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Connecting Visionaries in Radiation Safety, Science and Industry

MIRION Connect 24

Annual Users' Conference

July 29 - August 2 | Omni Dallas Hotel, Dallas, TX

MIRION TECHNOLOGIES

Themes

1. Overview supporting NDA technologies
2. Accuracy Improvement
3. Flexibility of Deployment

Innovative Technologies for D&D

Patrick Chard

Director – Application Support, Systems & Services

Mirion Connect | Annual Users' Conference 2024

Dallas, Texas

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D&D APPLICATIONS OVERVIEW

PRE SHUTDOWN

- Assessment of costs
- Radiation inspection of the facility
- Modeling of scenarios

SHUTDOWN OF FACILITY

- Evaluation of contaminated areas
- Mapping of large areas and walls

BUILDING DEMOLITION

- Rough sorting of rubble and debris
- Sorting and characterization of liquid and solid wastes

CLEAN UP TRANSPORT & STORAGE

Verification of wastes before transport & storage

FINAL VERIFICATION

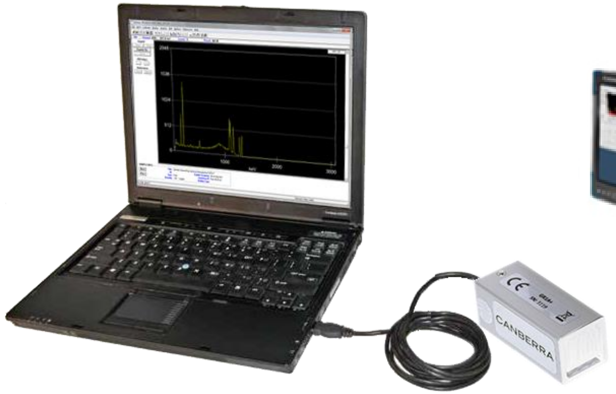
Final status measurement before returning the site to public

Workers and Environment protection

- *Comprehensive range of on-site environmental monitoring and laboratory sample measurements*
- *Radiation protection of workforce (ALARA) and sample characterization*

NDA System Types - Gamma

- Using gamma-rays:
  - Gross gamma counting
  - LRGS (NaI, Plastic Scintillator)
  - HRGS (HPGe)
  - MRGS (CZT)
  - Gamma Imaging



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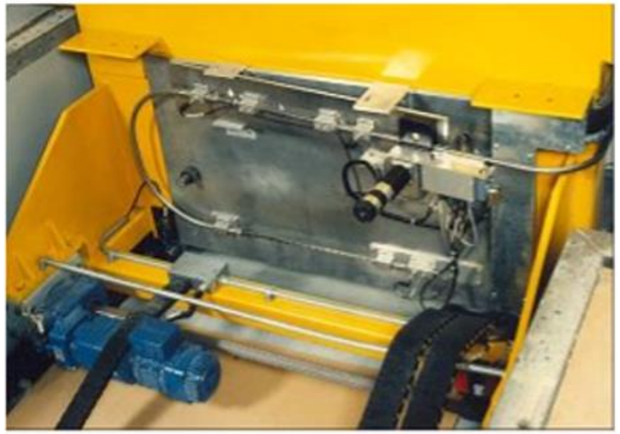
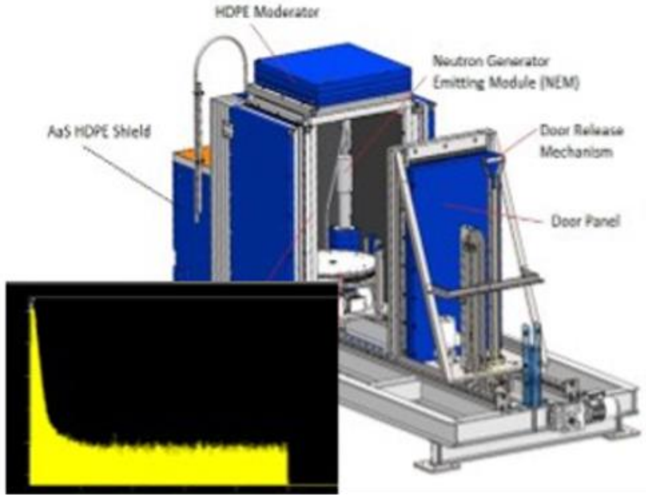
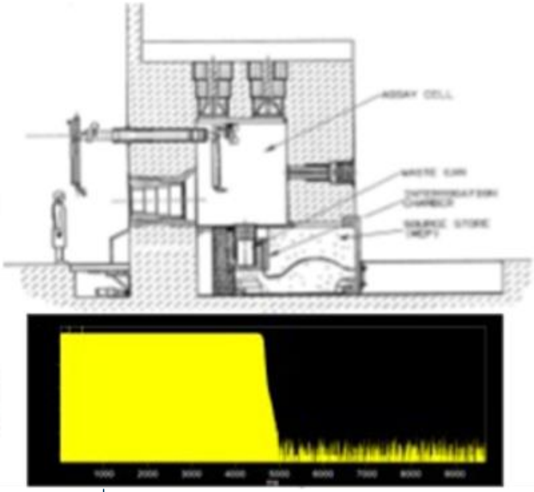
NDA System Types - Neutron

- Using Neutrons
  - Total neutron counting
  - Passive neutron coincidence (for Pu)
  - Active neutron techniques (for U or Pu)
    - Active well
    - Cf-Shuffler
    - DDA







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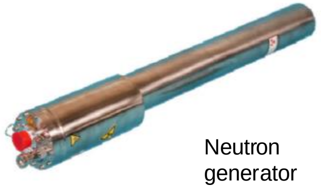
Technology Building Blocks

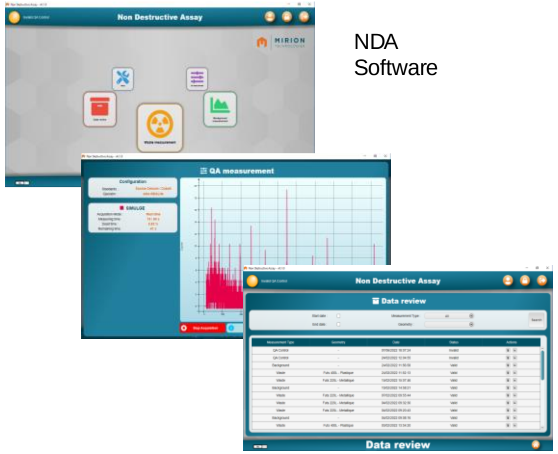
Real-Time X-Radiography



Neutron generator

microGe on Boston Dynamics Quadruped

RoboCount mobile HRGS



NDA Software

Complementary technologies from outside partners / suppliers

- **Outside laboratories**
- **X-Radiography**
- **n sources & generators**

- **Robotics**
- **Specialist mechanics**

Detection → **Control, Electronics & processing** → **User interface HMI**

- 3He tubes
- Alternative n detectors
- γ detectors: Ge, NaI, LaBr, CZT, Plastic scintillators

- Neutron analysers (Shift Registers)
- Amplifiers for n detectors
- Mixer units
- Physics methods, algorithms & IP
- Licensed analysis codes
  Conveyors & Automation
- Electrical Engineering, sw & Physics experts

- Software coding for physics algorithms
- User interaction with system
- Data reporting
- Data storage

Content

ACCURACY IMPROVEMENT

- Complimentary technologies
- Advanced ISOCS tools

DEPLOYMENT FLEXIBILITY

- Modelling
- Robotics / Automation

Complementary Technology

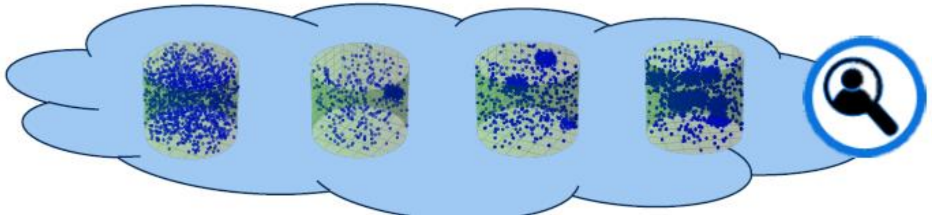
Gamma NDA Systems

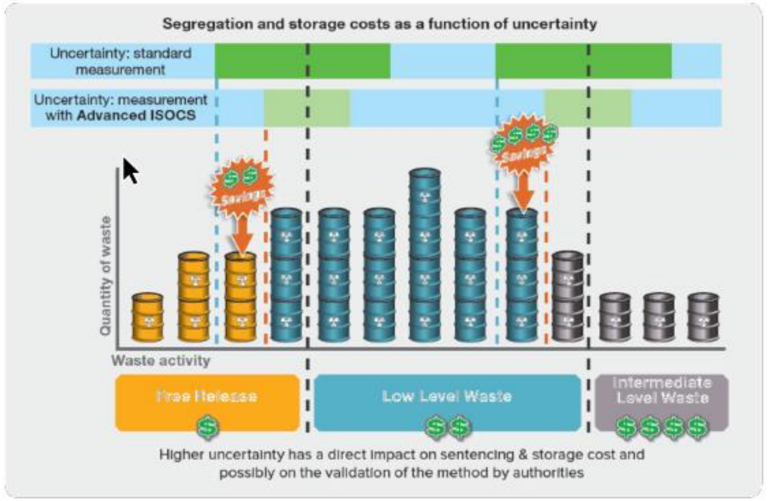
Key driver in waste assay :

- Avoid over-sentencing
  => Reducing the uncertainty (TMU)

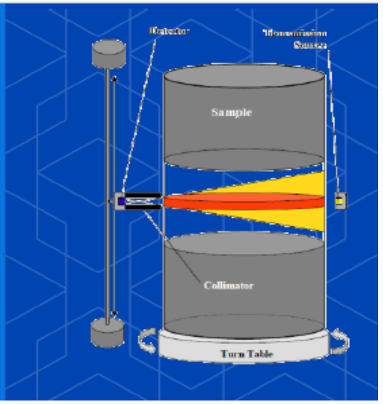
Main uncertainty components:

- **Source distribution** in the drum
- **Matrix distribution** in the drum

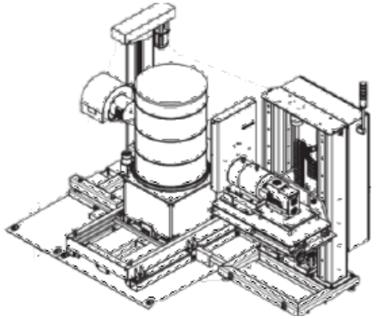




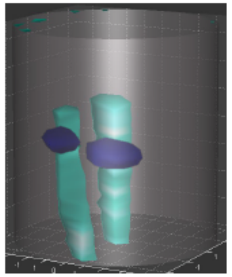
Gamma NDA Systems with transmission source

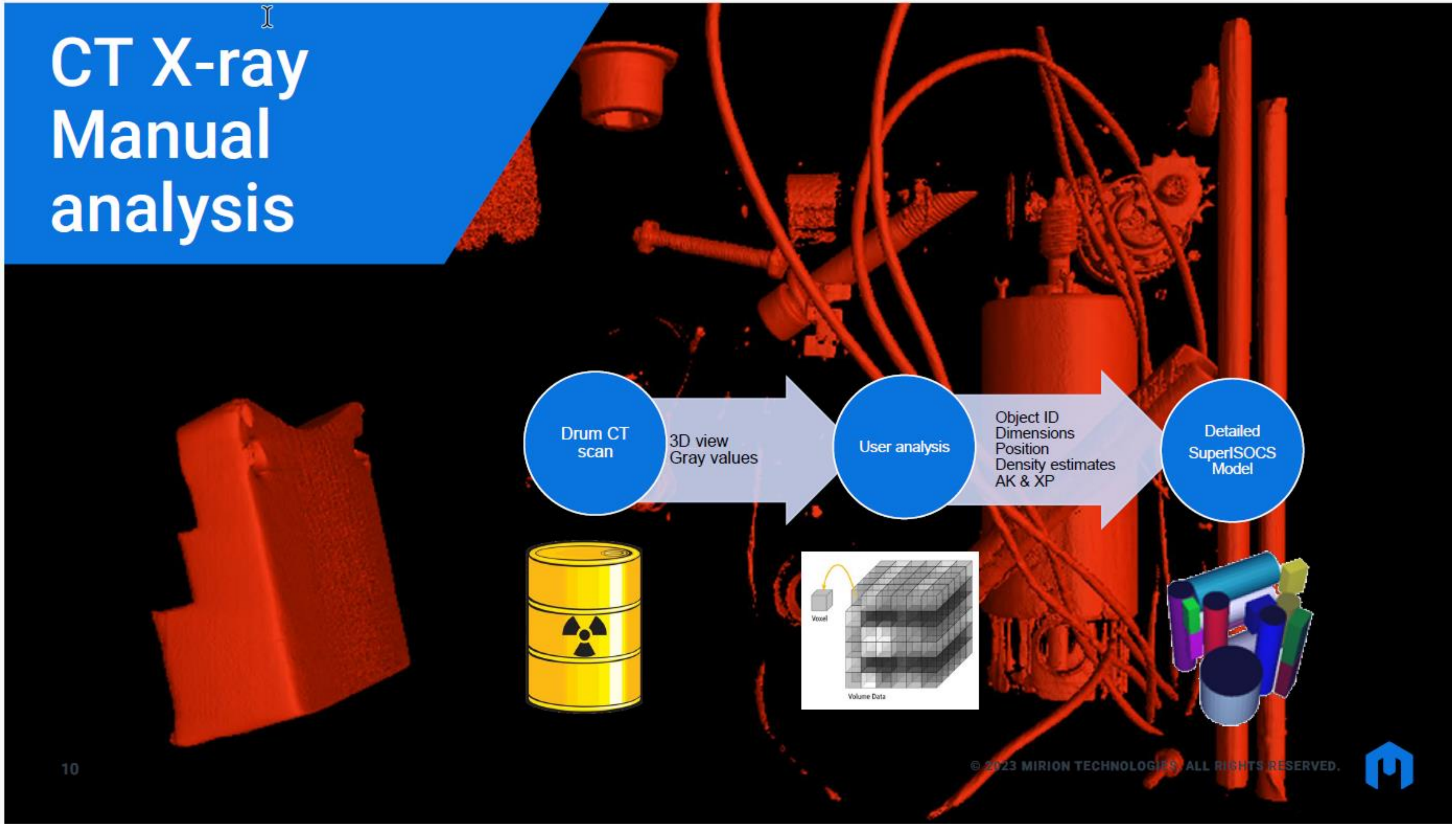



Modular SGS Segmented Waste Assay Systems



- Segmented Gamma Scanner ➡ Reduces uncertainty from activity and density vertical heterogeneity
- Tomographic Gamma Scanner ➡ Greatly improves uncertainty on both activity and density distribution (3D)




CT X-ray
Manual
analysis
Drum CT
scan
3D view
Gray values
User analysis
Object ID
Dimensions
Position
Density estimates
AK & XP
Detailed
SuperISOCS
Model
Voxel
Volume Data
10
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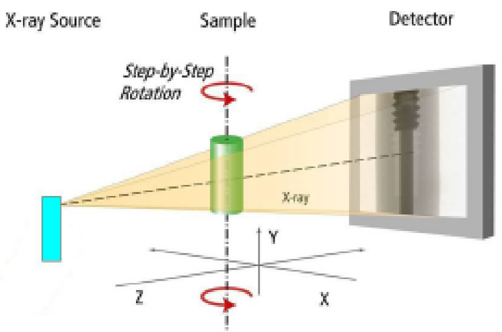
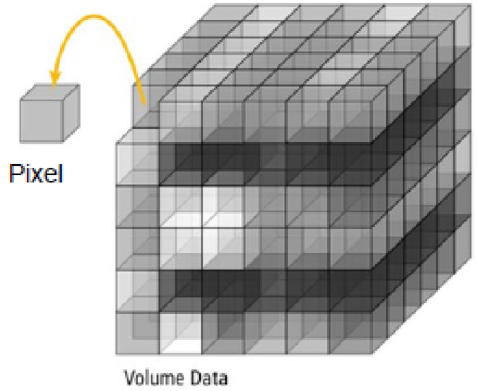
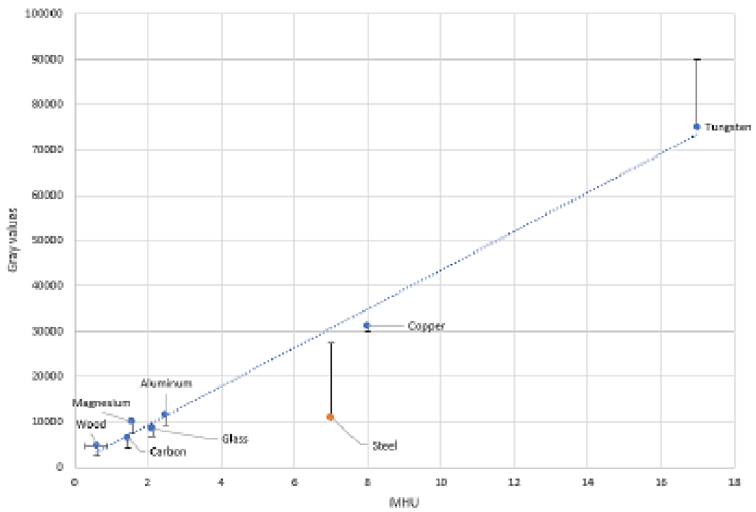
CT X-ray : an attenuation estimate





- Outputs 3D pixel map of gray values (relative X-ray attenuation) :
  - Very **fine spatial resolution** (sub-mm)
  - Relation between gray value and material/density
    - *Varies with CT system setup (Energy/filters/...)*
    - *Needs to be characterized*
    - *Can provide **equivalent material/density with similar attenuation***



Test drum Creation & Scan

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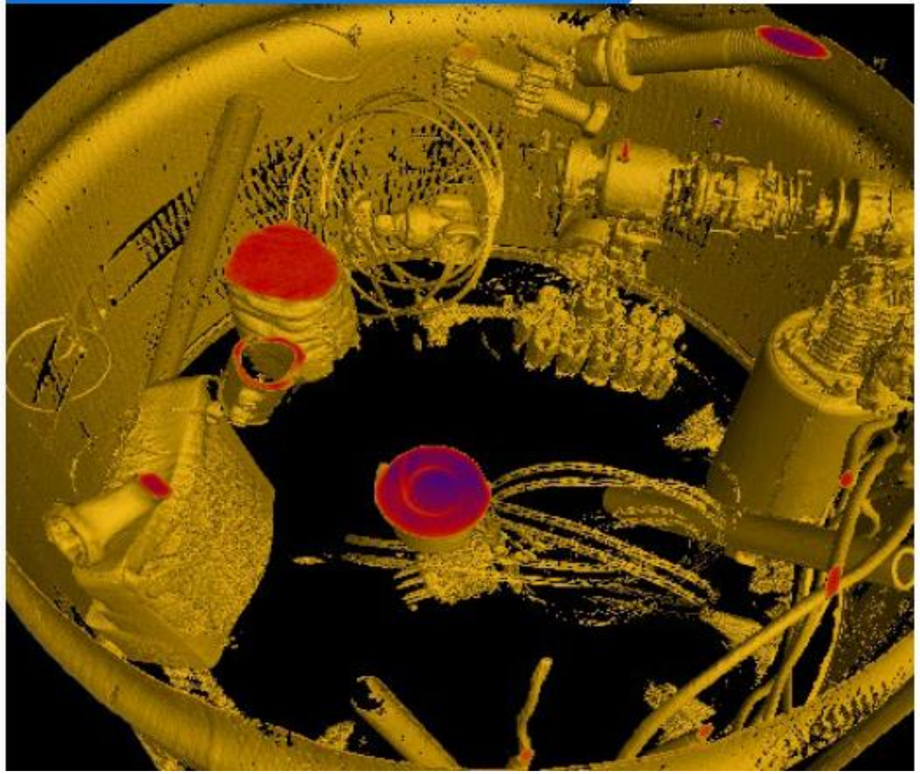
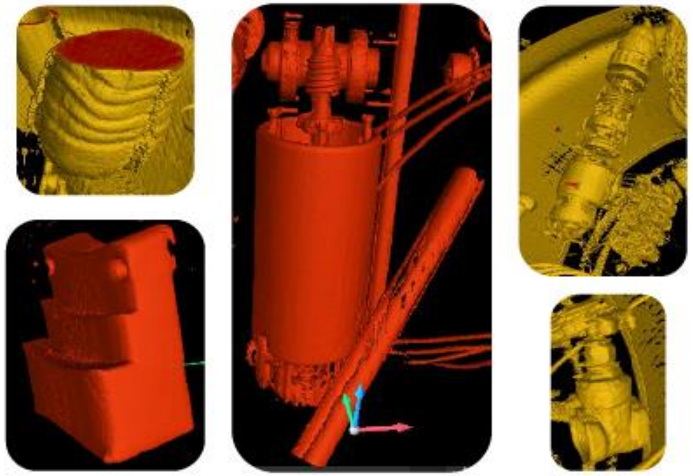
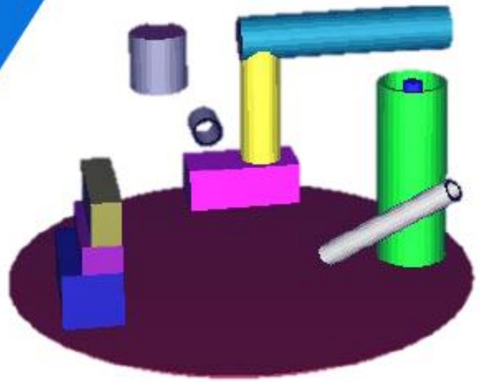
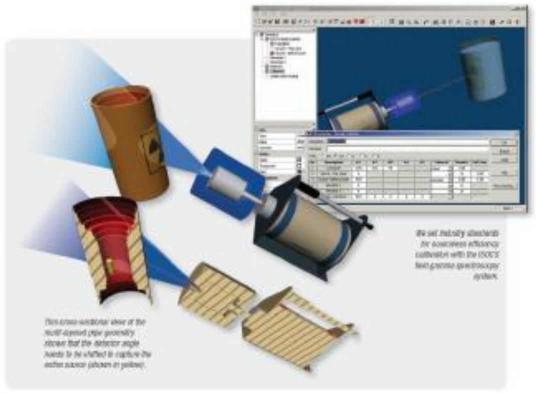
User analysis

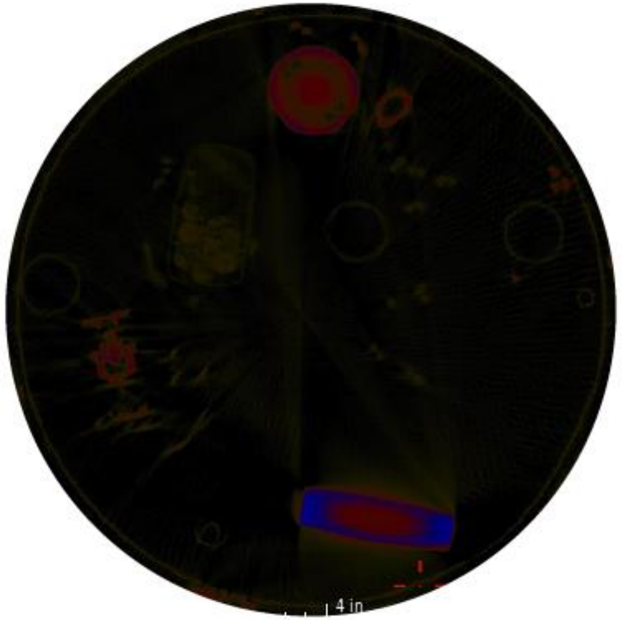




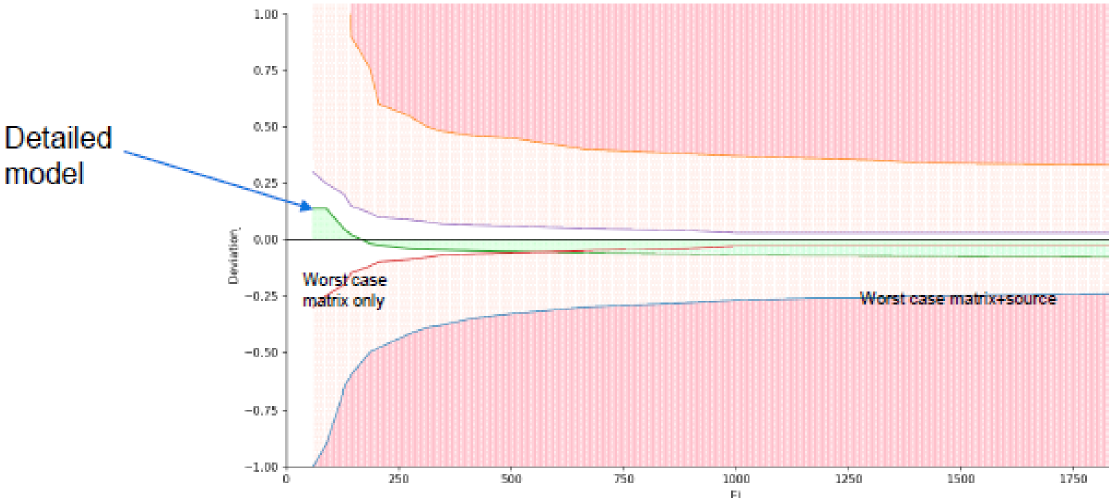
Detailed SuperISOCS model







Use for gamma analysis



Activities evaluated

with **efficiency curve** based on :

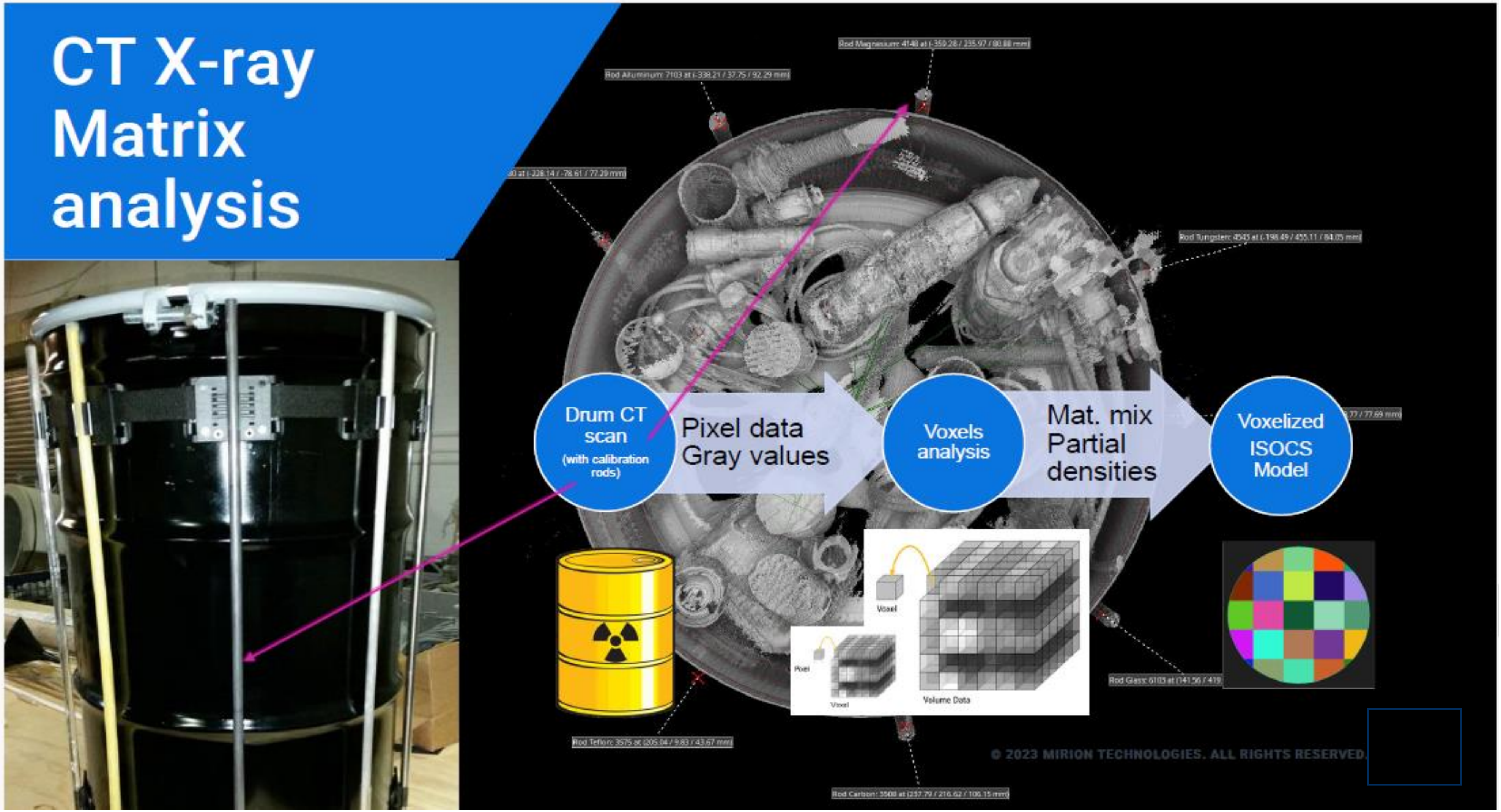
- Observed geometry
- Equiprobable distribution of source (in photons/s/g) among items and matrix

Bias correction (compared to homogeneous case):

- **up to 14% bias**
- higher than worst case a *priori* underestimation for matrix heterogeneity (Ei>662keV).

TMU range :

- slightly improved
- but source position uncertainty (main component) considered unchanged


CT X-ray
Matrix
analysis
Drum CT scan
(with calibration rods)
Pixel data
Gray values
Voxels analysis
Mat. mix
Partial
densities
Voxelized ISOCS Model
Voxel
Pixel
Volume Data
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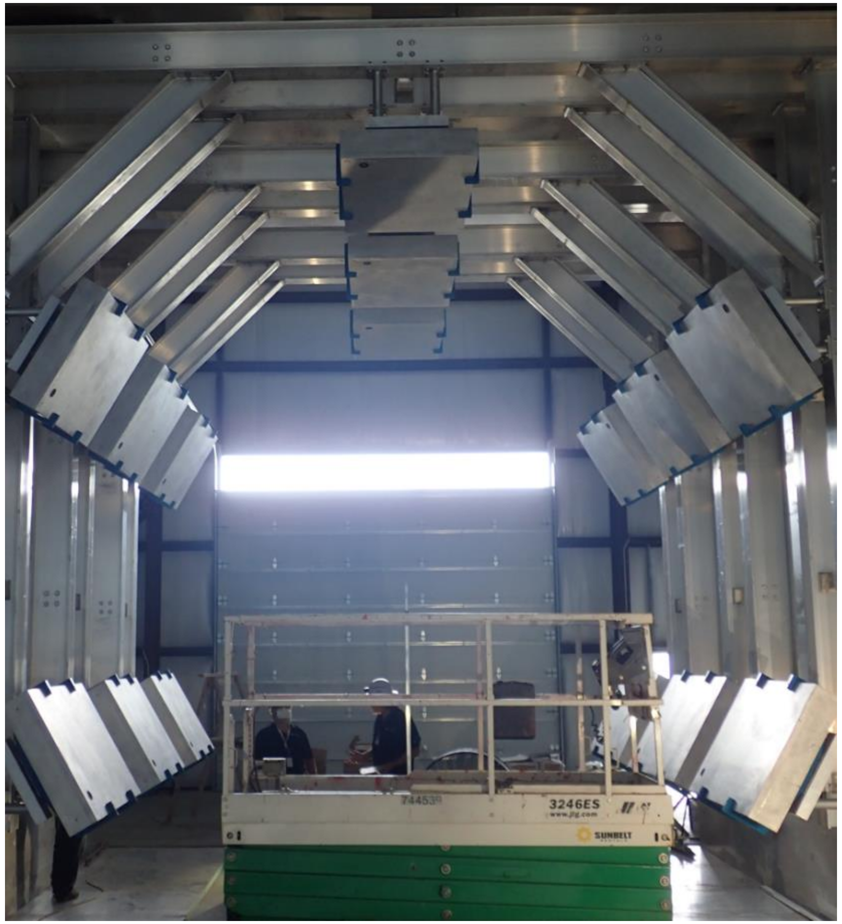
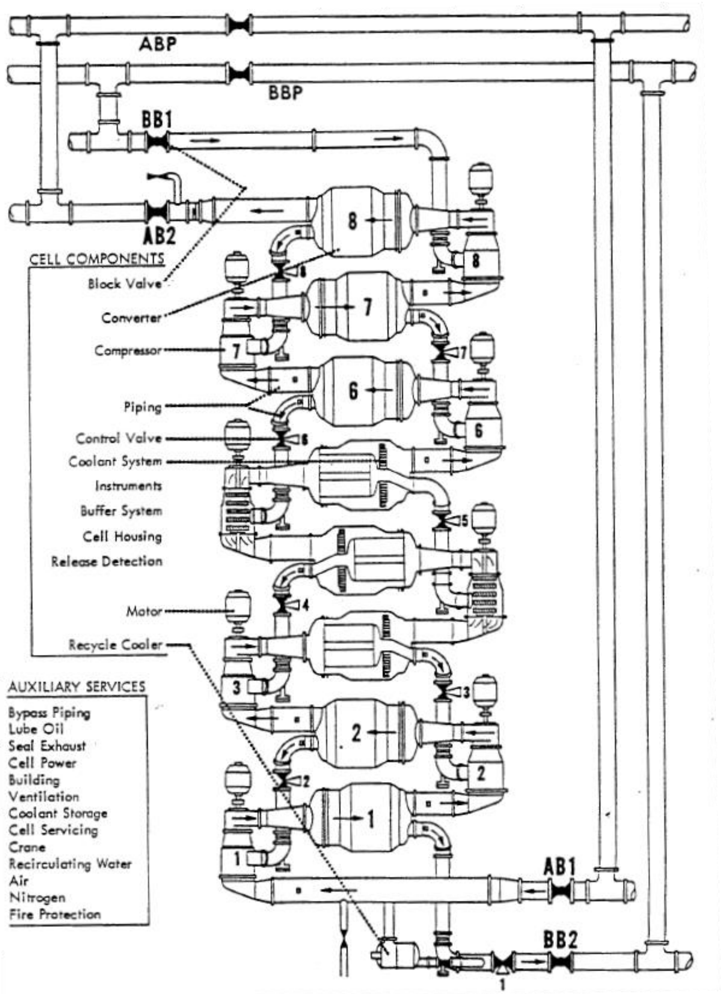
“ISOCS for Neutrons”



- The LINAS is a large, shielded, passive neutron detection system used for quantifying the holdup mass in plant equipment.
- The system was built for the Paducah Gaseous Diffusion Plant (GDP) cascade equipment up to 13.5 feet (~4 meters) in diameter and 24 feet (~7 meters) in length.
- Prior to disposition, the extracted plant equipment must be characterized for fissile (U-235) content



- Consists of cells containing several **large** pieces of plant equipment.
- Each cell contains a closed system consisting of compressors, converters, coolers, gate valves, pipes, *etc*.
- Heated UF6 gas is "forced" into the vacuum but kept less than 1 atm.
- The converters contain a permeable nickel membrane (barrier) where the forced UF6 gas separates **U-234 and U-235 from U-238**.
- There are **100's of cells** in a single building (step-wise fractional increase of the enrichment)
- The series of cells is called a cascade
- Process Knowledge is known (enrichment, isotopics and/or U-235:U-234 ratio).

Deposits of UO2F2

LINAS Data Quality Objectives (DQOs)

- Accommodate objects (plant equipment) as large as the ‘000’ converter and objects as small as 24” diameter pipe and 20’ intermodal and Sealand waste containers.
  - Objects will be transported via large carts with support cradles and will be included in the measurement
- **U-235 Minimal Detectable Activity (MDA) of 25 grams or less** for any given object and from any cascade
- **Total Measurement Uncertainty (TMU) of 35% or less, 1-sigma**, for any given object.
- Uniform detection efficiency as much as possible over object volume
- Throughput capability of 10 or more objects per day
  - Target measurement time of 30 minutes.
- Service period of several decades

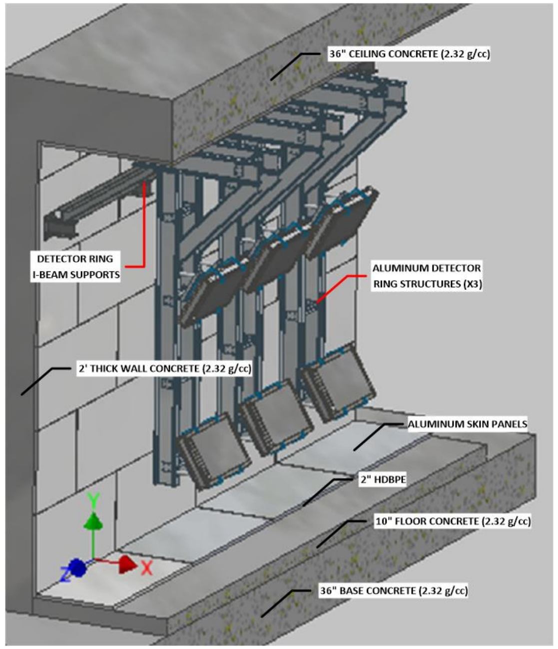
Technical

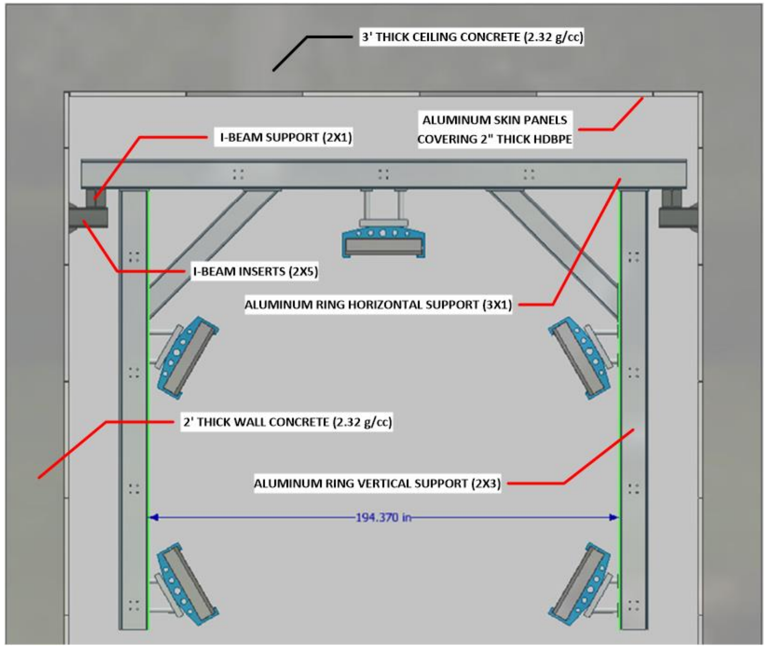
- Cosmic Ray Spallation (CRS) neutron background: Presence of metal
- Metal content also alters the system detection efficiency
- Hydrolyzation impact on assumed neutron-specific activity

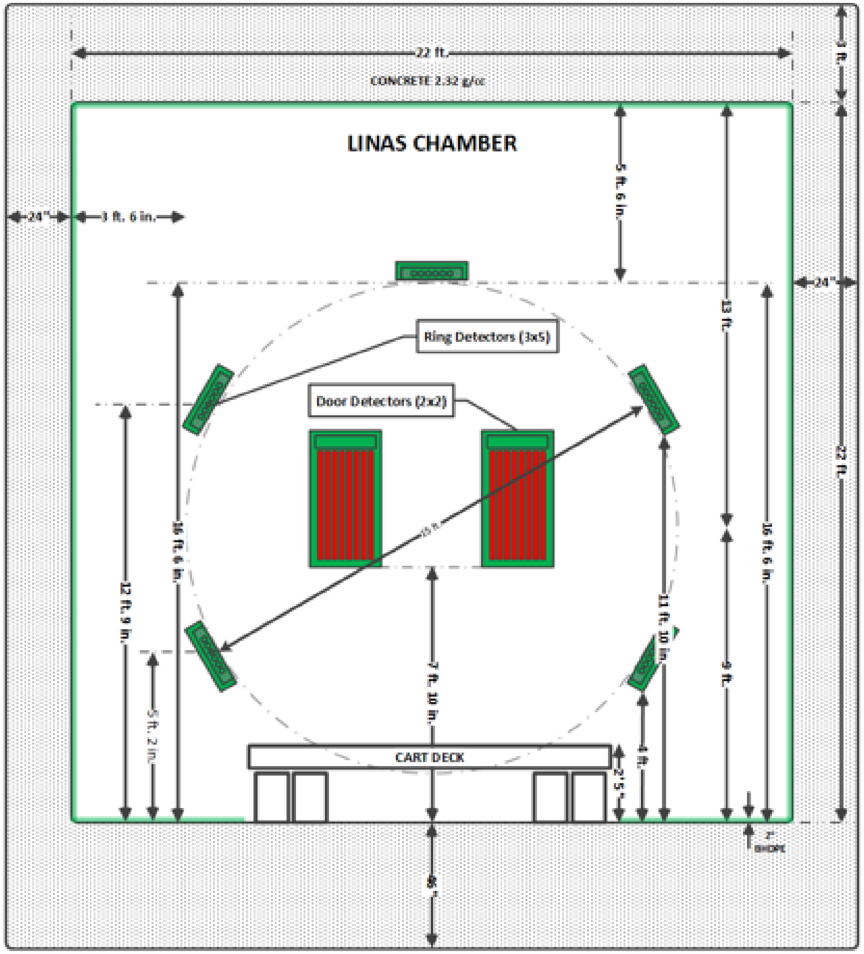
Logistical

- Requires the neutron detection efficiency of each and every plant equipment type, and associated metallic weight, occupying a specified volume and location within the assay chamber.
- MCNP can be cumbersome, time consuming with no simple method for quality control.
- Wide variety of objects requiring a variety of calibrations (and verifications)
- Large-scale measurement campaign: individual objects, surface area, number of objects
- Coordination between multiple vendors and participants

LINAS – Design: Neutron Detection Rings



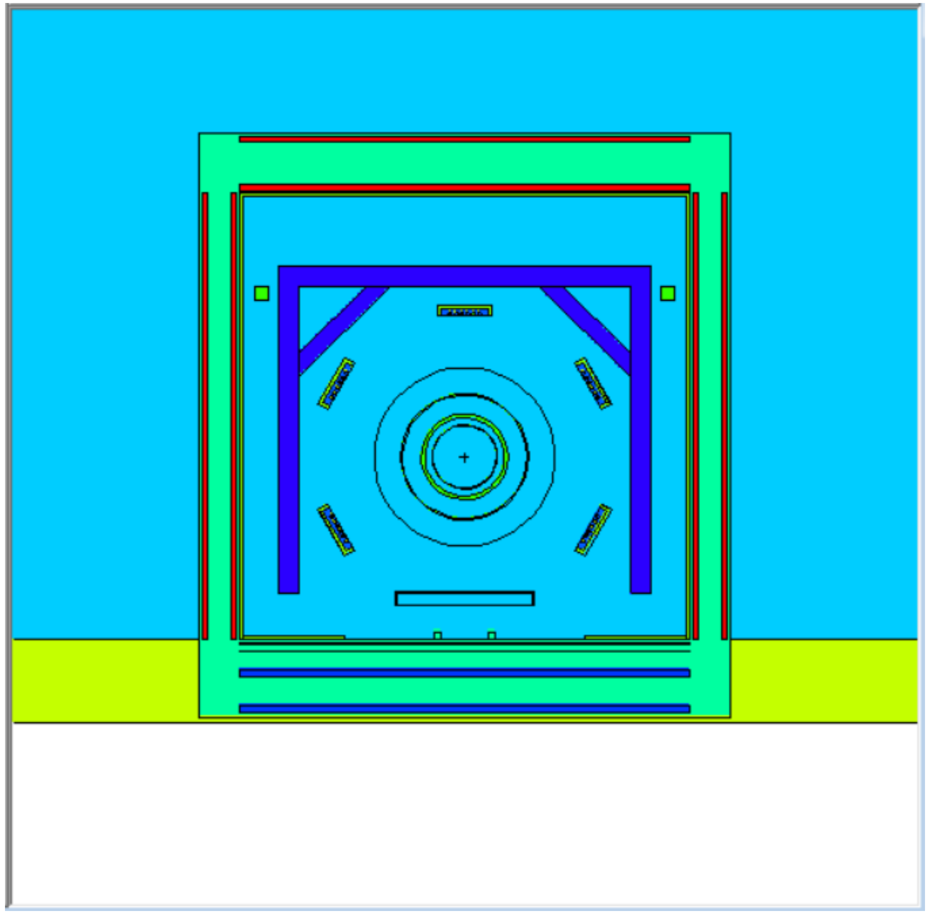




- Neutron detector slabs in three rings – 5 slabs per ring arranged at 60° intervals
- Thick concrete shielding

New Approach for efficiency calibration

- Provide a simplified efficiency generation method that is quality controlled, with the lowest possible Total Measurement Uncertainty (TMU)
- The NeutVox method involves:
  voxelization of the neutron detection efficiency throughout the entire volume of the LINAS chamber
- Applying that technique to generate an efficiency map for any type of plant equipment as well for any object shape and weight that will fit within the LINAS chamber.



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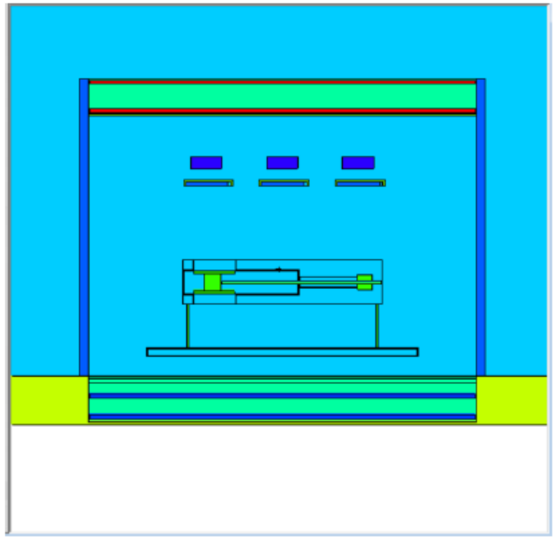
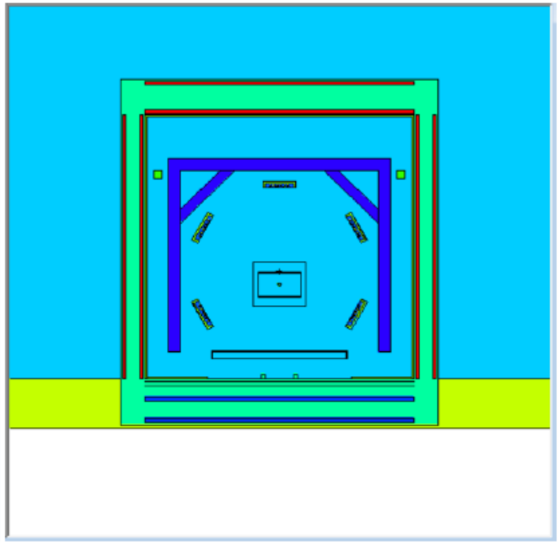
Basis of NeutVox approach

- Complete Pre-characterisation of efficiency by MCNP6.2 for each slab for sources in 3 dimensional voxels (approx. 9000) inside the measurement cavity
- Method to determine summed slabs efficiency for specified source distribution across voxels
- Matrix correction process – to deal with impact of varying density of metal

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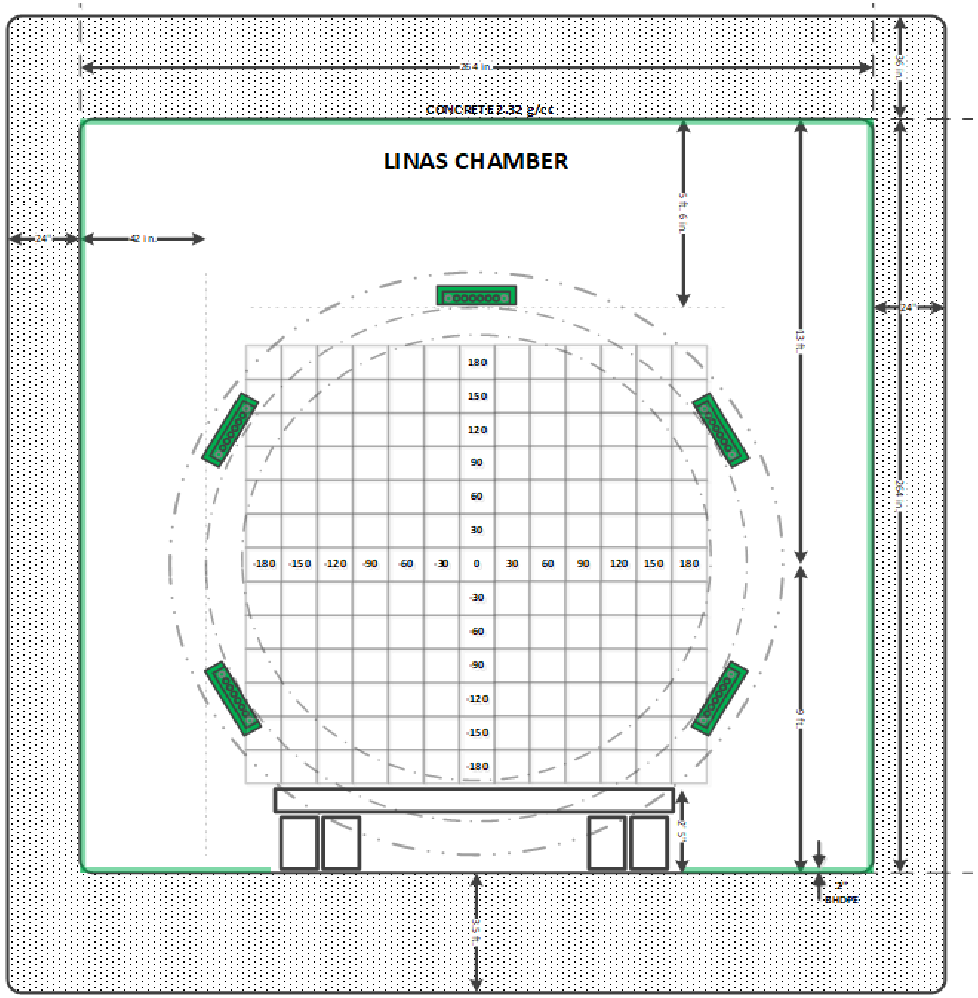
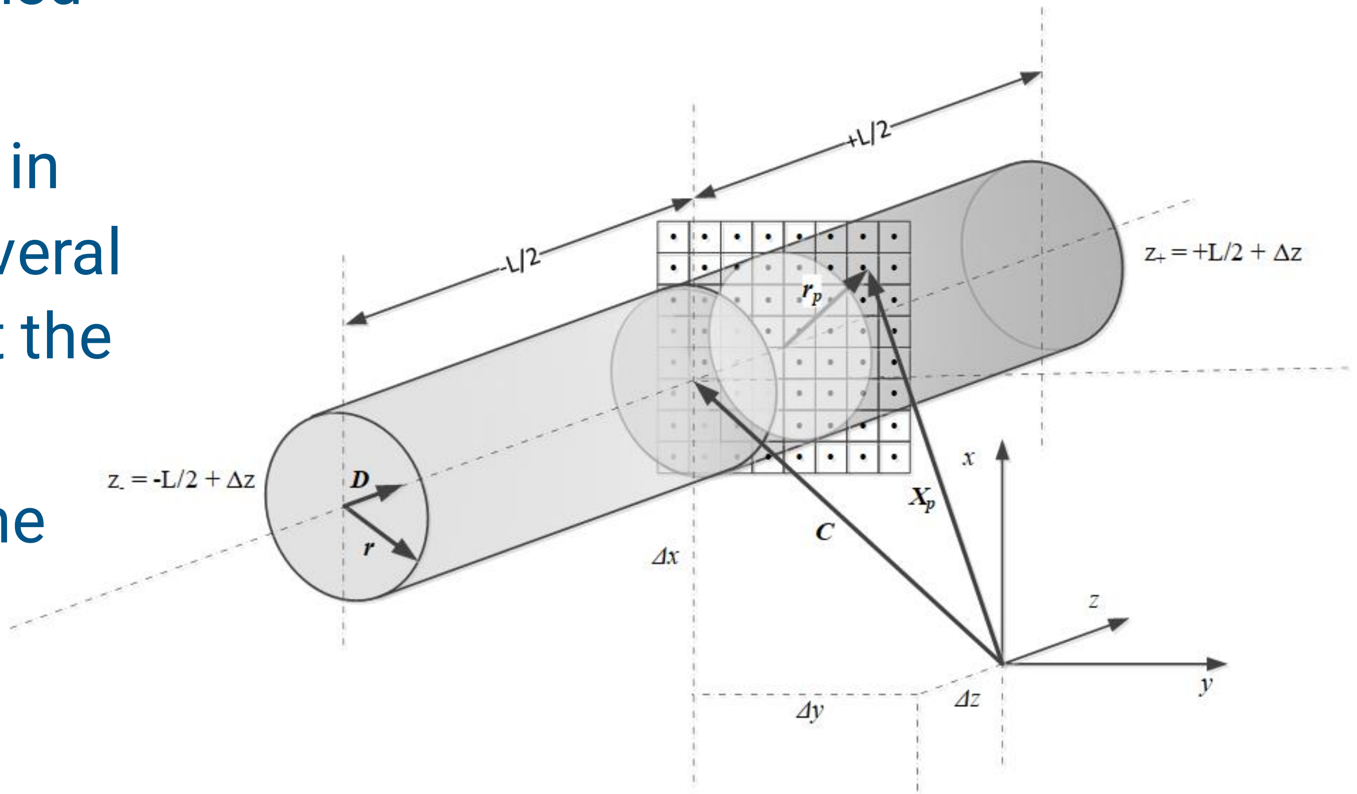


- Cross-section (Z-plane) of the voxel grid within the LINAS chamber.
- The inside circle represents a cross-section of the volume occupied by the largest plant equipment object which is the 000 converter (13.5’ x 24’).
- Each voxel center that is within the 000 converter volume is assigned a zero-density efficiency computed from MCNP.

- Dot-product analysis to determine summed slabs efficiency for specified source distribution across voxels
- Figure to the right shows a cylinder in the LINAS chamber intersecting several voxels. The interest is the points at the voxel centers.
- The dot-product method involves the following two test criteria:
  - Test #1: $z_{-} < \hat{\boldsymbol{D}} \cdot (\boldsymbol{X_p} - \boldsymbol{C}) < z_{+}$
  - Test #2: $\|\boldsymbol{r_p}\| < \|\boldsymbol{r}\|$



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- Compute the fractional volume (v) of the object relative to the 000 converter.
- Compute the average density (ρ) of the object from the gross weight subtracting the cart/cradle weights.
- Table shows the metals matrix efficiency delta as a function of the relative fractional volume and the object average density.
- The metals matrix correction is computed with the parameterization shown below.
- Matrix correction > 1 for objects < 40,000 pounds and < 1 for objects > 40,000 pounds.

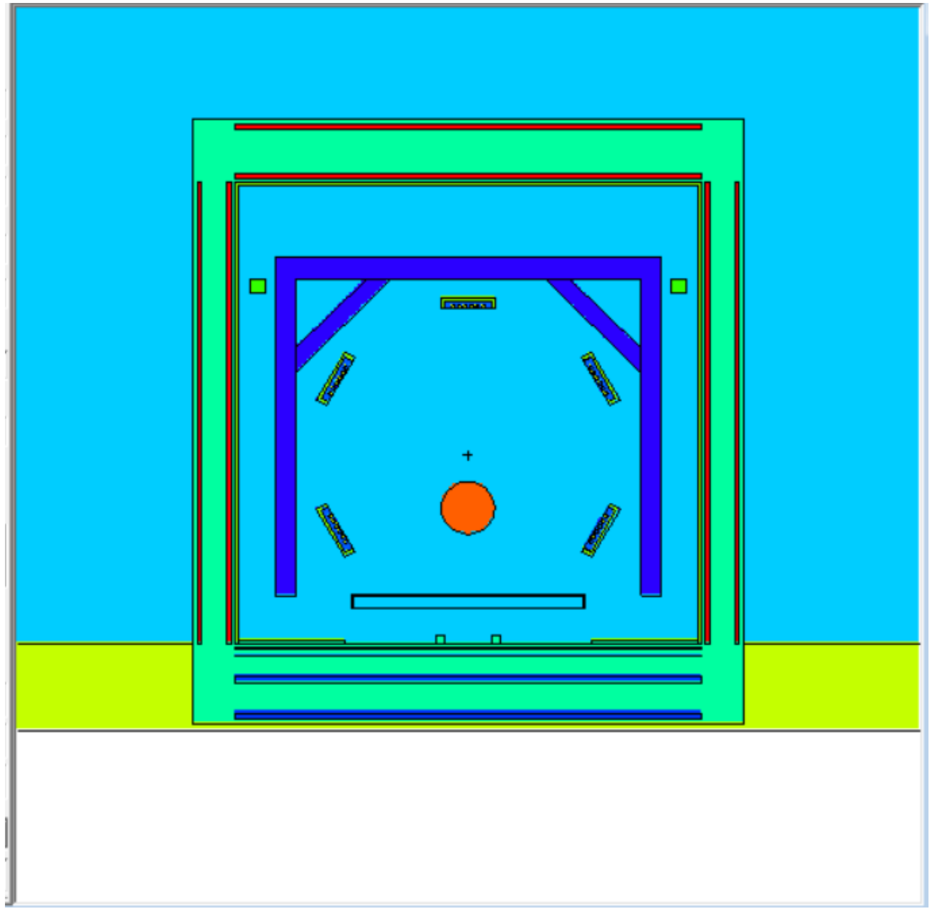
Table 2 Fractional difference in efficiency between the higher-density samples and the 0-density sample.

Density \ Volume	0.125	0.244	0.330	0.422	0.549	0.670	0.849	1.000
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.2	-0.0088	-0.0096	0.0033	0.0101	0.0134	0.0191	0.0296	0.0359
0.4	0.0023	-0.0112	0.0260	0.0285	0.0255	0.0362	0.0470	0.0579
0.6	-0.0041	0.0056	0.0334	0.0469	0.0514	0.0478	0.0662	0.0837
0.8	-0.0027	0.0006	0.0258	0.0458	0.0426	0.0439	0.0646	0.0979
1	-0.0045	-0.0002	0.0307	0.0285	0.0478	0.0389	0.0677	0.0830
1.2	-0.0041	-0.0117	0.0292	0.0270	0.0310	0.0303	0.0413	0.0651

$$f(v,\rho) = \begin{cases} 1 \; if \; v < 0.2 \\ 1 + (v-0.2) * (-0.17429)\rho^2 + (v-0.2) * 0.27422\rho \; if \; v \geq 0.2 \end{cases}$$

Benefits for bulk waste assay

- Concept is similar to ISOCS: but sub-voxel efficiencies are determined by MCNP 6.2 and has the full MCNP6.2 neutron physics
- Allows efficiency calculation for specified source-term variations, using automated and rapid analysis → (results in seconds)
- Provides an uncertainty estimation tool where undefined source distribution and object location distribution can be studied systematically
- Scaleable to other systems / geometries



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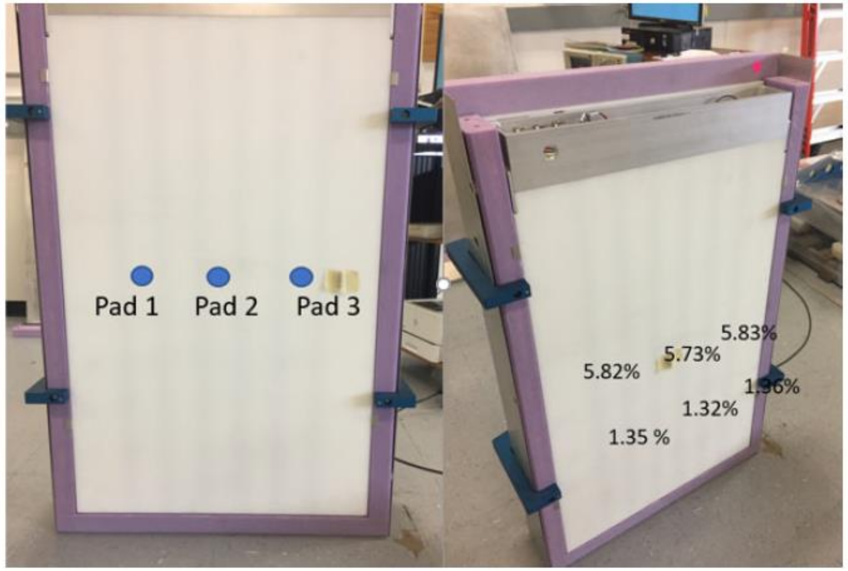
Validation: Slab efficiency characterisation

- Initial slab characterisation with MCNP6.2
- 252Cf source in near-contact and at distance.
- Compare MCNP6.2 with experiment

Number of He-3 counters per slab	Measurement Configuration	Experimental measurement at 29.5 cm, %	MCNP at 29.5 cm, %	Exp./MCNP rel.
Six counters	Concrete floor	3.55	N/A	N/A
	Aluminum table	2.83	2.89	0.98
Eight counters	Concrete floor	4.2	N/A	N/A
	Aluminum table	3.34	3.39	0.99



The blue marks indicate the measurement positions of the neutron source relative to each PAD (Pad 1, Pad 2, and Pad 3). The detection efficiencies were measured with the ^{252}Cf at distances of ≈0 cm and at ≈29.5 cm (six counter slab).

NeutVox validation

- Sample objects modelled as "complete MCNP 6.2 model" and then compared with NeutVox
- Various surrogate items provided for testing

Crushed bundle


Gate valve


OO compressor

TMU analysis

Sample Object	Volume (ft³)	Volume (cm³)	RSD (%)
Large Cylinder (18' x 9')	690	$1.95 \cdot 10^7$	11
ST-90 Box (79" x 46" x 47")	100	$2.79 \cdot 10^6$	3.0
Intermodal (65%) (230" x 85" x 61")	690	$1.95 \cdot 10^7$	11
Intermodal (100%) (230" x 92" x 94")	1150	$3.32 \cdot 10^7$	15
Pipe (19' x 30")	93	$2.64 \cdot 10^6$	7.3
Gate Valve (114" x 43" x 25")	70	$2.05 \cdot 10^6$	3.5
York Recycle Cooler (180" x 80")	520	$1.48 \cdot 10^7$	7.7
Trane Recycle Cooler (147" x 130")	1130	$3.20 \cdot 10^7$	15
10 MW Freezer Sublimer (64" x 49")	71	$2.00 \cdot 10^6$	2.7
20 MW Freezer Sublimer (100" x 58")	150	$4.37 \cdot 10^6$	3.5
00 Compressor (unif.) (155" x 55")	230	$6.62 \cdot 10^6$	4.0
000 Compressor (unif.) (208" x 75")	530	$1.50 \cdot 10^7$	5.8

Impact of source heterogeneity

TMU Contributor	**RSD (%)**
Sample Type & Enrichment (combined)	7
Counting Statistics *	15
Background Variation Correction Factor	1
Modeling	7
Sample Geometry	14
Estimated TMU:	**23**

Example overall TMU budget (30 inch gate valve)

LINAS Results – TMU

TMU Contributor	% RSD
Sample Type & Enrichment	7
Counting Statistics[A]	15
Background Variation Correction Factor	1
Modeling	7
Sample Geometry	14
Estimated TMU:	**23**

$$TMU = \sqrt{\sigma_{ST}^2 + \sigma_E^2 + \sigma_{MODEL}^2 + \sigma_{SIG}^2 + \sigma_{BKGD}^2 + \sigma_{GEO}^2}$$

Sample type - Variations in nSA, e.g., “wet” vs. “dry”, UO2F2 mixing with UF6
Model - Uncertainty in the efficiency attributable to modeling
Geometry - Uncertainty in the efficiency attributable to geometrical variations
:

Target TMU: 35% 1-sigma

[A] The % RSD contribution from counting statistics represents an example value drawn from the V&V measurements corresponding to equipment with a low mass (5.37 g U-235) of depleted uranium (DU) and a count time of 900 seconds.

LINAS – Summary

- Characterizing uranium holdup in large-scale metallic plant equipment at Paducah GDP
- Minimum Detection Activity (MDA)
  - < 25 grams of U-235 (<15 g for most items)
  - Measurement times 600 – 1800 seconds
- Total Measurement Uncertainty (TMU) < 25%
- NeutVox generalized calibration proven and scaleable for many object types and heterogeneous activity

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LINAS & NeutVox– References

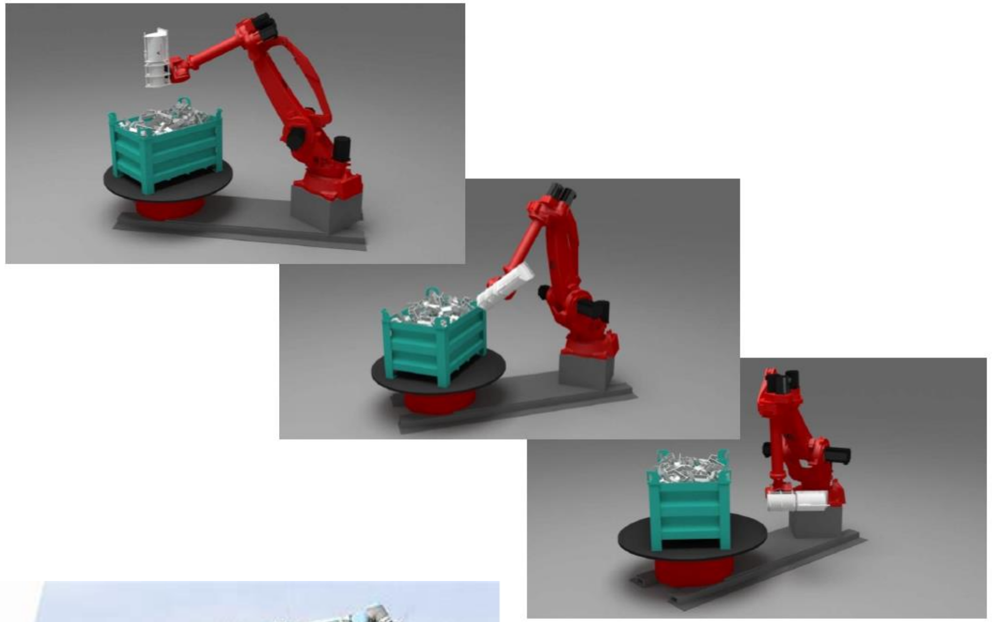
- https://www.energy.gov/em/articles/paducah-completes-first-kind-scanning-facility
- https://www.energy.gov/em/articles/new-paducah-facility-ensure-safe-disposal-process-building-equipment
- Design, Implementation and Validation of the Large Item Neutron Assay System (LINAS) at the Paducah Gaseous Diffusion Plant (PGDP)
  WM2024 conference presentation (March 2024)
- Neutron Efficiency Voxelization Needs for Waste Characterization of Large Plant Equipment Uranium Holdup at the Paducah Gaseous Diffusion Plant (PGDP)
  INMM2024 conference presentation (July 2024)

Robotic NDA deployment

Robotic Deployment – Nothing Fancy

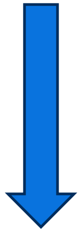
Mount detector on Robot

Usage of proven robotics technology
- Accuracy
- Reliability



New Flexible Robotic Deployment

- Bring the detector to the object



- Improved flexibility for multiple geometries
- Can move detector instead of rotate object
- Allows access to confined areas where cannot remove the objects to assay station
- Building Block Technology Approach
- Industry partnerships for robotics supply

Robotics - Benefits

DuAL RoboCount™ 2020

The project RoboCount was started with the intention of disrupting the current market of industrial radiation measurement by achieving the following:

- decrease the number of sensors necessary to carry out a measurement
- remove the limitation of only being able to measure objects of a specific shape
- remove the reliance on a proprietary OS
- remove the need for conveyors and turntables
- reduce the space necessary for the installation of the system

The aim of the project was to set up a pilot system that would demonstrate the ability to achieve as many of the above-mentioned goals as possible on a limited budget.

2024 developments – “Robotised NDA System”

- Detector scans an object in a programmable way

- The same hardware can scan:

  - Multiple objects
  - Multiple geometries (e.g. far-field, SGS)

- Compatible with Mirion NDA2000 for:

  - PLC interface
  - ISOCS models and collimation
  - Advanced scanning protocols
  - TMU analysis engines

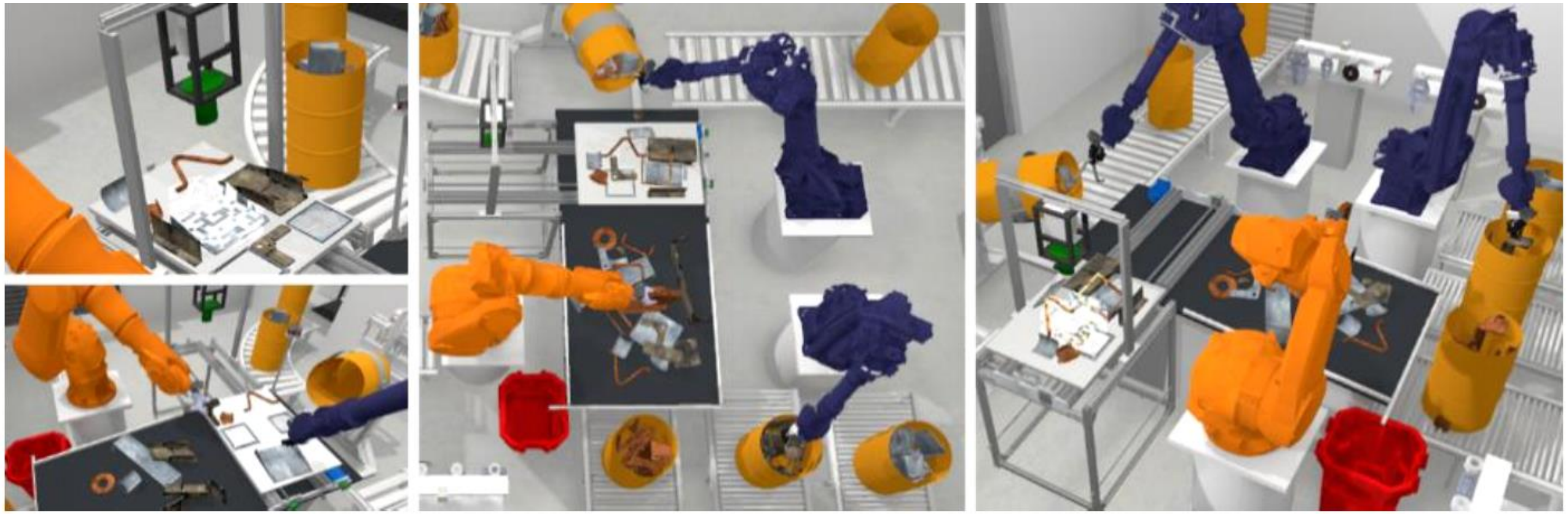
Photo from DUAL

MIRION Connect 24
Annual Users’ Conference

Engage. Explore. Empower.

Combination of 3D mapping and Robotics: Introduced at MC2023

- Establishing Robotics suppliers partners – in industry and academia
- R&D program in Germany with AINT, coupling laser scanning for object recognition, with automated HPGe gamma spectrometry scan and SUPERISOCS



2024 developments – "Waste Sort n Seg"

- 3D camera to identify shape
- LIDAR for dimensioning
- Object Recognition (AI)

- Use Robot arm with detector for "Sort and Segregate"

- And haptic feedback robot for "pick and place"

- Candidate detector = application-dependant:
  - Surface contamination
  - Gamma Spectrometry (LRGS, HRGS, MRGS)
  - Dose-rate

- Integrate Advanced ISOCS ("SUPERISOCS") modelling

Automatic
Autonomous

AINT: KONTEC 2023

Thank you