pipe nipple; however, it is difficult to see low-density material.

Visualize the W Shot

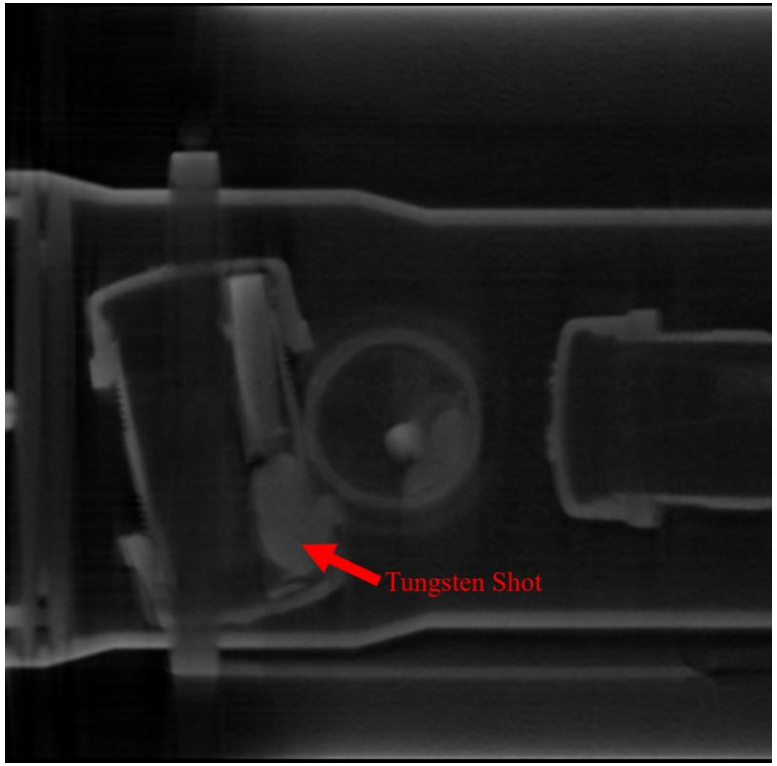


Figure 16: The YZ orthogonal projection of the ASD-POCS reconstruction visualizing the tungsten shot in the upper pipe nipple.

Visibility of Nuclear Waste Components in Pipe Nipple #1

Visualize Wood Screws / W Rod

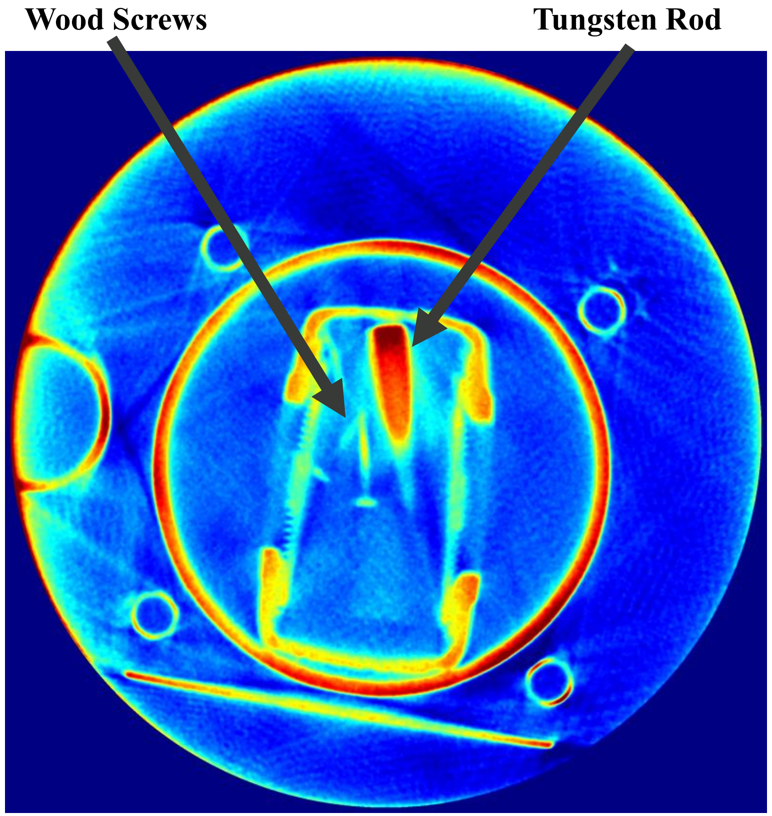


Figure 17: The tungsten rod and wood screws of the upper pipe nipple is visualized using the ‘Jet’ lookup table in ImageJ.

Visualize the Plastic Vial of H_2O

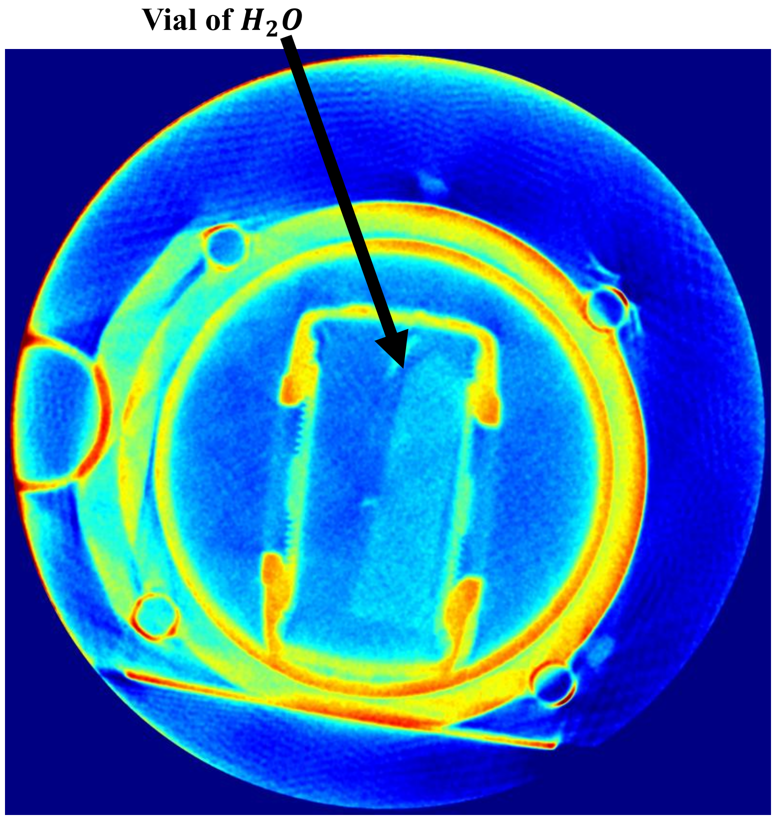


Figure 18: The plastic vial of H_2O can be seen in the upper pipe nipple when using the 'Jet' lookup table in ImageJ.

Visualize the W Shot

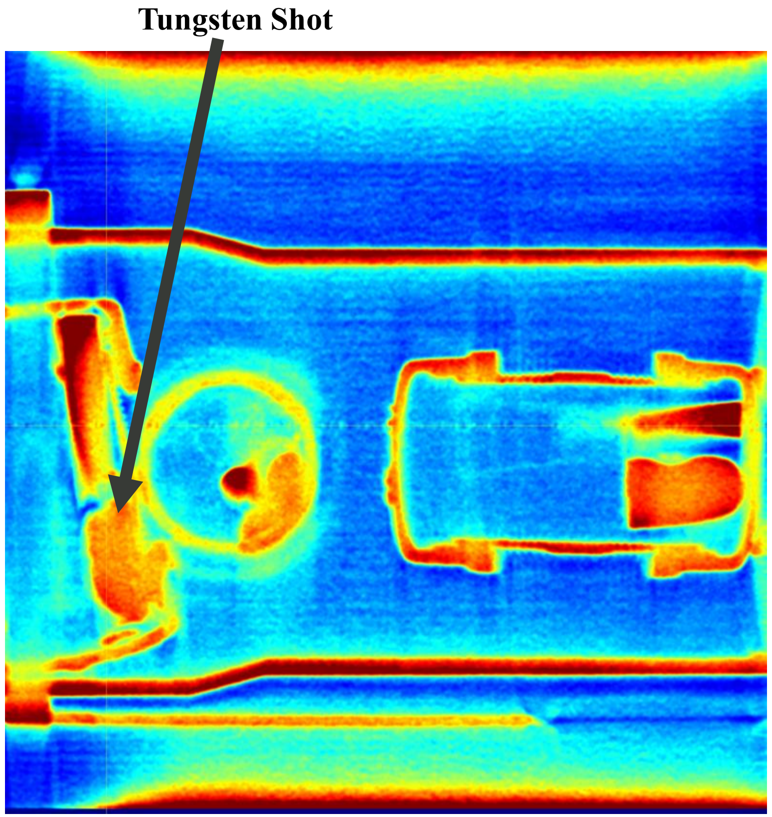
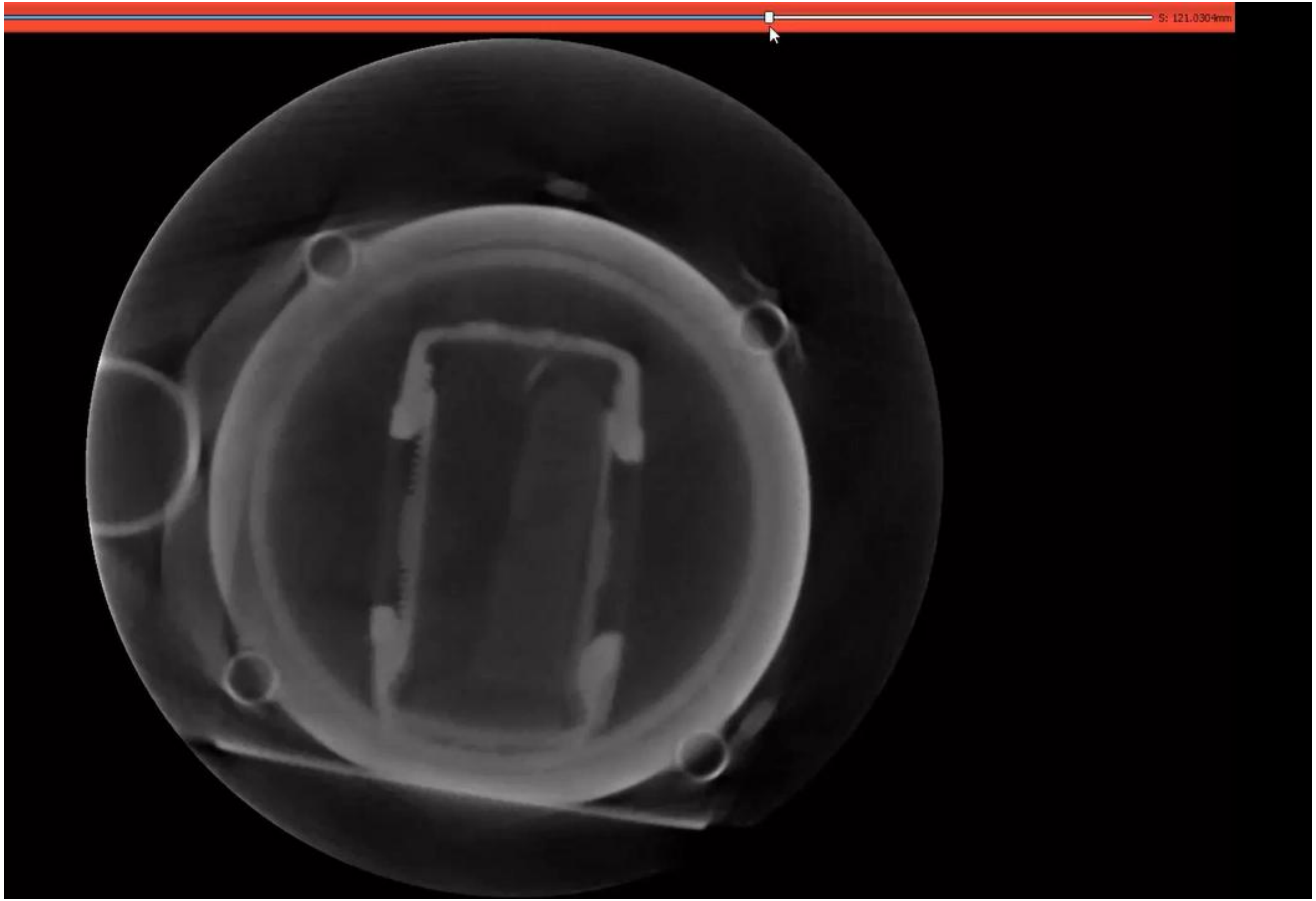
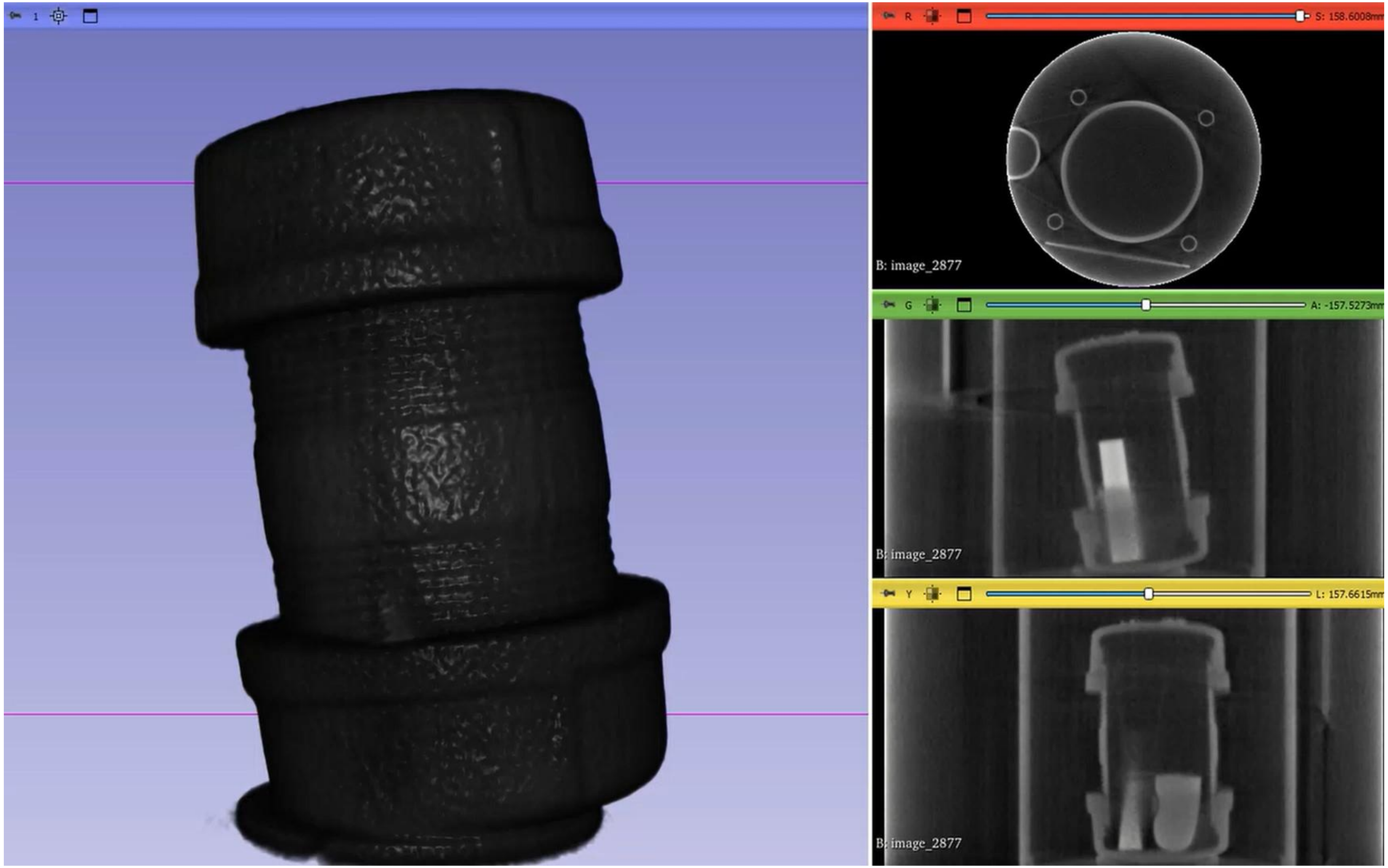


Figure 19: The three pipe nipples are visualized using the ‘Jet’ lookup table in imageJ.

Visibility of Nuclear Waste Components in Pipe Nipple #1



Visibility of Nuclear Waste Components in Pipe Nipple #3



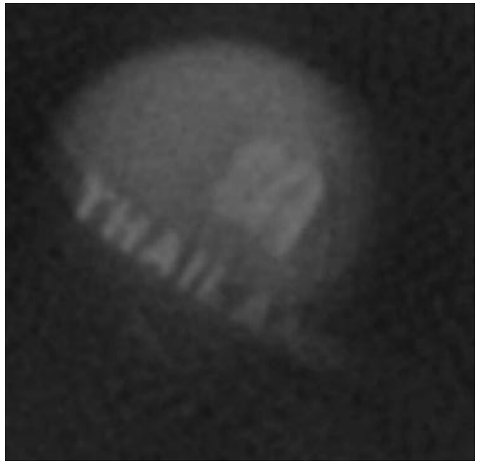
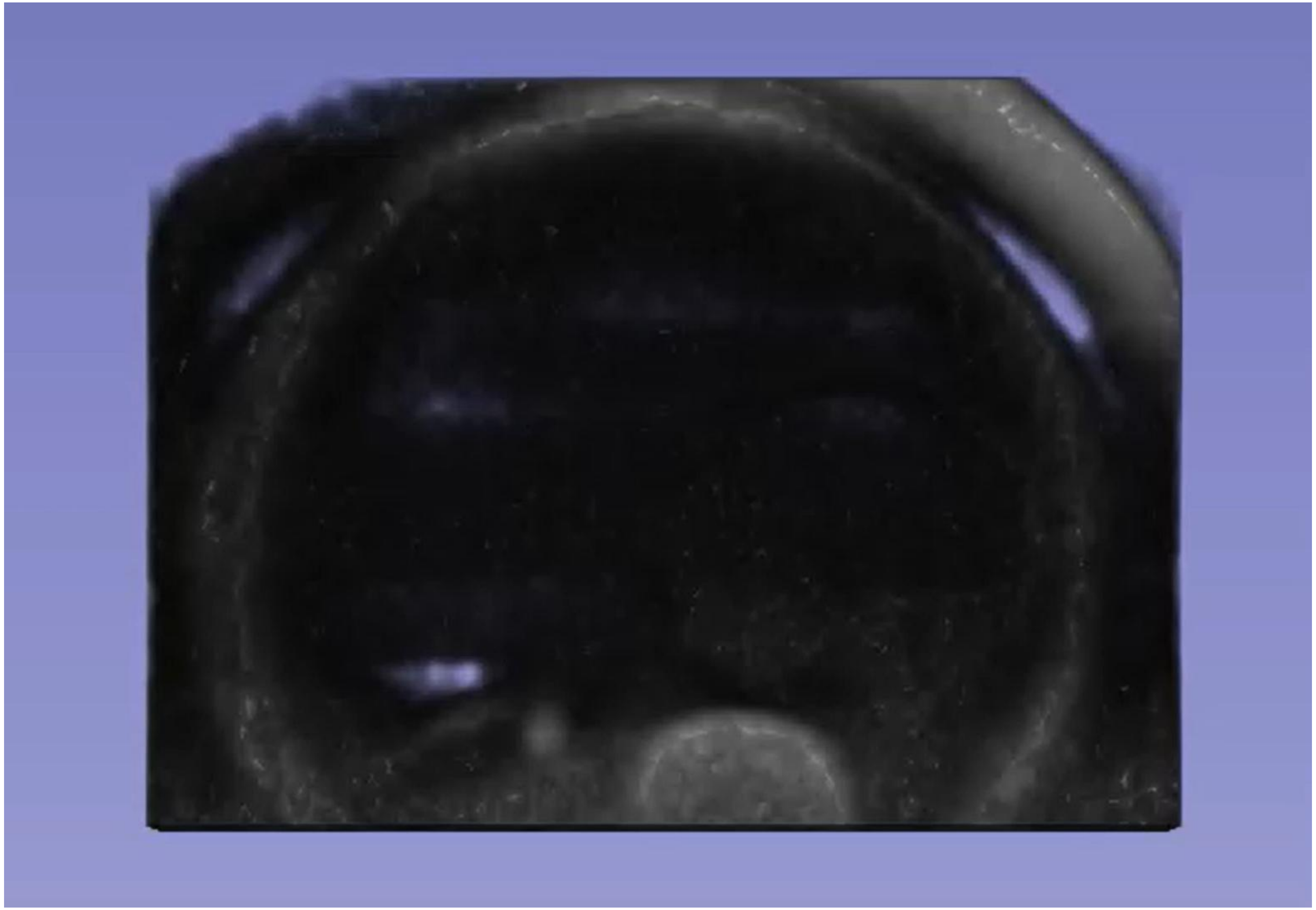


Figure 20: Engraving of “SA THAILAND” on the pipe nipple can be seen in the CT reconstruction of Pipe Nipple #3.

Water Level in Pipe Nipple #1 (25 mL H_2O)



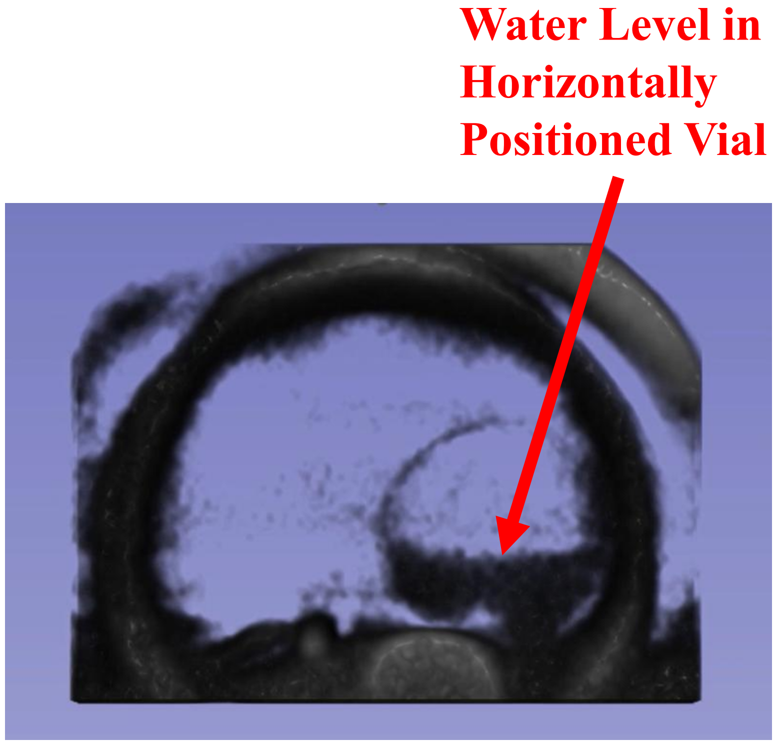
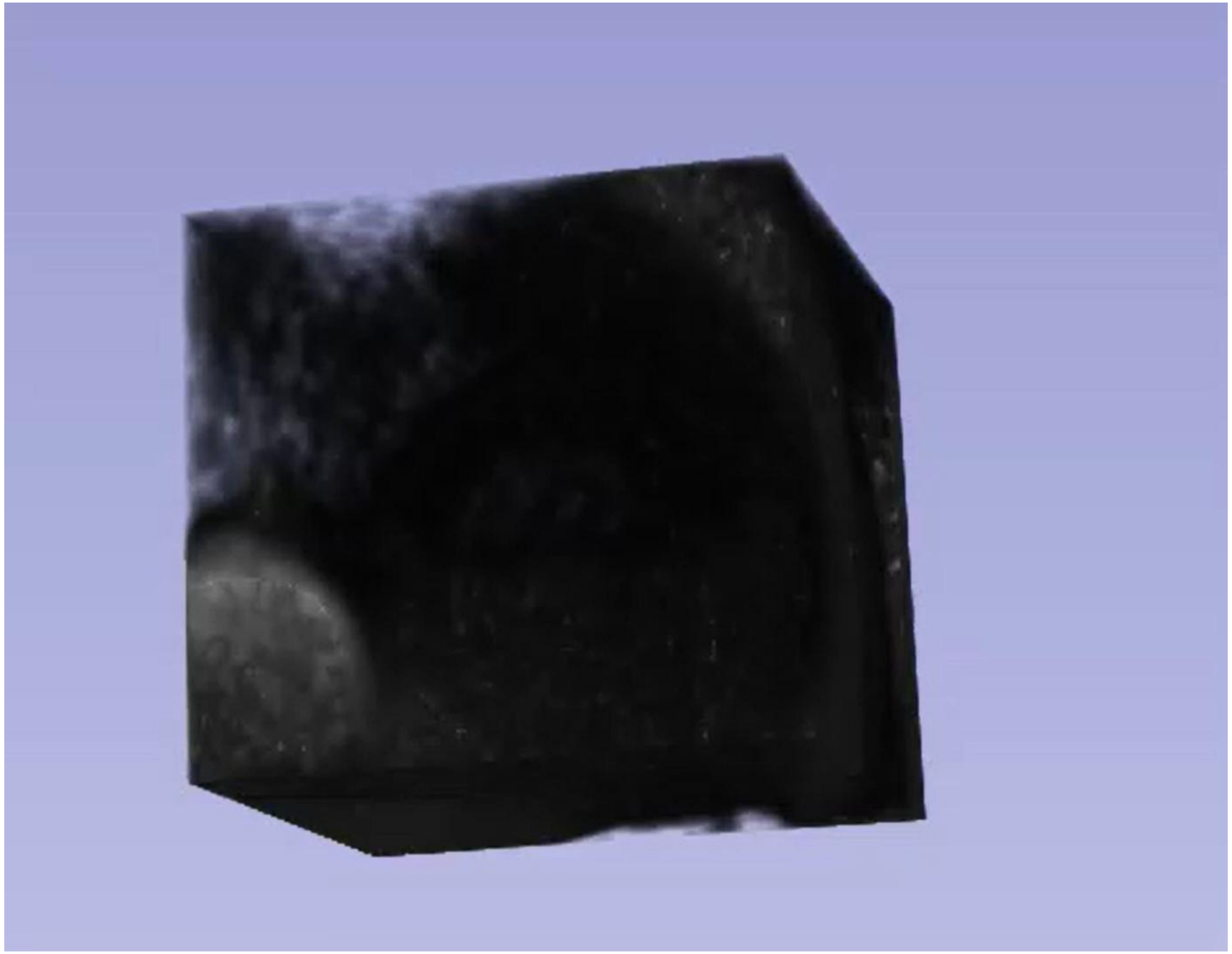


Figure 21: The water level line in the first pipe nipple is shown as the vial is positioned horizontally.

Water Level in **Pipe Nipple #2** (40 mL H_2O)



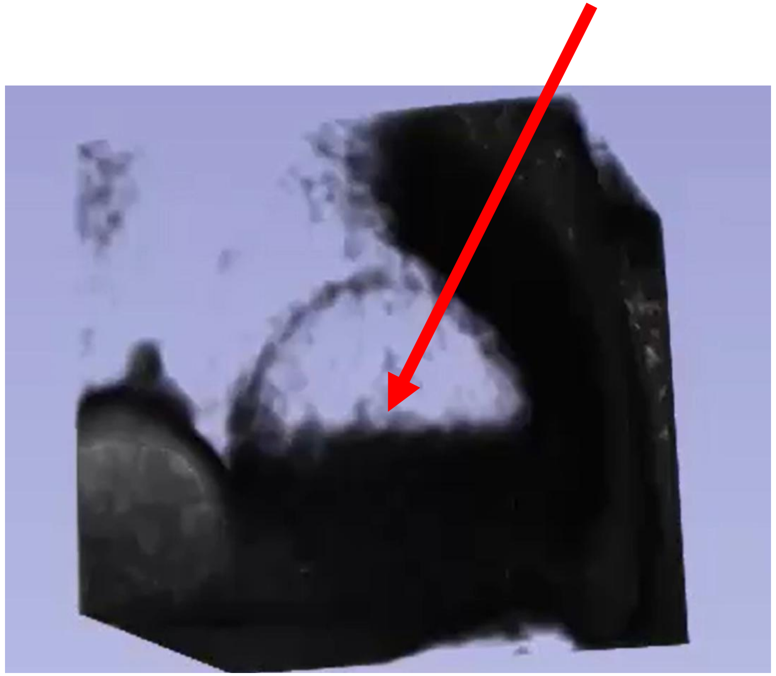
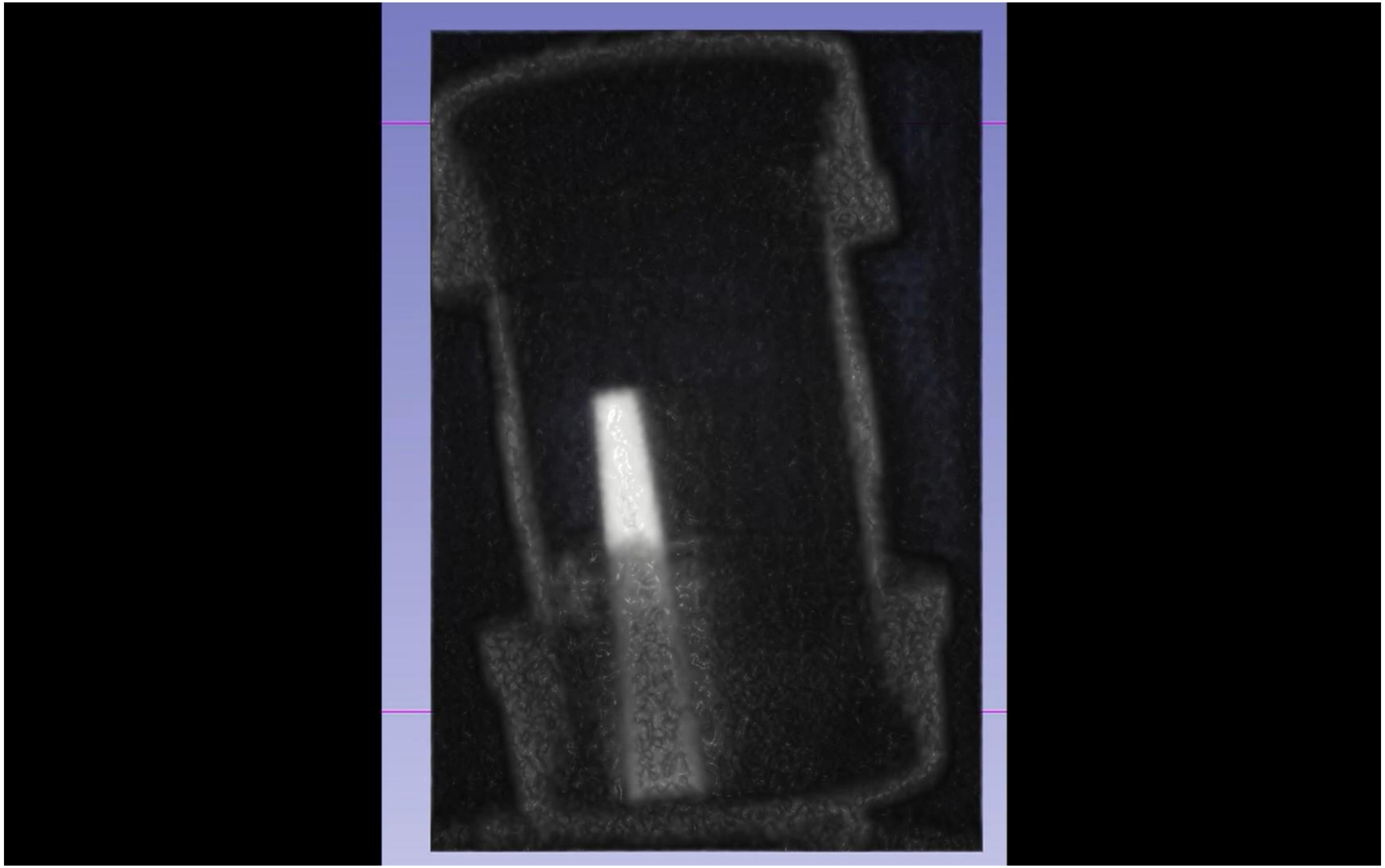


Figure 22: The water level line in the second pipe nipple is shown as the vial is positioned horizontally.

Water Level in **Pipe Nipple #3** (10 mL H_2O)



Water Level in Vertically Positioned Vial

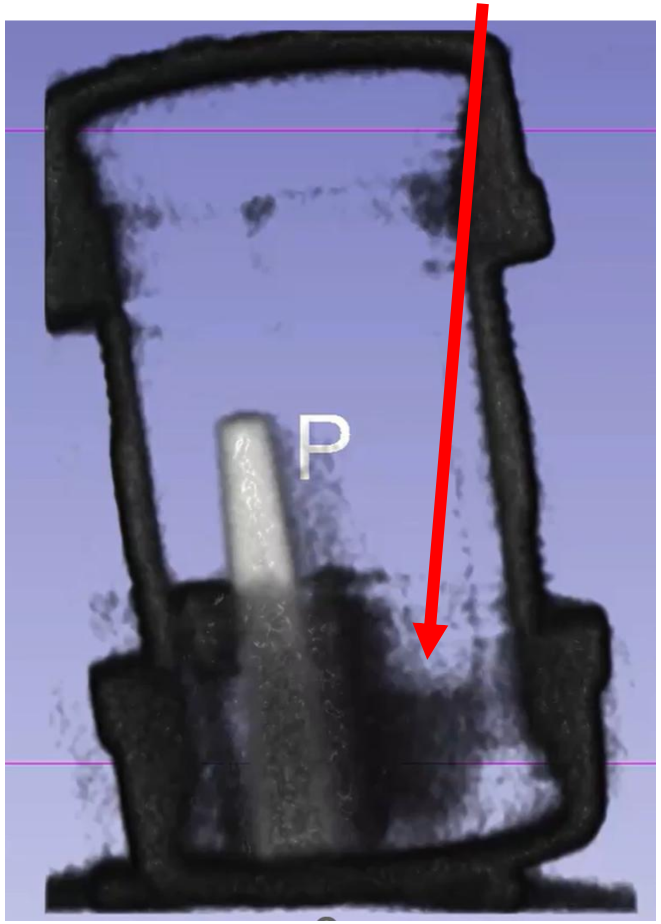


Figure 23: The water level line in the third pipe nipple is shown as the vial is positioned vertically.

Comparison of Water Levels in the Different Pipe Nipples

Pipe Nipple #1 (25 mL H_2O)

Figure 24: The 25 mL water level in the first pipe nipple is visible through a lead blanket and multiple layers of lead.

Pipe Nipple #2 (40 mL H_2O)

Figure 25: The 40 mL water level in the second pipe nipple is visible through a lead blanket and multiple layers of lead.

Pipe Nipple #3 (10 mL H_2O)

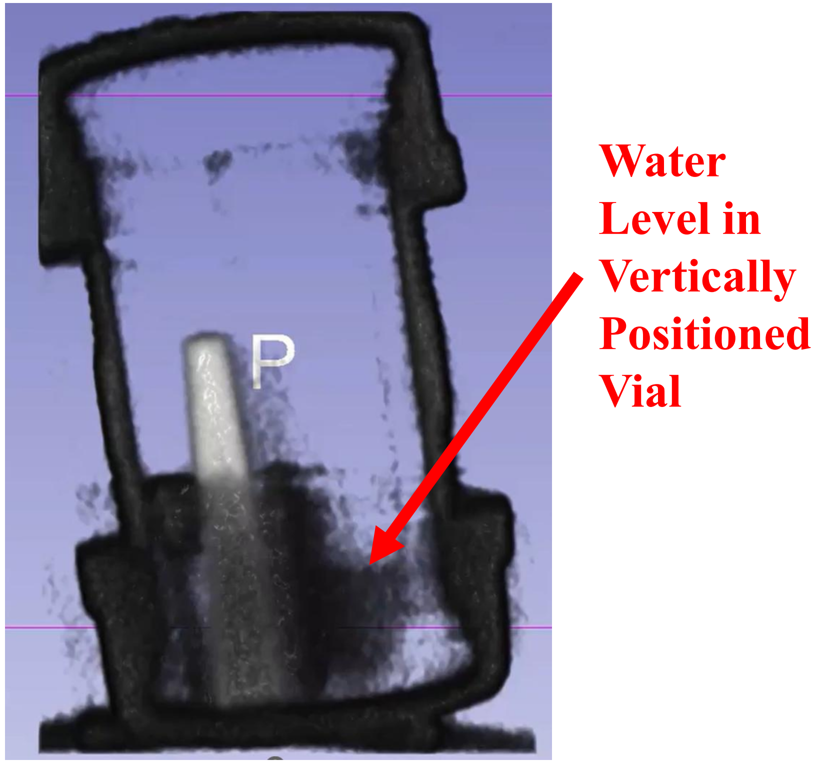


Figure 26: The 10 mL water level in the third pipe nipple is visible through a lead blanket and multiple layers of lead.

Conclusion

- The 7 MV betatron system **successfully visualized the different materials** within the containment vessel through lead and multiple layers of steel **with a non-optimized system**
- Time for data acquisition:
  - Stitch Image Time ~15 min
  - CT Acquisition Time for **360 Images ~45 minutes**
- Among the reconstruction methods, FBP offered the fastest execution time but exhibited significant noise, similar to SART. ASD-POCS emerged as the most effective approach for reducing noise while preserving resolution
- **Integration of X-ray active interrogation with SGS** improves the accuracy of DOE legacy waste classification, minimizing the need for manual handling of drums where SGS alone is insufficient
  - Improves safety, ensures regulatory compliance, minimizes classification errors, and lowers overall disposal costs
- Future Work:
  - With a dedicated system designed for this application, CT scan times are expected to be **reduced to 10–15 minutes**
  - **Partial Angle Tomography**

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References

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[3] S. Patra and C. Agarwal, “Segmented gamma-ray assay of large volume radioactive waste drums containing plutonium lumps,” *Applied Radiation and Isotopes*, vol. 153, p. 108827, 2019.

[4] W. Gu, K. Rao, D. Wang, and J. Xiong, “Semi-tomographic gamma scanning technique for non-destructive assay of radioactive waste drums,” *IEEE Transactions on Nuclear Science*, vol. 63, no. 6, pp. 2793–2800, 2016.

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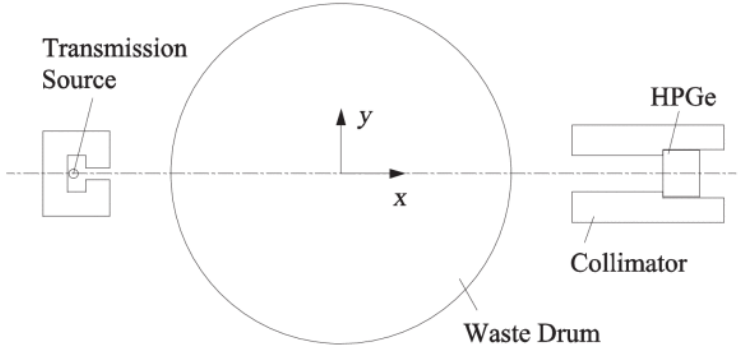
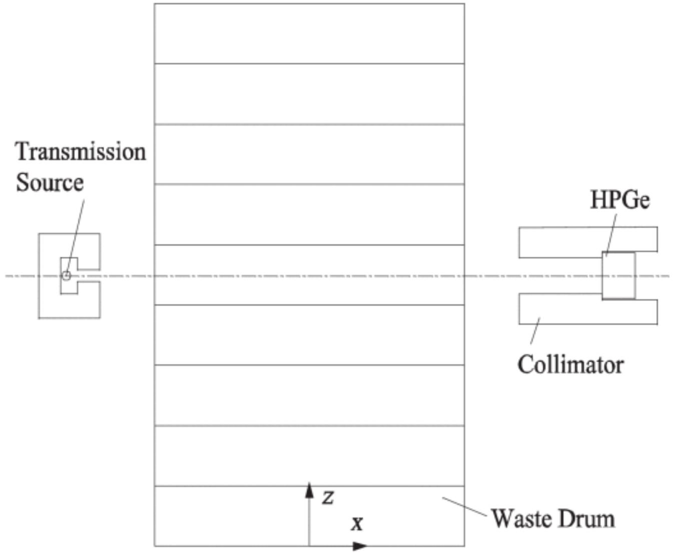
Tomographic Gamma Scanning (TGS)

- TGS is an assay technique that improves upon SGS by identifying radioactive material in non-uniform waste drums
- The drum **rotates** and **translates** during the scan for multiple angles
- Collimated gamma beam passes through the drum and is measured by a detector
- Reconstructs **3D distribution** of radioactive material
- Locates **hot spots** and estimates **activity**
- Can take between **30 minutes to 2 hours or more** per drum depending on:
    - Number of axial slices
    - Detector efficiency
    - Drum activity level



(a) Layout in x-y plane



(b) Layout in x-z plane

Figure 3: Schematic of the TGS scanner, illustrating the system's ability to rotate and translate the drum to acquire multiple viewing angles.*

* W. Gu, K. Rao, D. Wang, and J. Xiong, "Semi-tomographic gamma scanning technique for non-destructive assay of radioactive waste drums," *IEEE Transactions on Nuclear Science*, vol. 63, no. 6, pp. 2793–2800, 2016.

X-Ray Imaging Applications to Solve SGS Limitations

- X-ray imaging **reveals the internal structure** of a waste drum
    - Provides a density map of the drum, necessary for unknown legacy waste
    - Visually locates dense regions that SGS misses
- Quantifies lump properties
    - Including **size**, **shape**, and **position**
- Prevention of over- or under-correction
    - Under-correction: When large lumps are missed
        - **Prevent safety issues**
    - Over-correction: When density is overestimated
        - **Save money** by reducing the waste classification

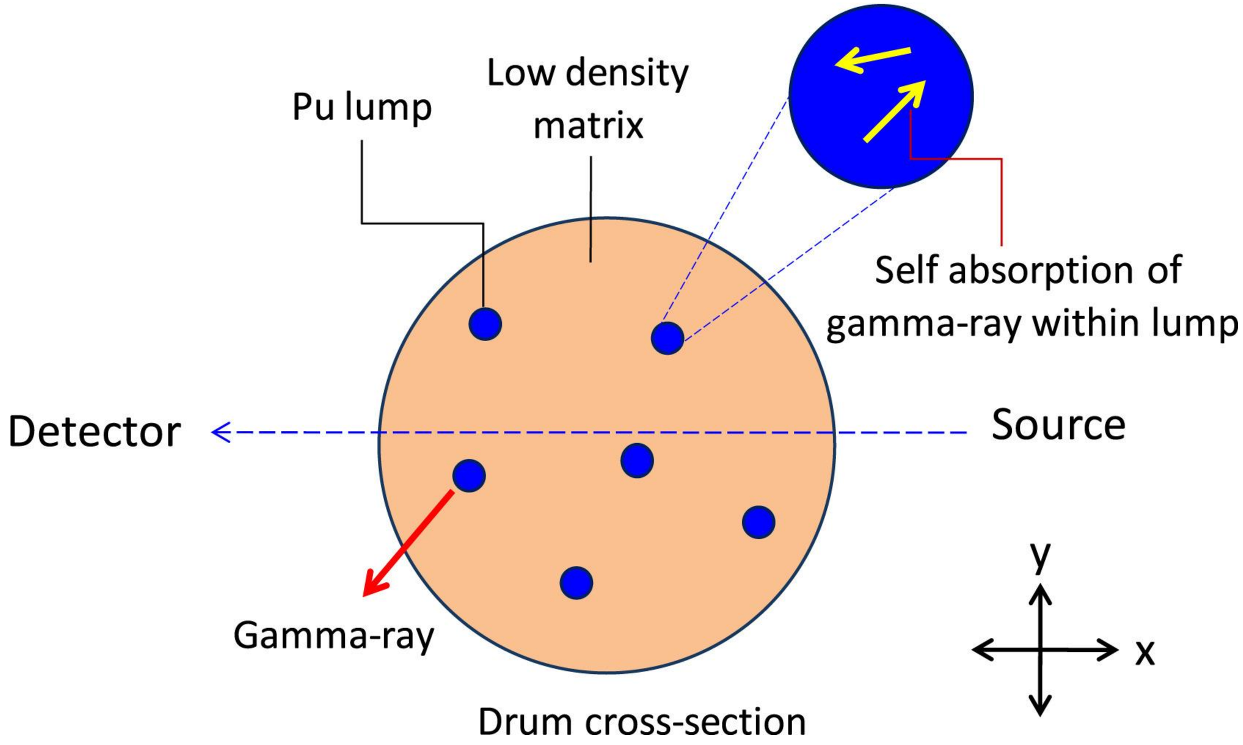


Figure 4: SGS implements an attenuation correction using an outside source, which can often miss dense, localized Pu lumps, causing an underestimation of the Pu mass inside the drum.*

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* S. Patra and C. Agarwal, “Segmented gamma-ray assay of large volume radioactive waste drums containing plutonium lumps,” *Applied Radiation and Isotopes*, vol. 153, p. 108827, 2019.

Reconstruction Algorithms

Filtered Back Projection (FBP)/Feldkamp-Davis-Kress (FDK) Methods

- Analytical methods
- **Fast** and **widely used**
- FBP: Commonly used in parallel-beam or fan-beam CT
    - Applies a frequency filter to balance resolution and noise
- FDK: An extension of FBP, but designed to handle cone-beam geometry
- Selected **FBP assuming a cone-beam geometry** due to limited time availability of the drum and computational constraints

Simultaneous Algebraic Reconstruction Technique (SART)

- **Iterative** Reconstruction Technique
- Uses direct additive updates to the image estimate
- Known for **robustness to noise** and **relatively fast convergence**
- Selected for relative simplicity

Adaptive Steepest Descent Projection Onto Convex Sets (ASD-POCS)

- **Iterative** Reconstruction Technique
- More advanced method that uses **total variation (TV)**
    - Reduce noise and improve image quality
- **Beneficial for limited data sets** by improving clarity and preserving important structural information
- Selected for its effectiveness in reconstructing high-noise data sets
- **Requires careful parameter tuning**

CT Output Comparison of FBP, SART, and ASD-POCS Reconstruction Algorithms

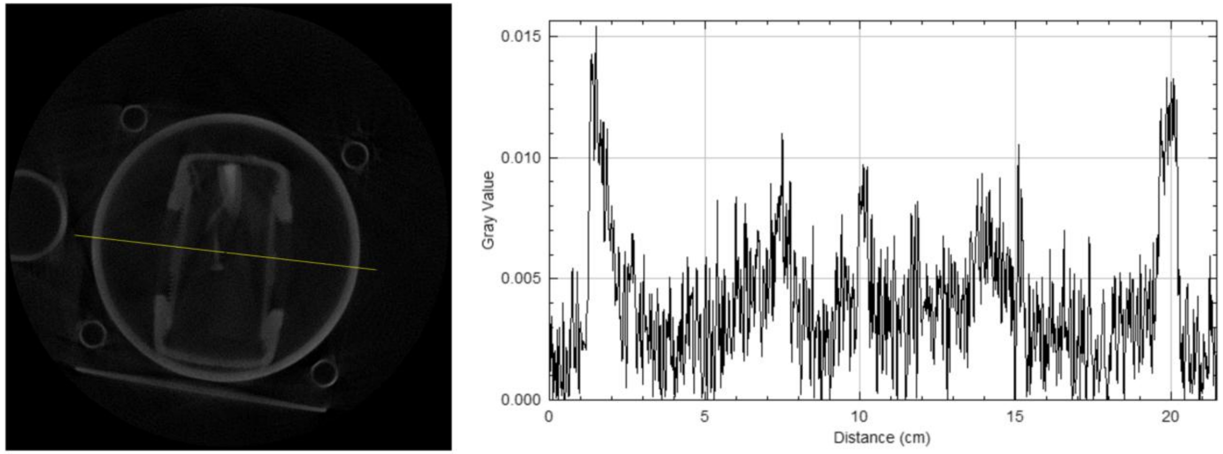

Figure 11: Slice 760 (left) Line Profile (right) using **FBP**

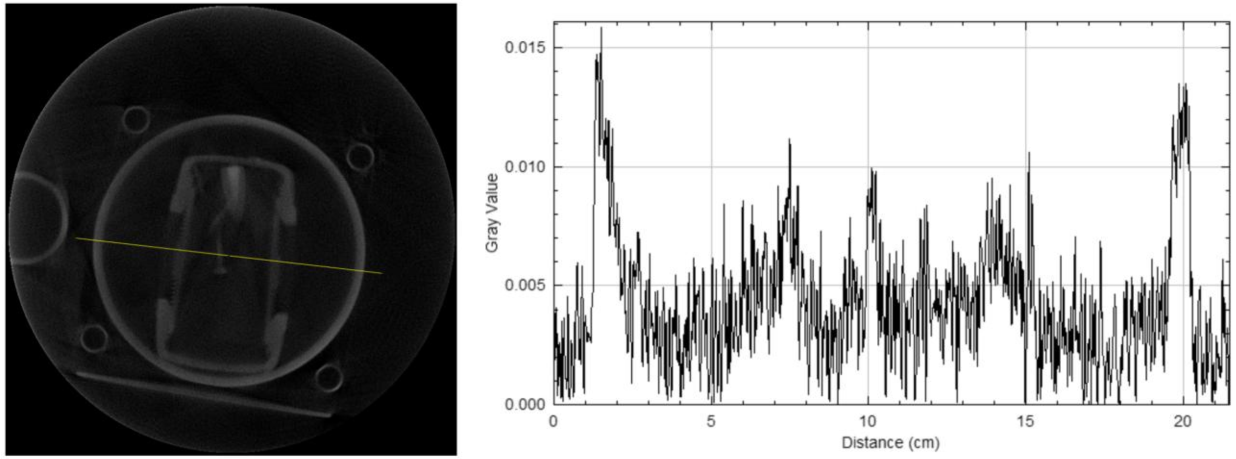

Figure 12: Slice 760 (left) Line Profile (right) using **SART** (20 iterations)

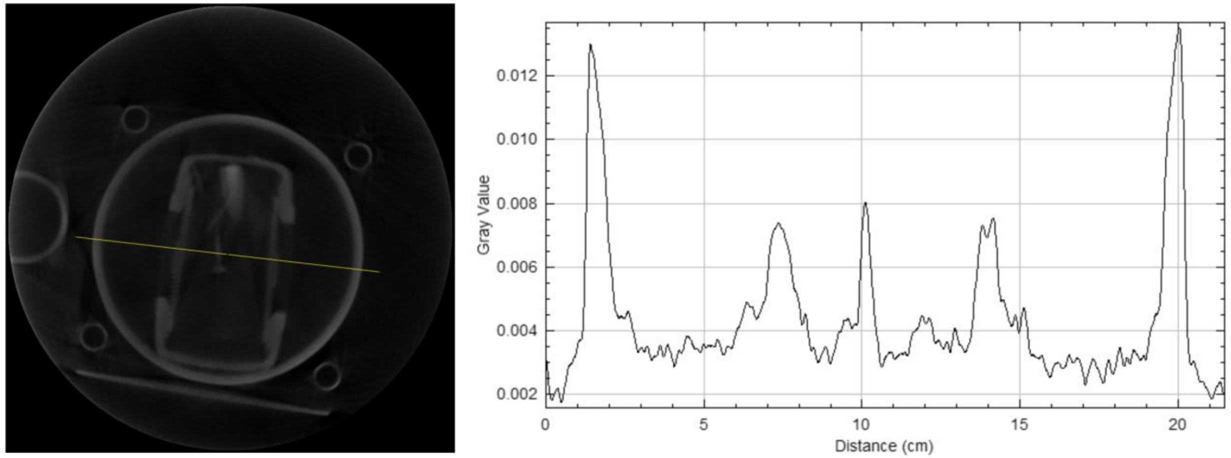

Figure 13: Slice 760 (left) Line Profile (right) using **ASD-POCS** (15 iterations)

- FBP reconstruction: Fast execution, but with moderate amounts of noise
- SART reconstruction: Similar noise to FBP; slower due to iterative updates
- ASD-POCS reconstruction: Preserves image detail with reduced noise; smoother output due to TV regularization.