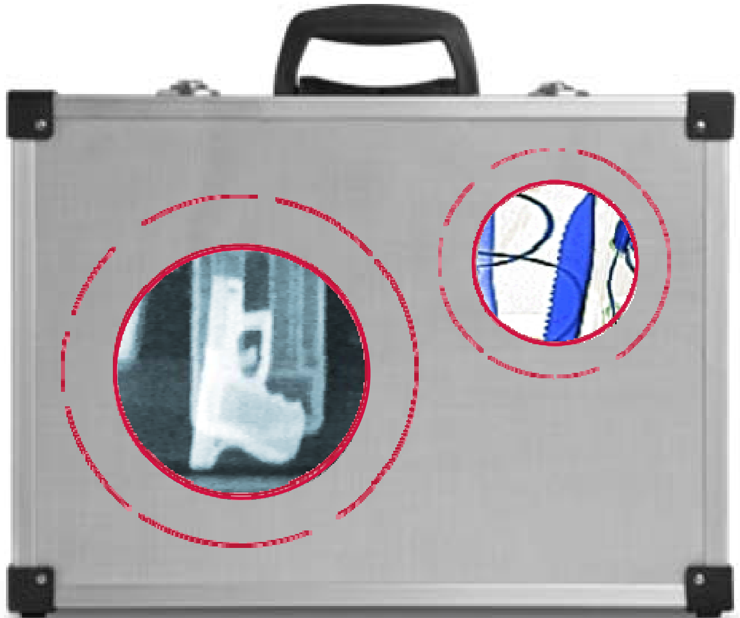


A Mobile X-ray/Neutron Cargo System for Aviation Security

Seth Van Liew

5/7/14

BTI BUBBLE Technology Industries

AS&E®
Detect the difference.

The problem and our solution

- **Need to detect and identify explosives, drugs, and other contraband**
- **Other technologies include X-ray diffraction imaging, NQR, trace, dogs, etc.**
  - Each have their advantages and drawbacks
- **Neutrons are a good complement to x-rays**
- **We developed a system designed for 170 kV x-rays and 2.5 MeV neutrons with enhanced atomic number determination and object isolation in the presence of clutter**
  - Capable of detecting and identifying real threats
  - Fits with current conops of TSA
  - Not a product – still some challenges

X-ray attenuations

Attenuation coefficients with X-ray [cm$?^{1}$]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													

Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray

Neutron attenuations

AS&E

BTI BUBBLE Technology Industries

Attenuation coefficients with neutrons [cm?¹]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													

*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.

Outline

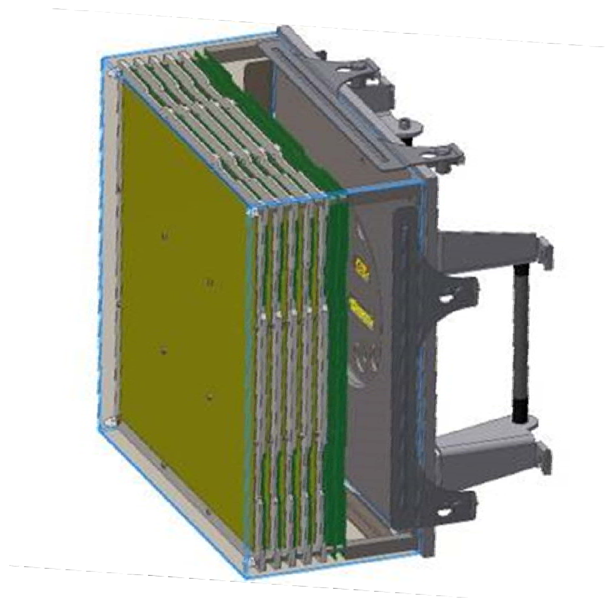
- **Using neutrons in security**
- **A mobile X-ray / Neutron system**
- **Laboratory hardware and data**
- **Algorithms**
- **X-ray / neutron fusion**
- **Conclusions**

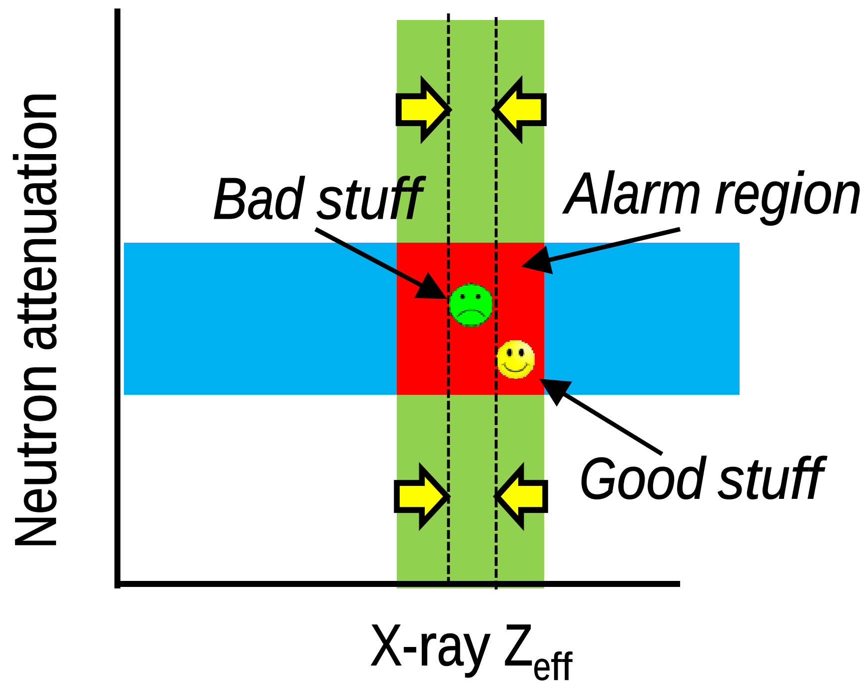
What we sought to accomplish

- **Positive identification of explosives, oxidizers, and narcotics**
- **Compact, mobile x-ray / neutron system that could potentially be used in a TSA environment**
- **Could fit with current conops at TSA**
  - 20 cm/s belt speed
  - 1 m x 1 m tunnel size for checked baggage
- **A reasonable unit price**
  - COTS components wherever possible
  - Smart system integration of components allowing for improved performance
  - Focus on innovative algorithms

Challenges

- **Need to deal with clutter**
  - Multiple views
  - De-cluttering segmentation algorithms
  - Object isolation algorithms
- **Need to improve x-ray Z_{eff} accuracy so benign materials would not be present in alarm region**
- **Need to develop high resolution, scalable neutron detector**
- **Need high efficiency neutron detector without liquid scintillator**





What we want in a neutron system

Fast

Good detection

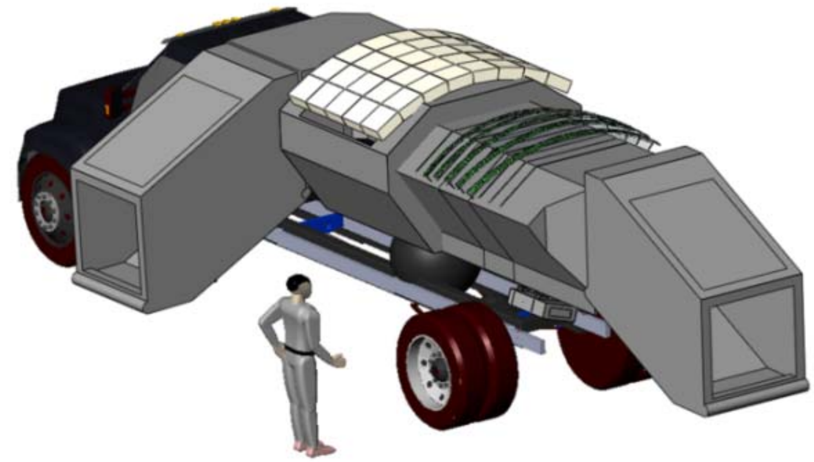
Low shielding weight

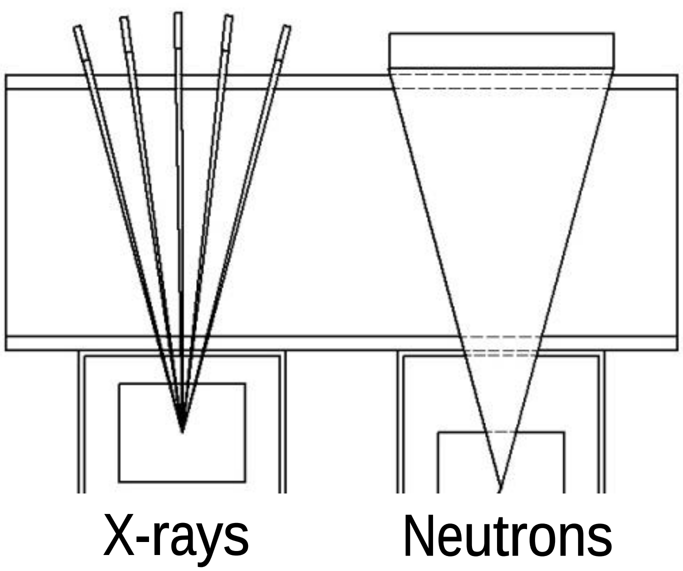
Pick two of the three!

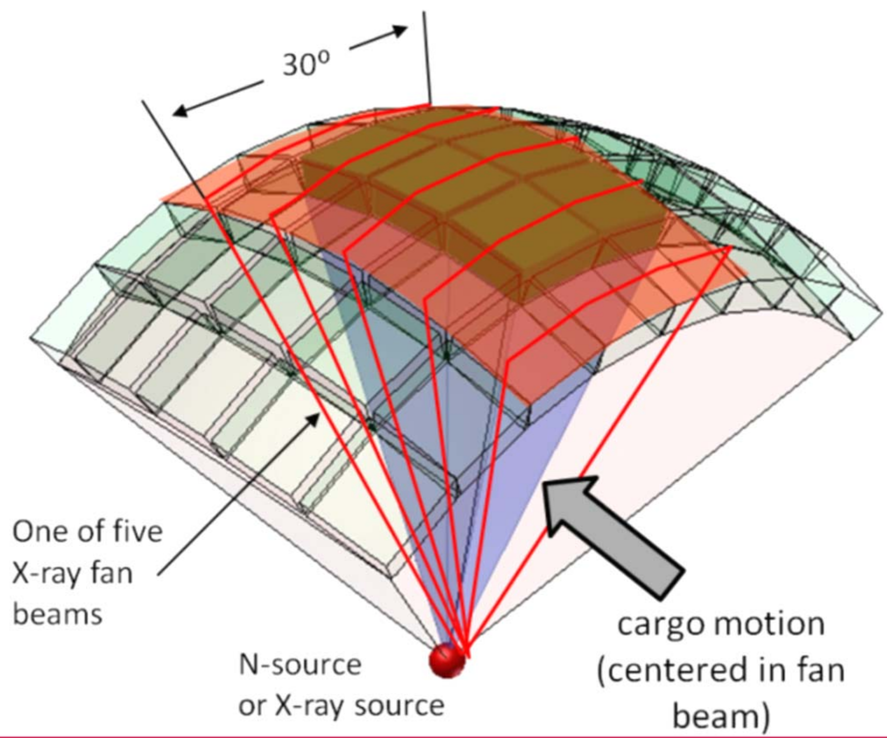
...and low cost

System Concept

- Matched field of views for neutrons and x-rays
  - Use sparse linear arrays for x-rays
- Bottom shooter to reduce neutron shielding weight
- D-D neutron generator (2.5 MeV)
- 170 kV x-ray source

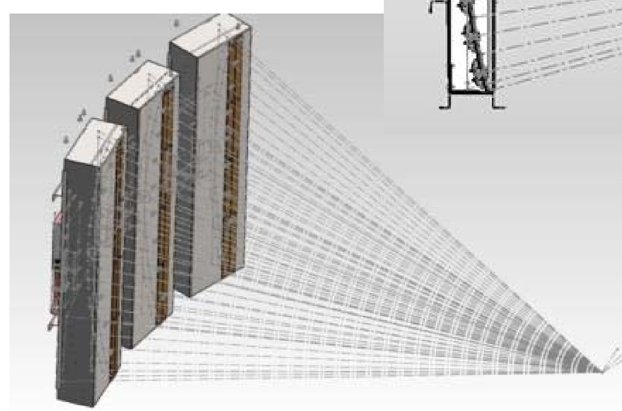


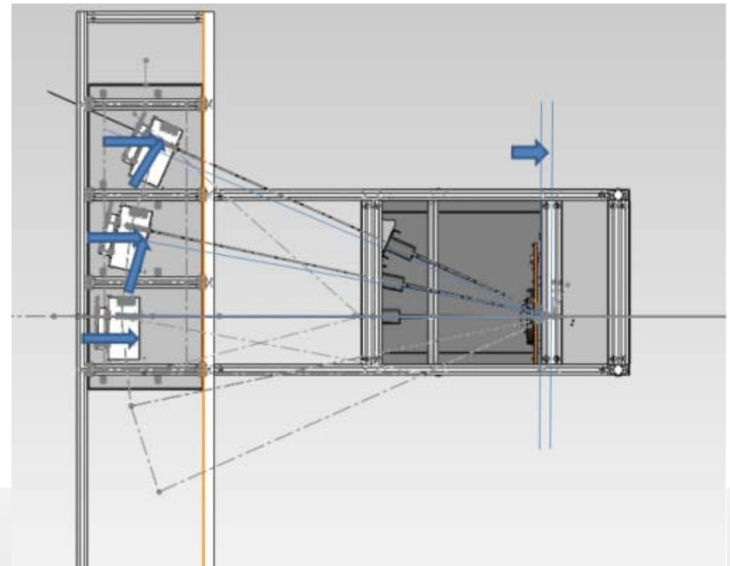


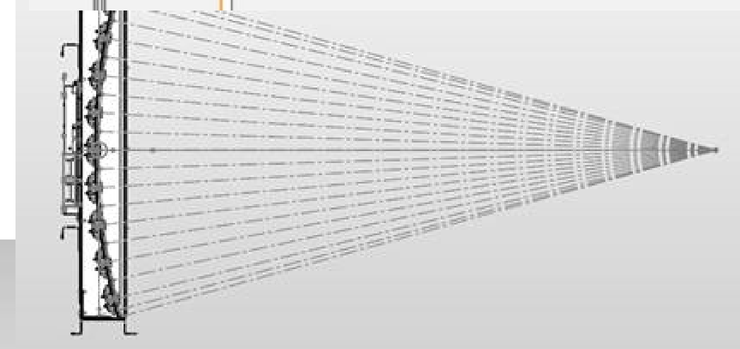


X-ray hardware

- 5 views arranged across 48°
- To save space and cost for testing, only implemented three physical views over half the span
    - Ran cargo through backwards to get other two views
- Used a 140 kV source

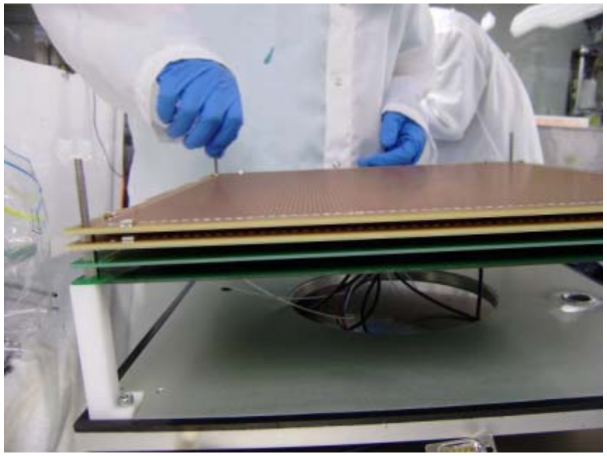






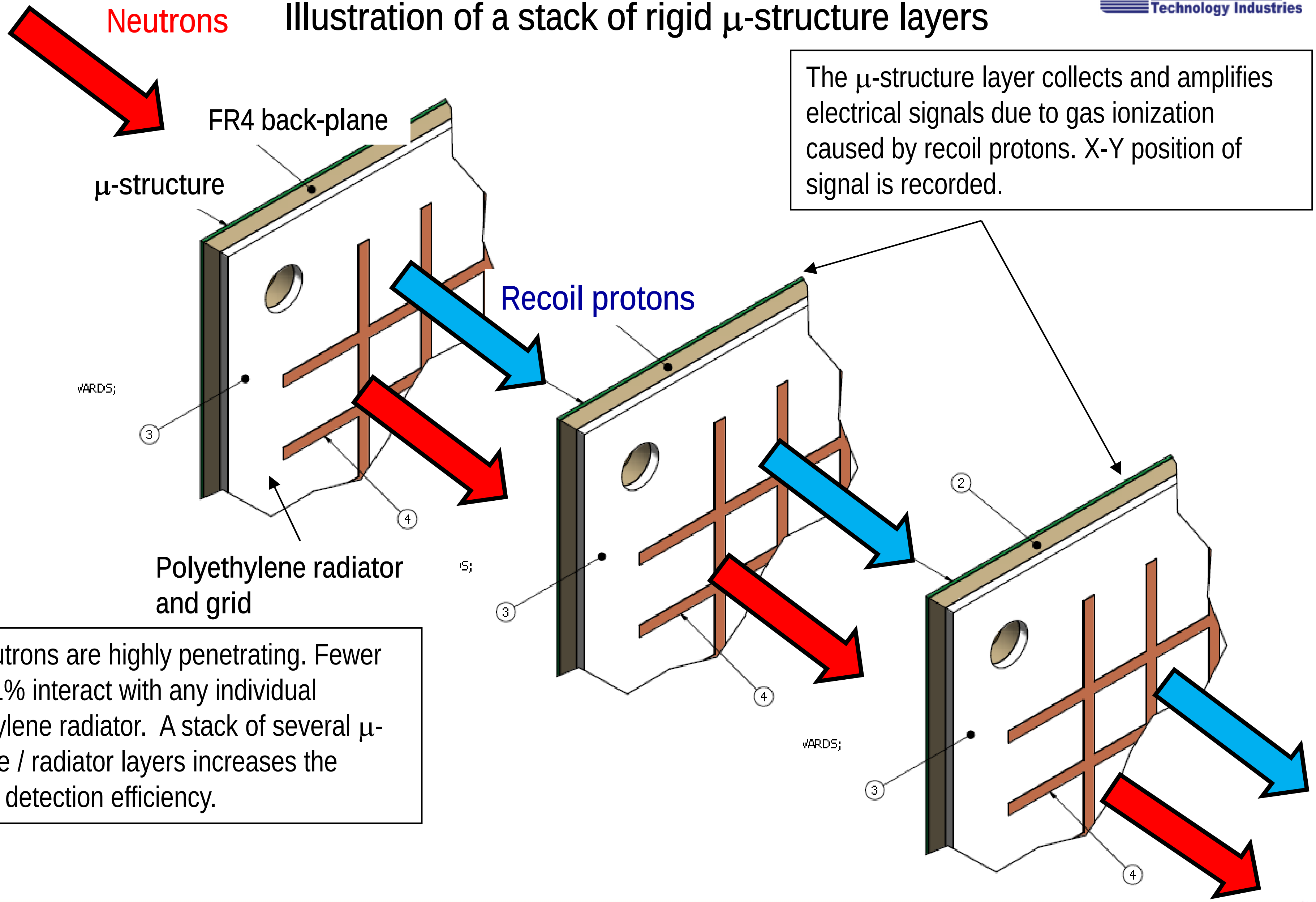
Neutron hardware

- Due to availability we used a DT generator at 14 MeV and a 3 MV Van de Graaff
- Microstructured neutron detector used
  - Single layer used in experiments however multiple layers possible
- Neutrons were in different locations from each other and from the x-rays, requiring careful setup of the experiment
- Performed long counter normalization
- Measured scatter corrections with shadow bars



Neutron microstructure detector design

Illustration of a stack of rigid μ-structure layers

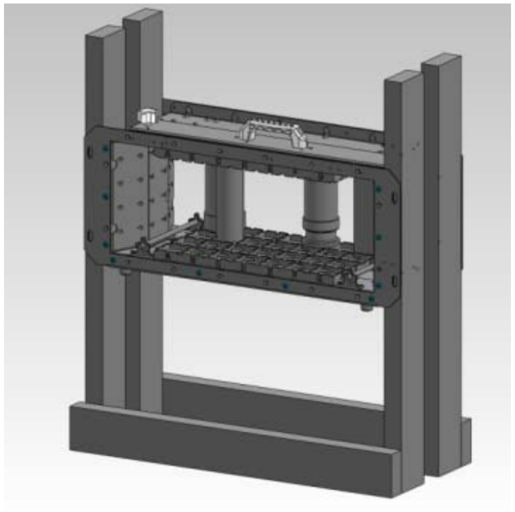


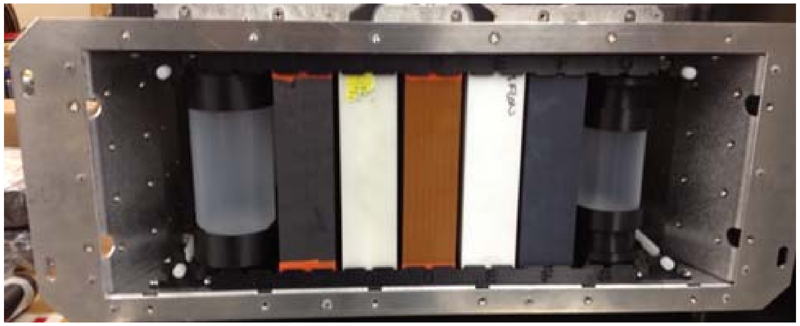
The μ-structure layer collects and amplifies electrical signals due to gas ionization caused by recoil protons. X-Y position of signal is recorded.

The neutrons are highly penetrating. Fewer than 0.1% interact with any individual polyethylene radiator. A stack of several μ-structure / radiator layers increases the neutron detection efficiency.

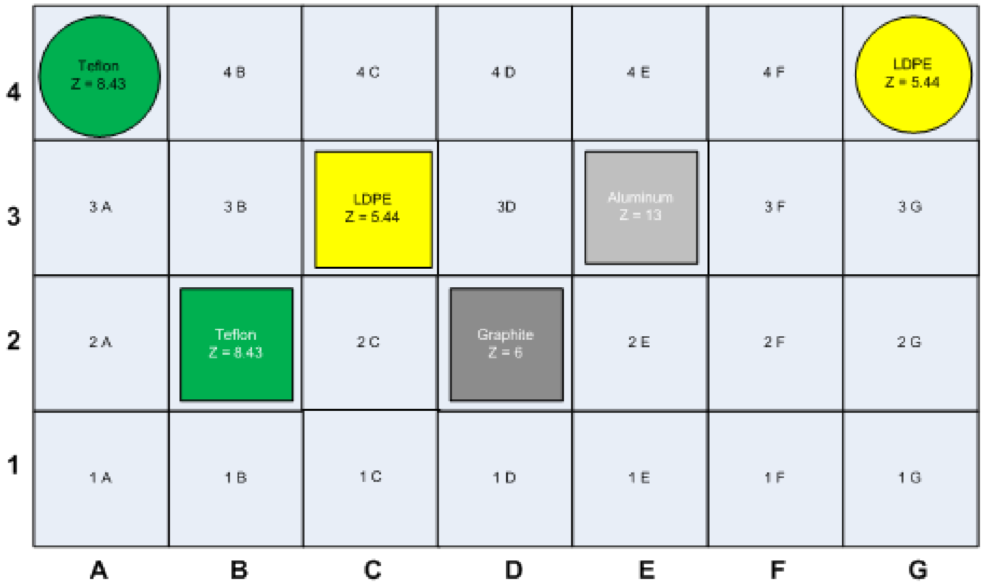
Experiments: Phantom

- How to get good data with when systems are not collocated?
- Registered phantom!
- This phantom was supplied with bar and rectangular stock
- Has dimensions of typical bag
- Can simulate clutter, overlap, etc, but in a controlled environment
- Used for both neutron and x-ray data
- Tested a variety of configurations of different benign materials and threats



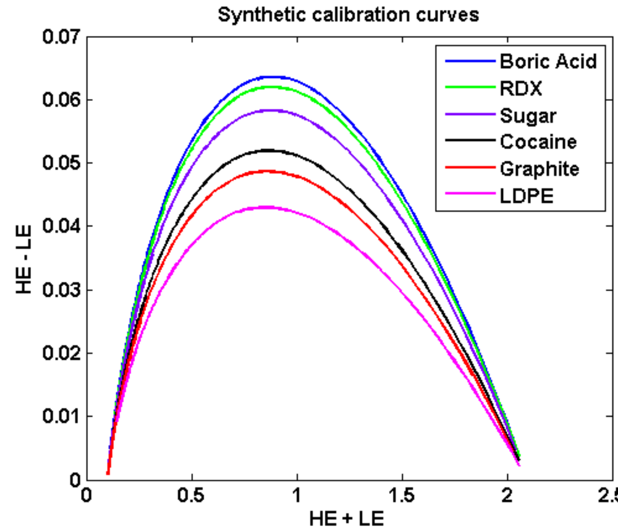


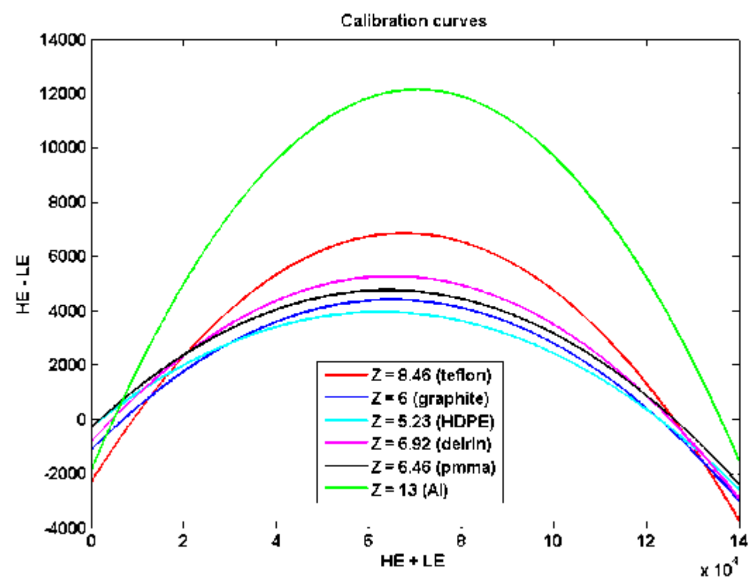
Top View: Material Grid

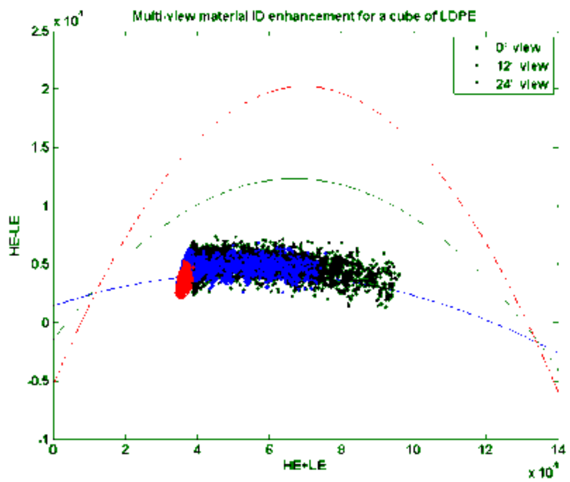


Better Zeff determination

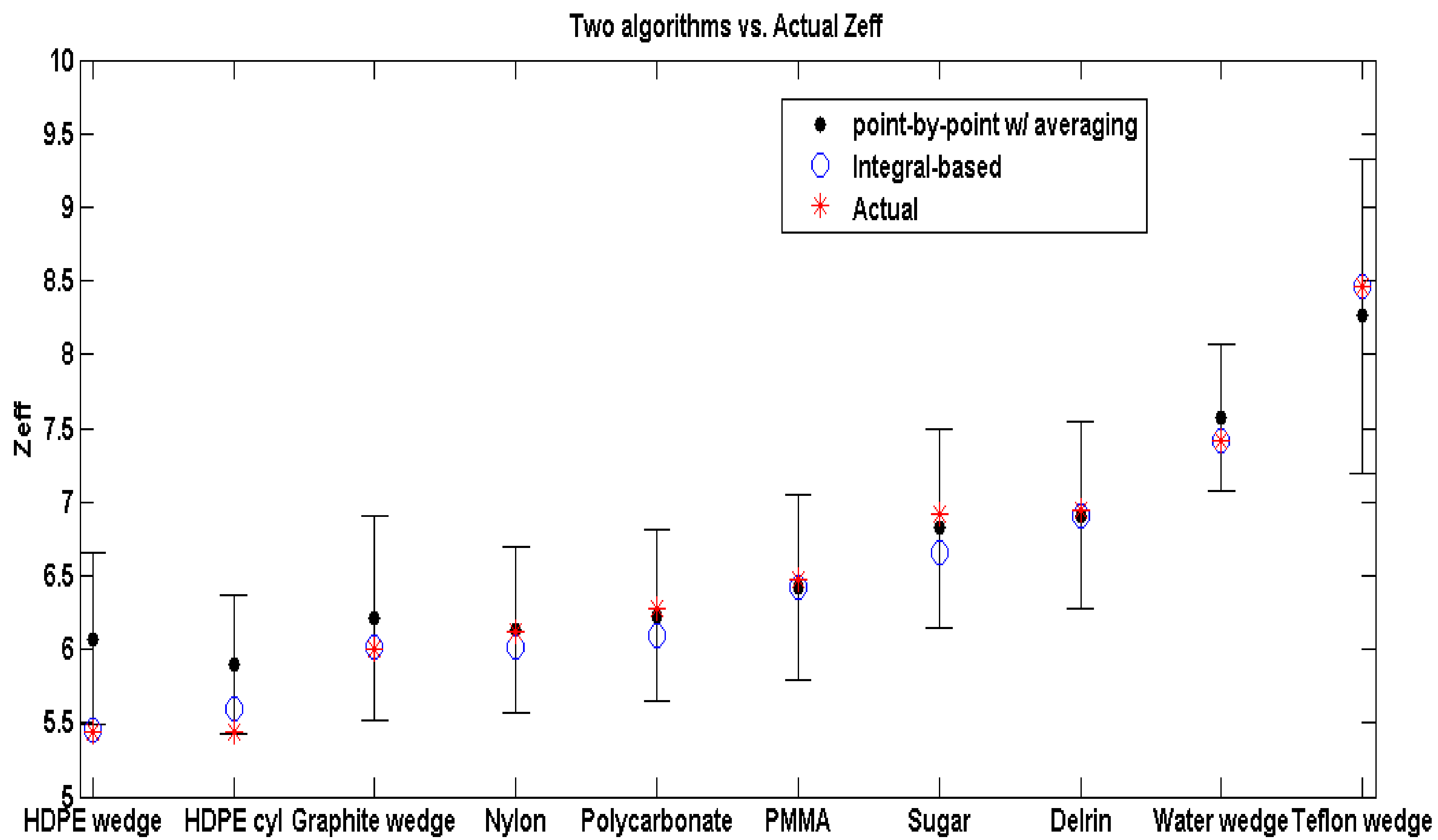
- Used finer calibration curves than the standard three calibration materials
  - Roughly every half-step in Z
- In addition, attempted to statistically match a given threat material to its own calibration curve using synthetic data
- Used multiple views to obtain better Zeff
- Developed new algorithm using a bulk-object averaging approach to enhance Zeff accuracy





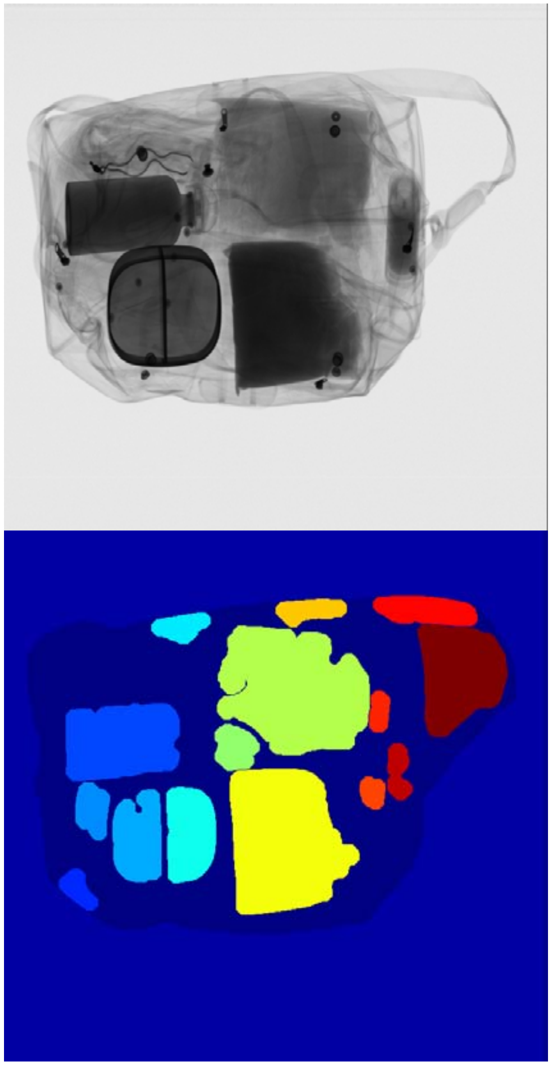


X-Ray Analysis: Algorithm Comparison – New and Old



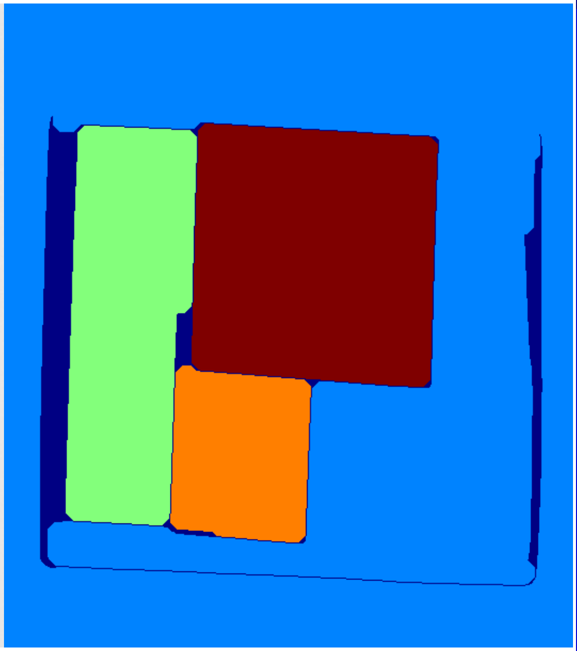
Multi-Stage Segmentation - Identify Objects

- We needed a way to automatically segment both overlapping and non-overlapping objects.
- We developed a segmentation algorithm that could do that
- This is a two-pass algorithm that feeds both sets of data to a material stripping algorithm that can then identify contiguous objects and where they overlap with other objects.

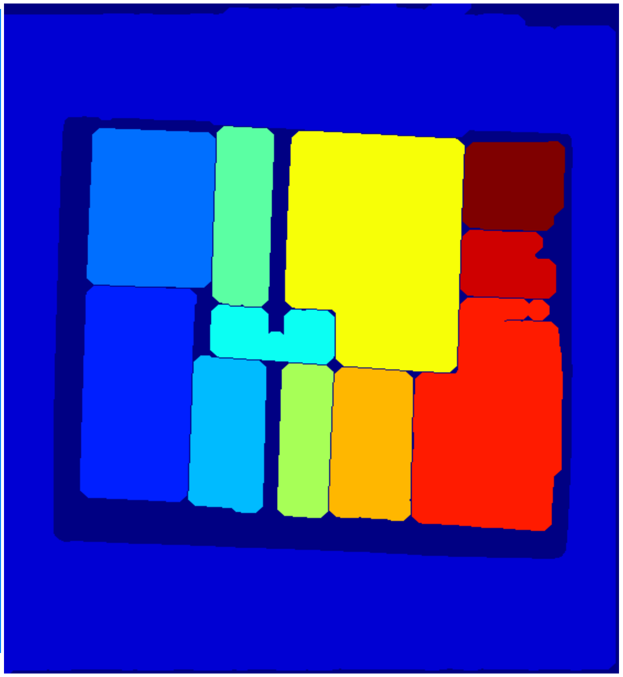


Multi-Stage Segmentation – 2 Pass Algorithm

Original B&W image

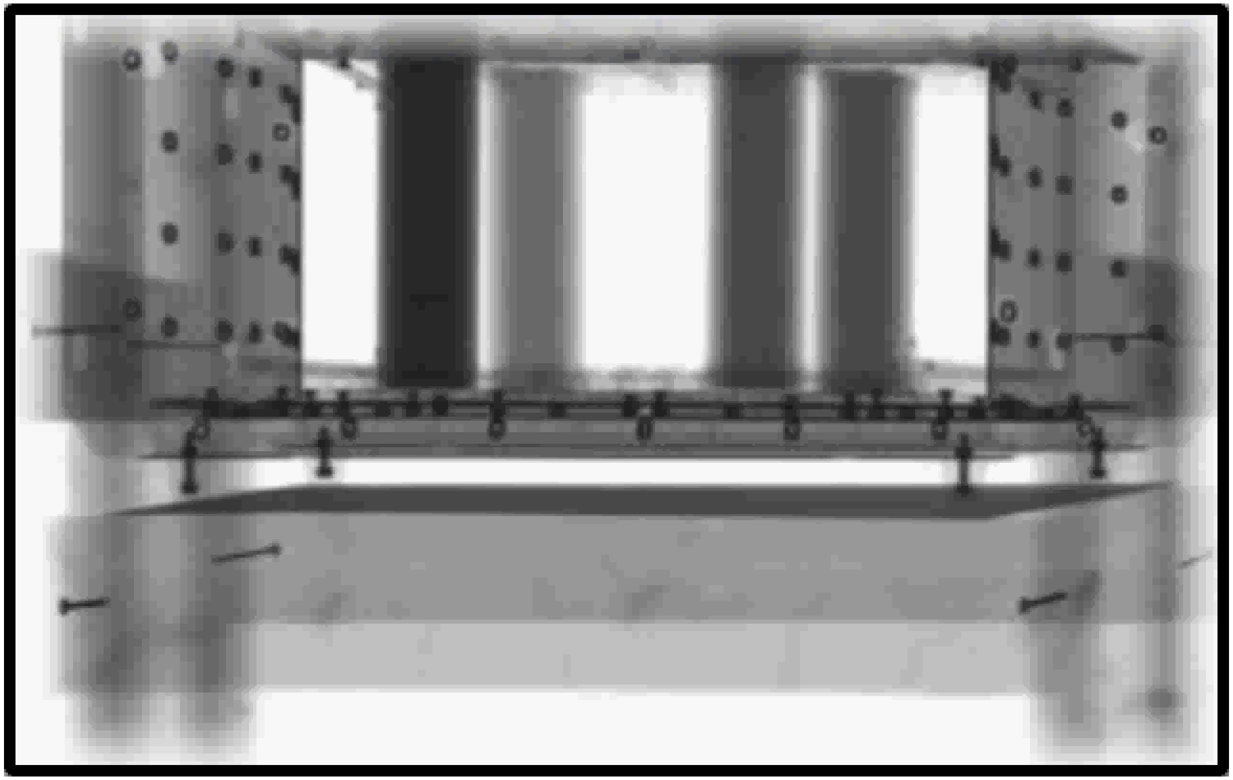


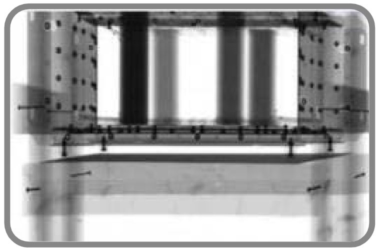
First Pass: Contiguous Objects



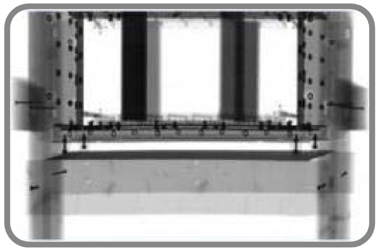
Second Pass: Overlapped Objects

Multi-view object isolation

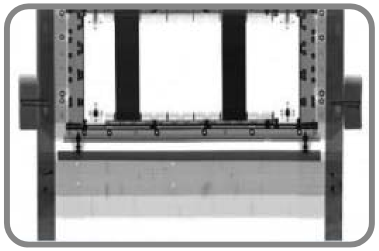




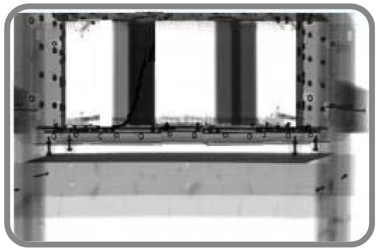
- 24 Degrees



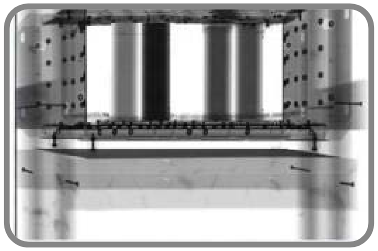
- 12 Degrees



0 Degrees

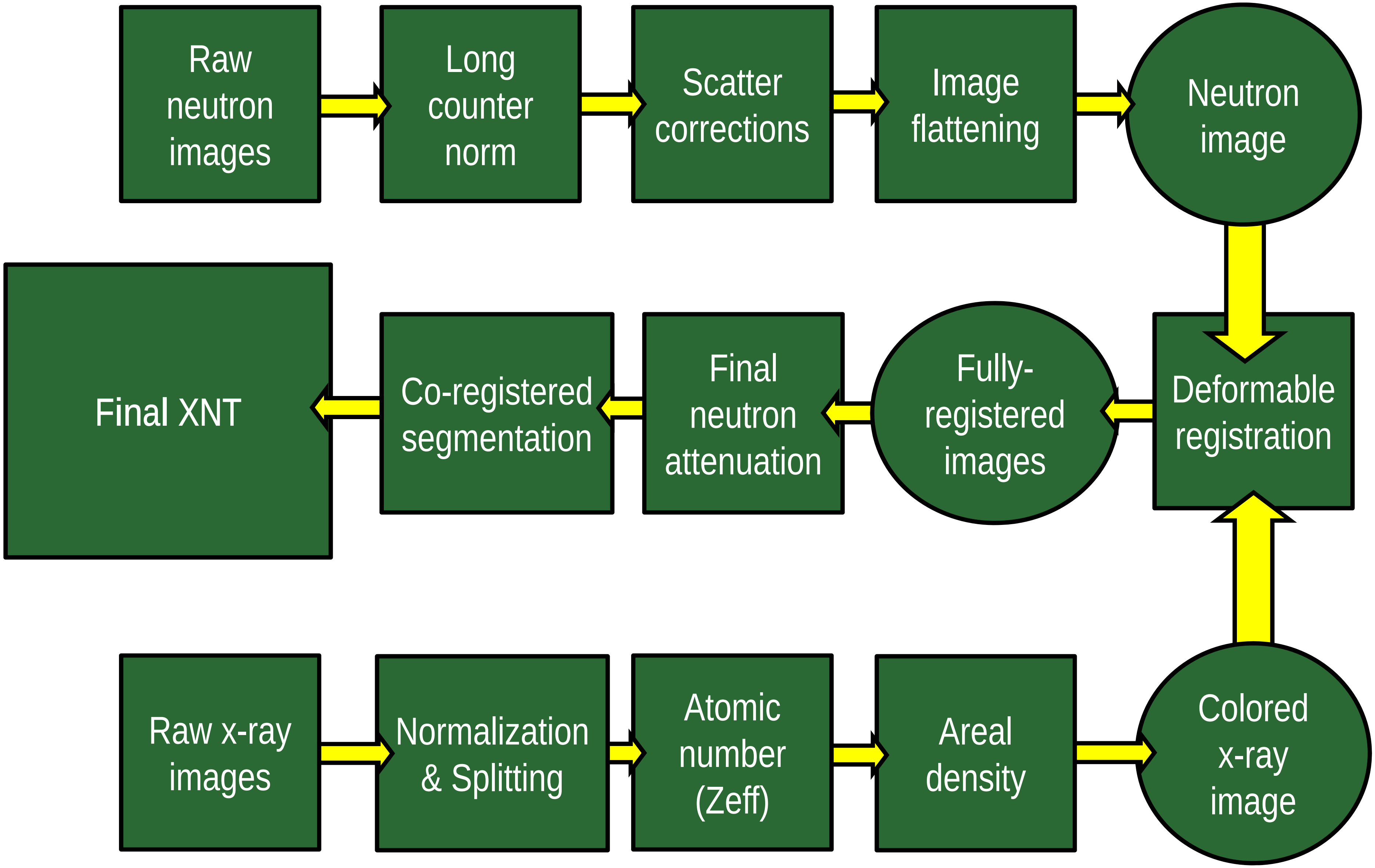


12 Degrees



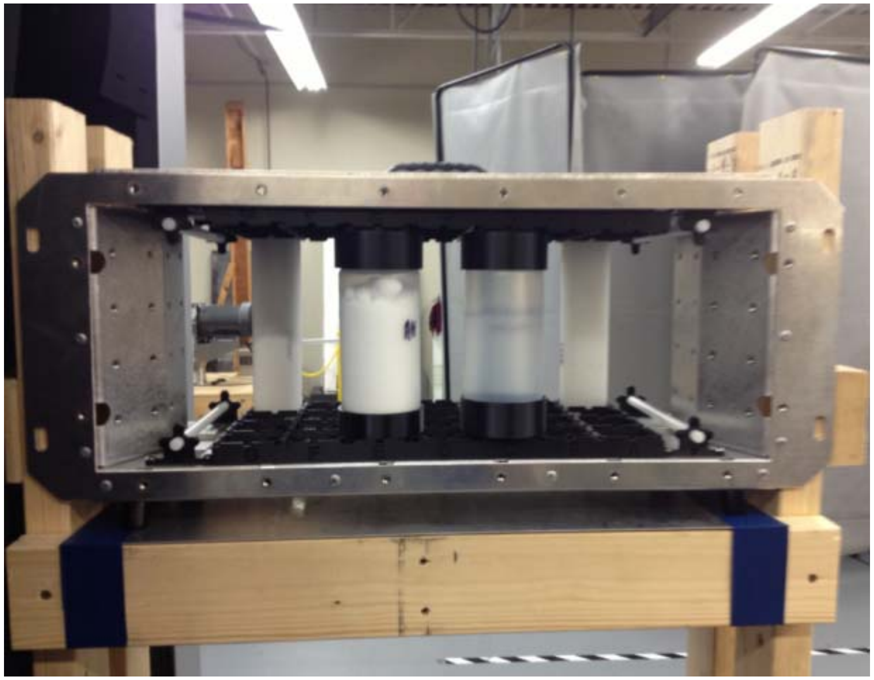
24 Degrees

X-ray / Neutron fusion (XNT) flow chart



Threat phantoms

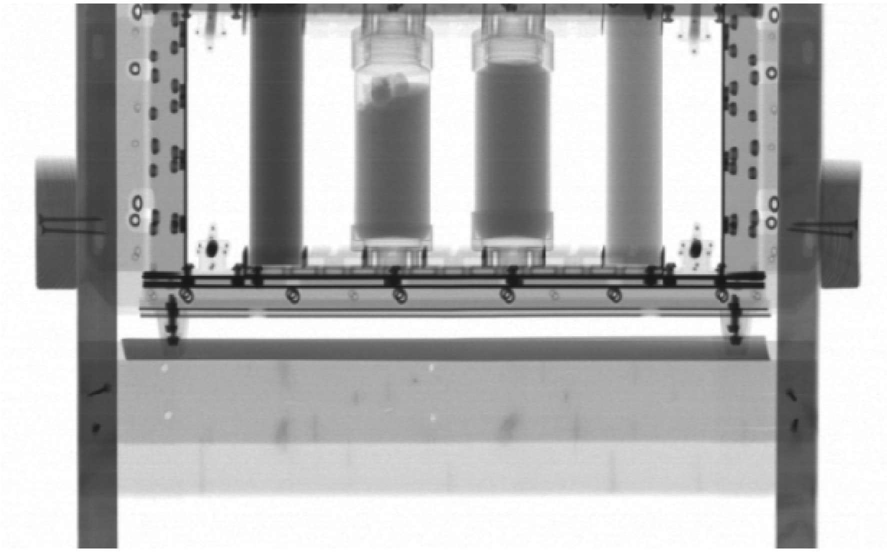
- Tested water and ammonium nitrate, which are nearly identical in effective atomic number in x-rays, among others

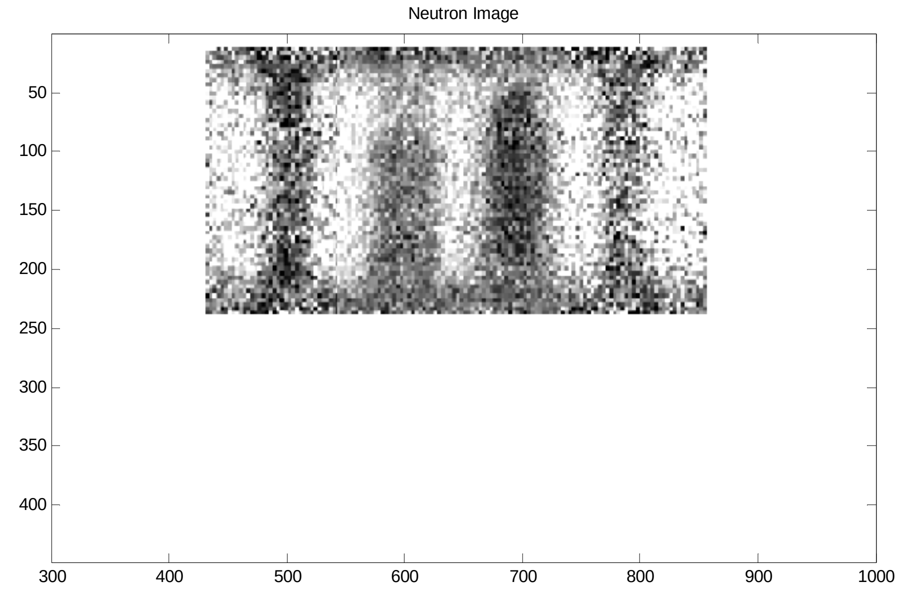


Suitcase Open with AN and Water

Suitcase Closed with AN and Water

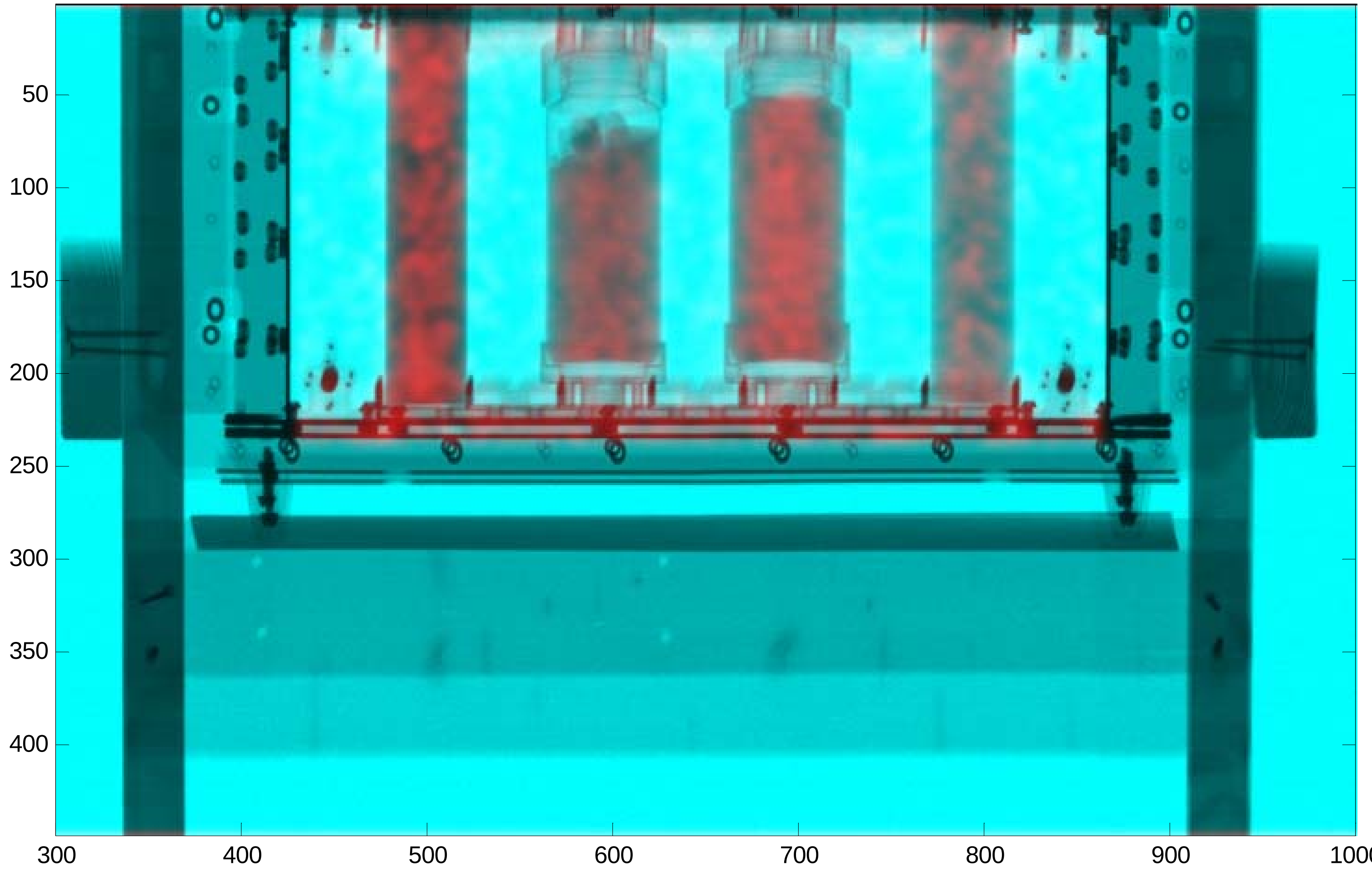
Processed Neutron and X-Ray Images



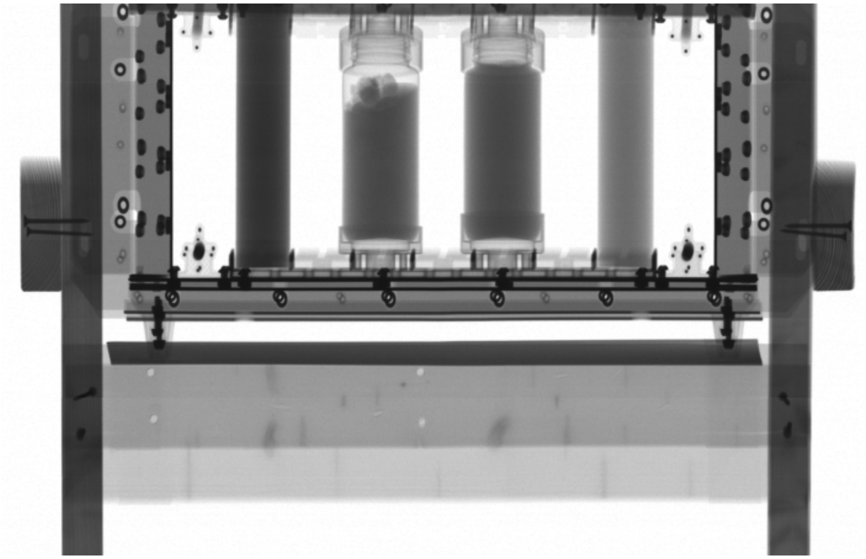
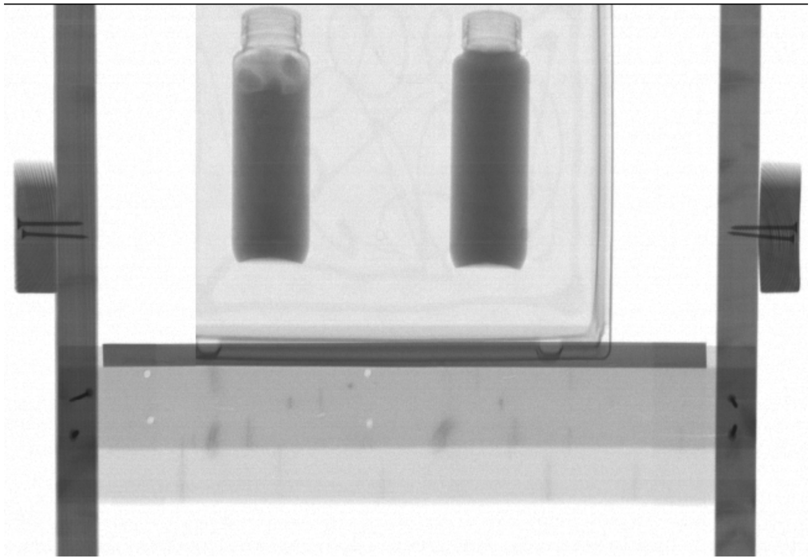
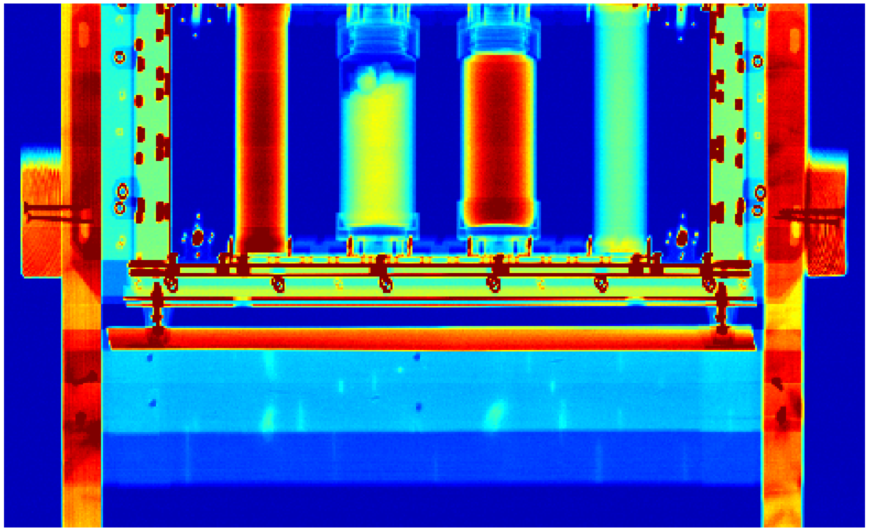
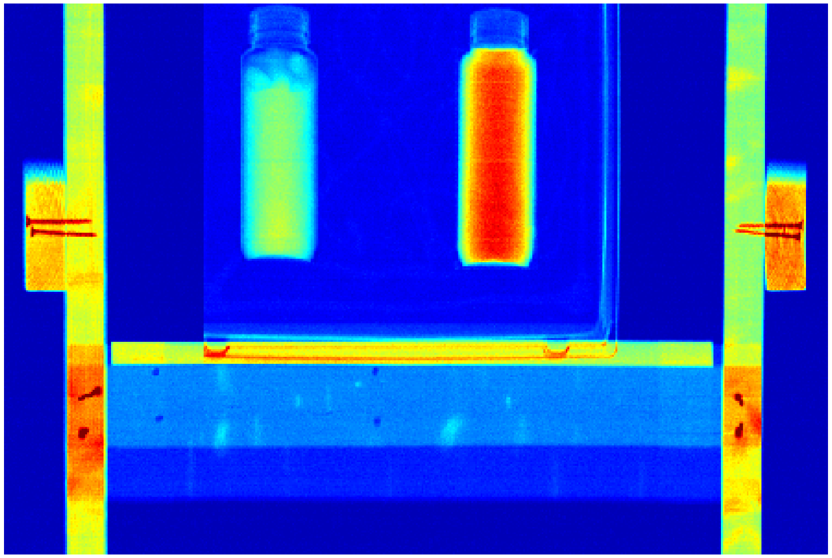


XNT Capabilities: Fused Neutron and X-Ray Images

X-Ray / (MaxSI - Neutron) Fusione Image

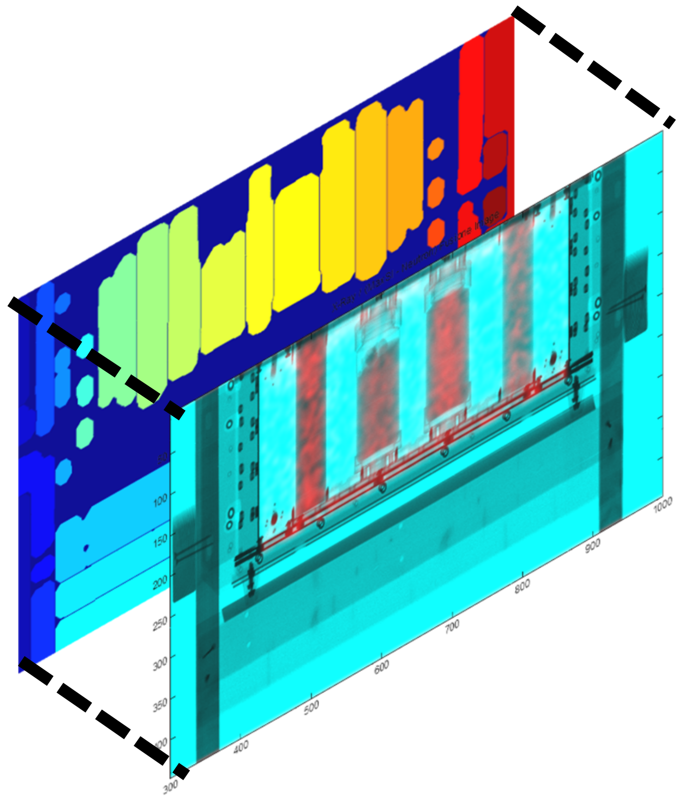


XNT Capabilities: X-ray and areal density images

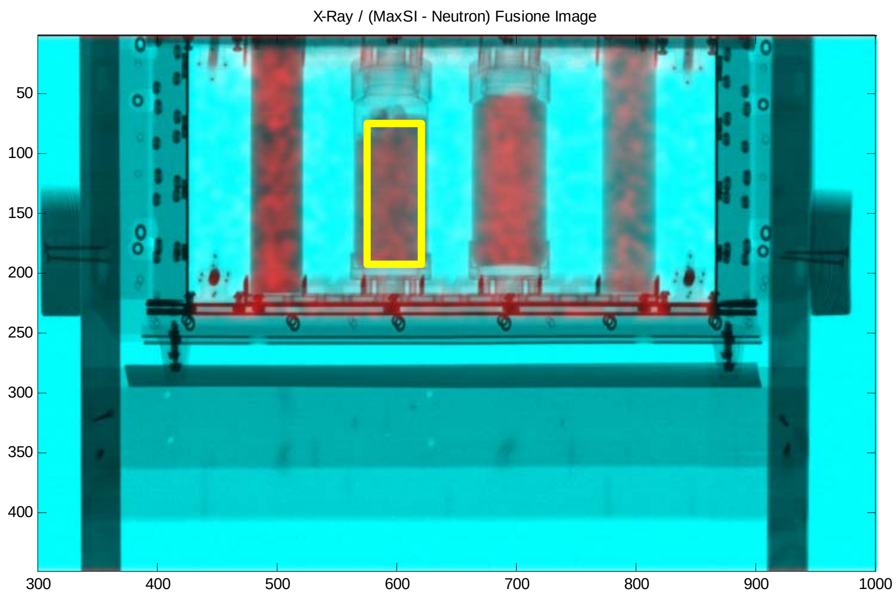
Segmentation and Feature Extraction

- Segmentation is performed on the co-registered images in order to identify all contiguous objects in the XNT overlay.
- This segmentation identifies all regions of the image whether they be air, benign material, or threat.
- Mechanically, segmentation is performed on the high-resolution XNT overlay, and the contours are then transferred to the individual images.
- Each region is then analyzed in both images to ascertain its atomic number and neutron attenuation.
- If a given region alarms based on a lookup table of XNT attenuations, the operator is notified.

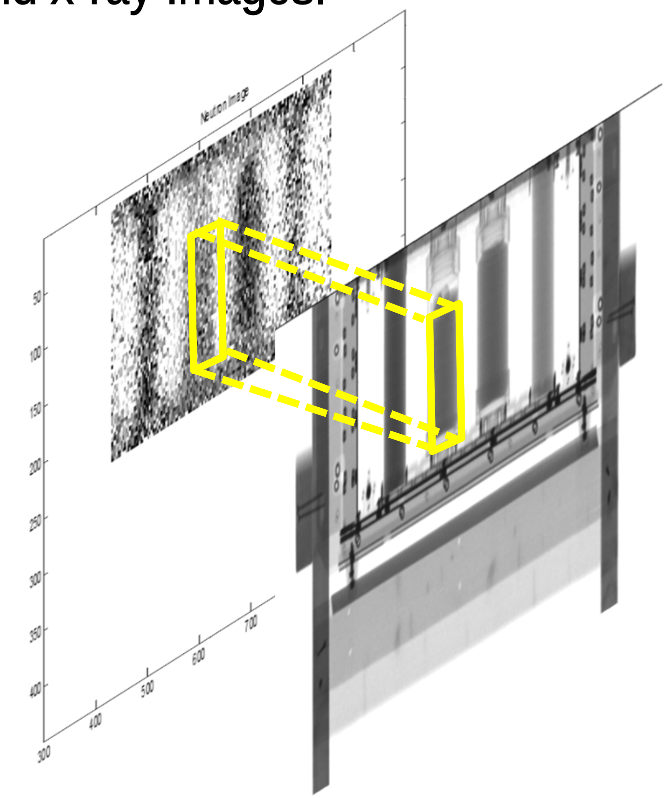


Co-Registered Image Segmentation

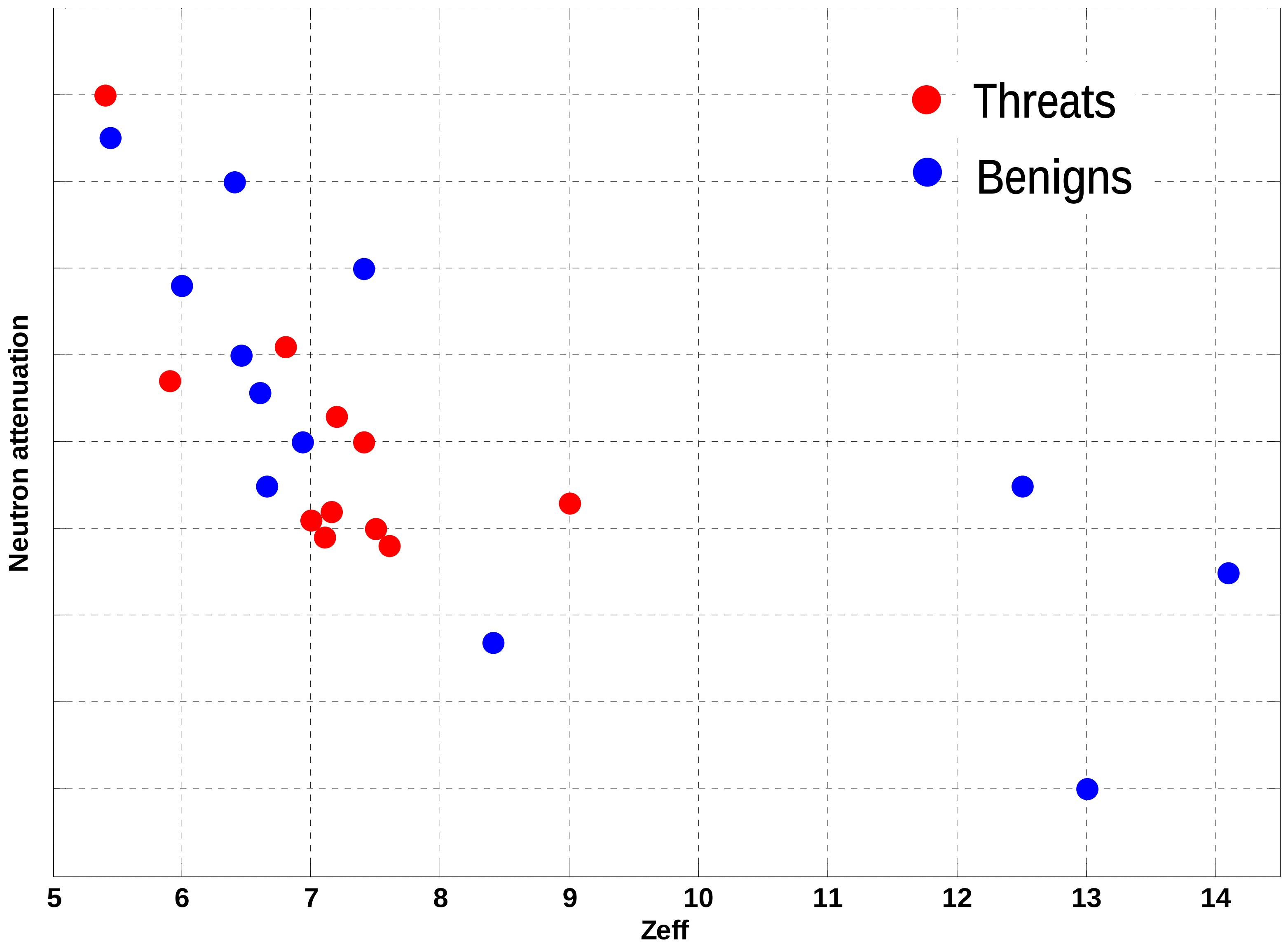
Segmentation performed once on co-registered image.



Contours propagate to both neutron and x-ray images.

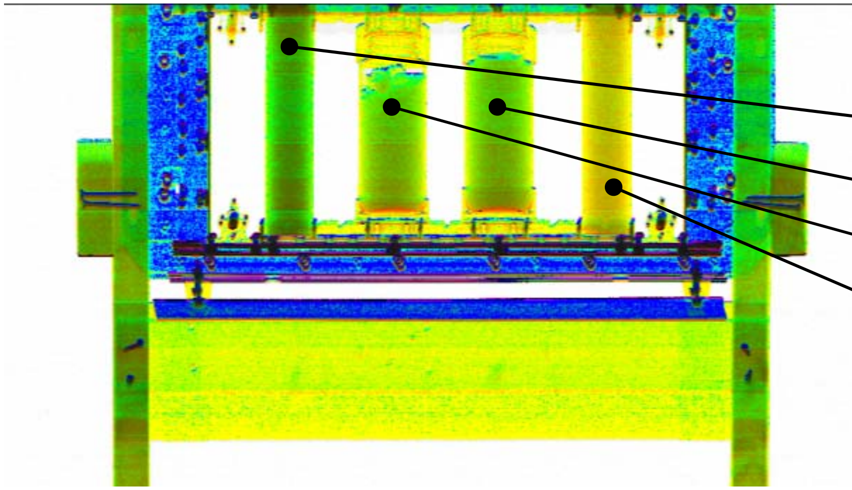


Example neutron and x-ray attenuations



XNT Material identification procedure

Dual Energy X-Ray Image



X-ray Zeff	Neutron attenuation
8.5	0.10
7.4	0.15
7.4	0.09
5.4	0.26

Each contoured region analyzed in both x-ray and neutron space

After comparing each region with the lookup table, threats can be identified

Threat	Zeff	Neutron
Thermite	21.5	0.0493
AN	7.41	0.0854
Cocaine	6.31	0.1708
Ecstasy	6.20	0.1844
Meth	5.72	0.2243
…	…	…

Conclusions

- XNT demonstrated to exceed material ID threshold for x-rays or neutrons alone.
- Multi-view x-ray technology dramatically improves material ID and decluttering of cargo.
- "Stackable" neutron microstructure detector is versatile and can work in a variety of environments
- **Image and data fusion of neutrons and X-rays demonstrated and can be automated.**
- Although the technology is still in development, it looks promising for certain applications
  - In the end, it's all about flux, detection, and shielding
  - …and cost

Collaborators

• **Vernon Koslowsky** – Lead Scientist at BTI	BTI
• **Ming Zhang** – Deformable registration	AS&E
• **Chris Alvino** – Image segmentation	AS&E
• **David Walazek** – Mechanical Design	AS&E
• **Cristian Dinca, Martin Rommel** – Concept and System Design and Simulations	AS&E
• **Dan Wakeford, Marius Facina** – Detector Development	BTI
• **Andrew Shinn, Patrick Forget, Ted Clifford** – Electronics & FW Design	BTI
• **Darren Locklin, Nick Bray, Richard Davis** – Mechanical Design	BTI
• **Gerry Mead, Ken Robins, Matthias Koslowsky** –System Assembly & Integration	BTI
• **Martin Koslowsky, Nicholas Hartmann** – Data Collection & Analysis	BTI
• **Harry Ing, Bob Andrews** – Physics Consultation & Technical Oversight	BTI

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