Fast Neutron Resonance Radiography (NRR) for Air Cargo Explosives Detection

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L-3 Communications Security and Detection Systems

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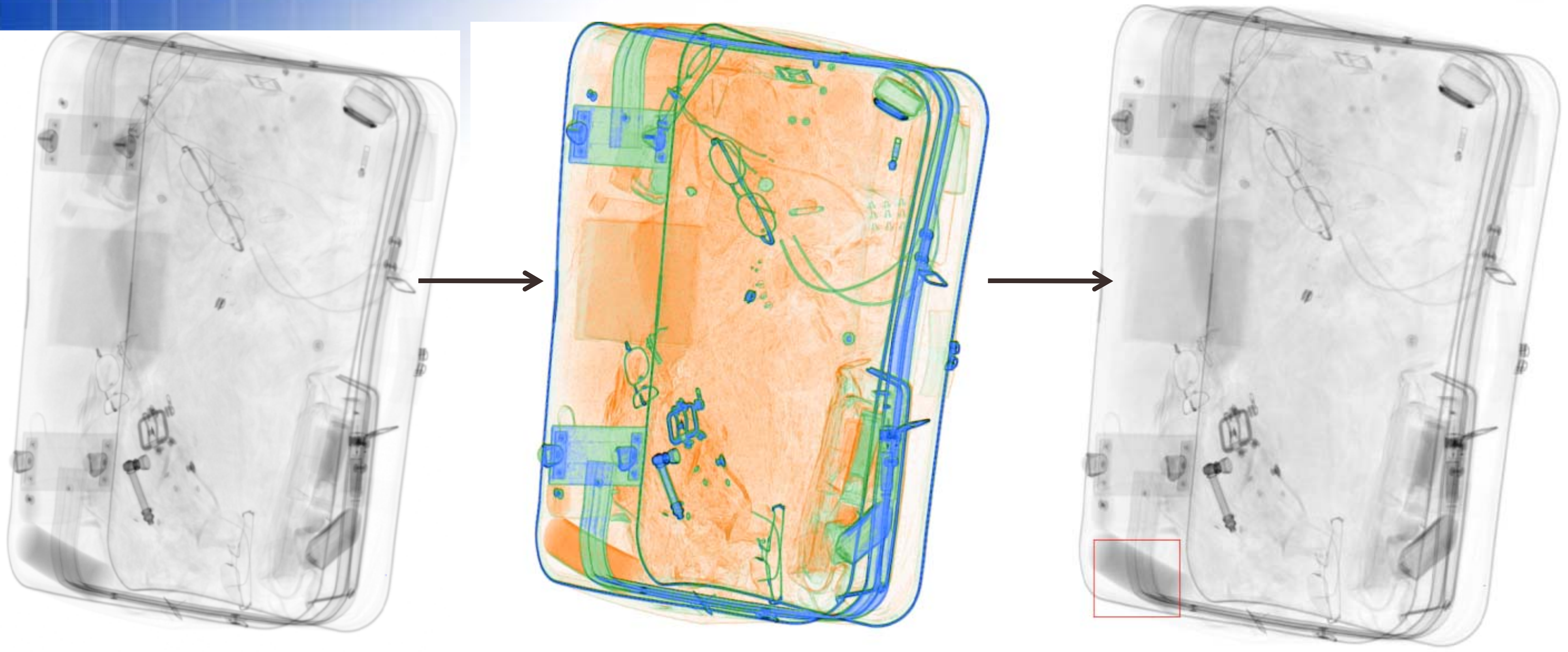
Outline

- Explosives Detection in Air Cargo Overview
  - System goal is TSA/CERT performance in a LD-3 container
- Method and Motivation
  - Generate Elemental Maps from attenuation images
- Implementation
- Experimental Results
  - Efficacy of Element Based Detection in Cargo, Stand Off Estimate of Chemical Formulas
- Lessons Learned

Results are from “NRR for explosives detection feasibility study” by L-3 SDS, MIT Nuclear Science and Engineering, and MIT Bates Laboratory.

Evolution of a Detection System (Explosives Detection in Luggage)

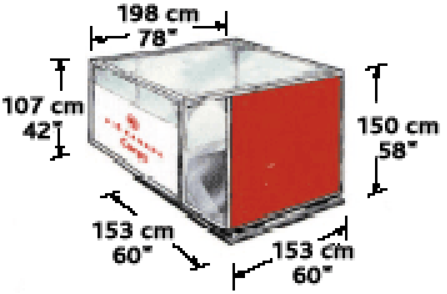


Single energy spectrum image only

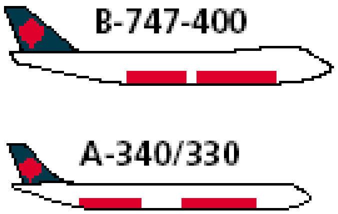
Material discrimination: broad Z measurement with dual energy spectra

Automated threat recognition: quantitative detection of specific targets (regulatory approval). Not previously demonstrated for air cargo.

Application: Detection of Explosives in Air Cargo



INTERNAL DIMENSIONS



LD3

HALF SIZE LOWER DECK CONTAINER FORKLIFTABLE (AVE, AVN, AKE, AKN SERIES)

Rate Classification	8
Maximum Net Weight	1490 kg (3285 lb)
Tare Weight	98 kg (215 lb)
Maximum Gross Weight	1588 kg (3500 lb)
Approx. Internal Volume	4.13 m^3 (146 ft^3)
Floor Loading Limit	977 kg/m^2 (200 lbs/ft^2)

Compared to luggage 4-5 X thickness and 70 X mass.
Do existing luggage EDS methods scale?

Neutron and Photon Beams are Exponentially Attenuated.

Attenuation of a neutron or photon beam I_0 by a material of thickness x:

$$I = I_0 e^{-N\sigma x}$$

N is the attenuation material atom density,

σ is the cross section.

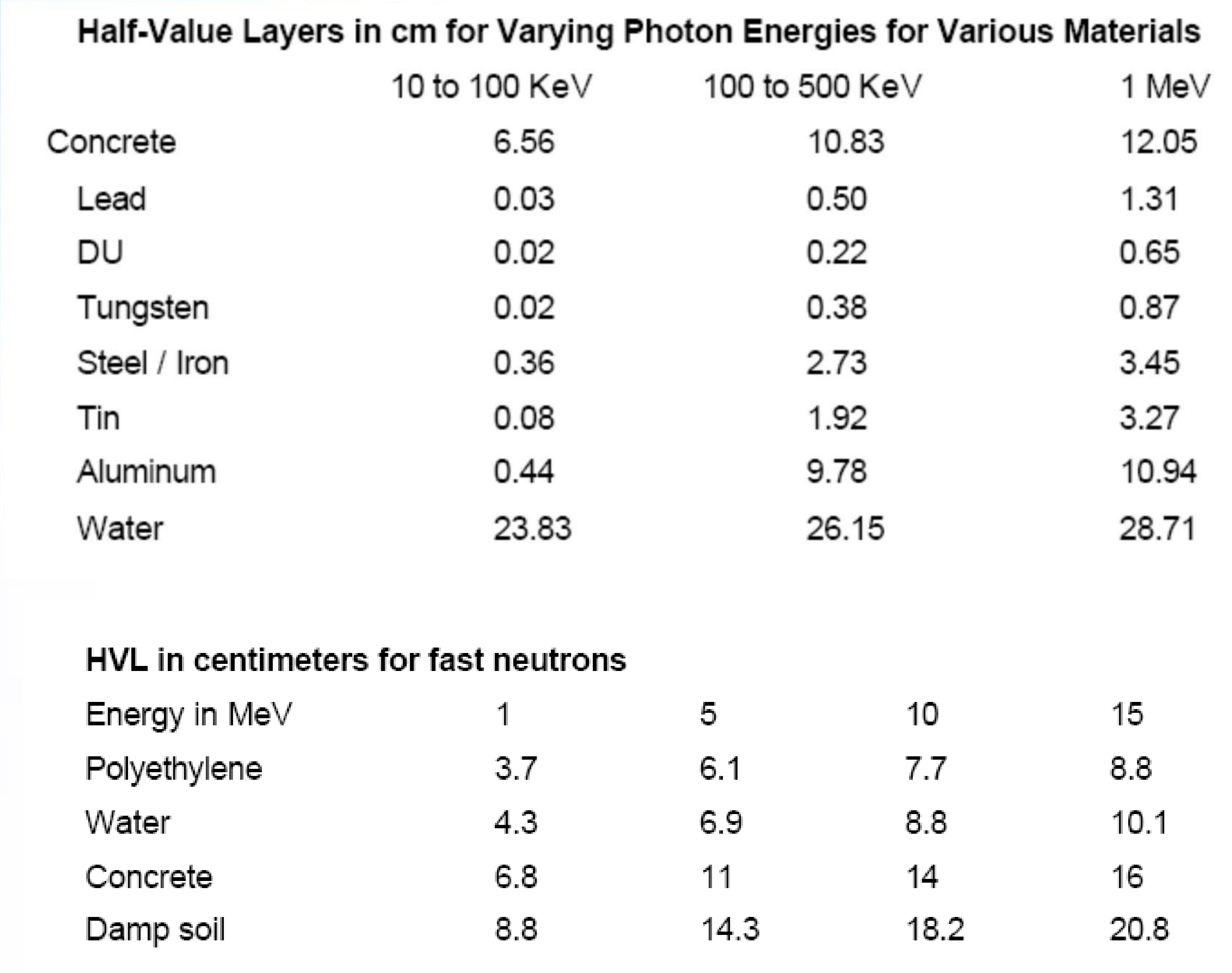
In English: The beam is attenuated exponentially with the product of (atoms/volume)*(area/atom)*thickness

In Dimensions (atoms/cm^3)*(cm^2/atom)*cm

The cross section (σ) is completely different for neutrons and photons. The cross section changes with attenuator Z and with probe energy.

The only options are to change probe type and energy.

Higher Energy Increases Penetration



Half-Value Layers in cm for Varying Photon Energies for Various Materials

	10 to 100 KeV	100 to 500 KeV	1 MeV
Concrete	6.56	10.83	12.05
Lead	0.03	0.50	1.31
DU	0.02	0.22	0.65
Tungsten	0.02	0.38	0.87
Steel / Iron	0.36	2.73	3.45
Tin	0.08	1.92	3.27
Aluminum	0.44	9.78	10.94
Water	23.83	26.15	28.71

HVL in centimeters for fast neutrons

Energy in MeV	1	5	10	15
Polyethylene	3.7	6.1	7.7	8.8
Water	4.3	6.9	8.8	10.1
Concrete	6.8	11	14	16
Damp soil	8.8	14.3	18.2	20.8

Standard X-ray EDS Methods at Higher Energy

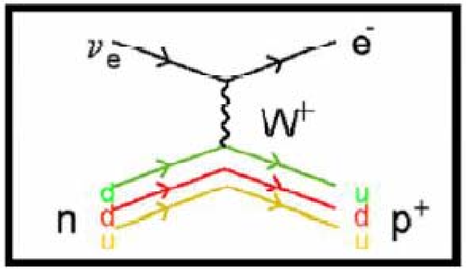
- CT can work, but ~2.0m diameter bore size means highly complex system with bigger source (has been tried). Still need spatial and contrast resolution.
- Dual energy X-ray works best with one energy below 100 keV. Possible but much less effective > 5 MeV.
- Coherent scatter photons are already lower in energy and would have trouble getting out of the cargo.

Neutrons vs. Photons.

Property	Neutrons	Photons
Discrimination	Elemental	Generic (Z_{eff} / density). Can be molecular.
Penetration	Best at High/Medium Z	Best at Low/Medium Z
Interaction	Nucleus	Electrons
Residual Radioactivity	Yes. Also can induce Fission	No
Shielding	Tricky (Borated Poly / Ricorad). Neutrons provide greater biological dose per particle.	Easy – lead.

Neutron Properties

Neutron Decay – mean lifetime 880 (sec), Q 780 keV



Primordial element formation $n + e^+ \longleftrightarrow p + \bar{\nu}_e$

$$p + e^- \longleftrightarrow n + \nu_e$$

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

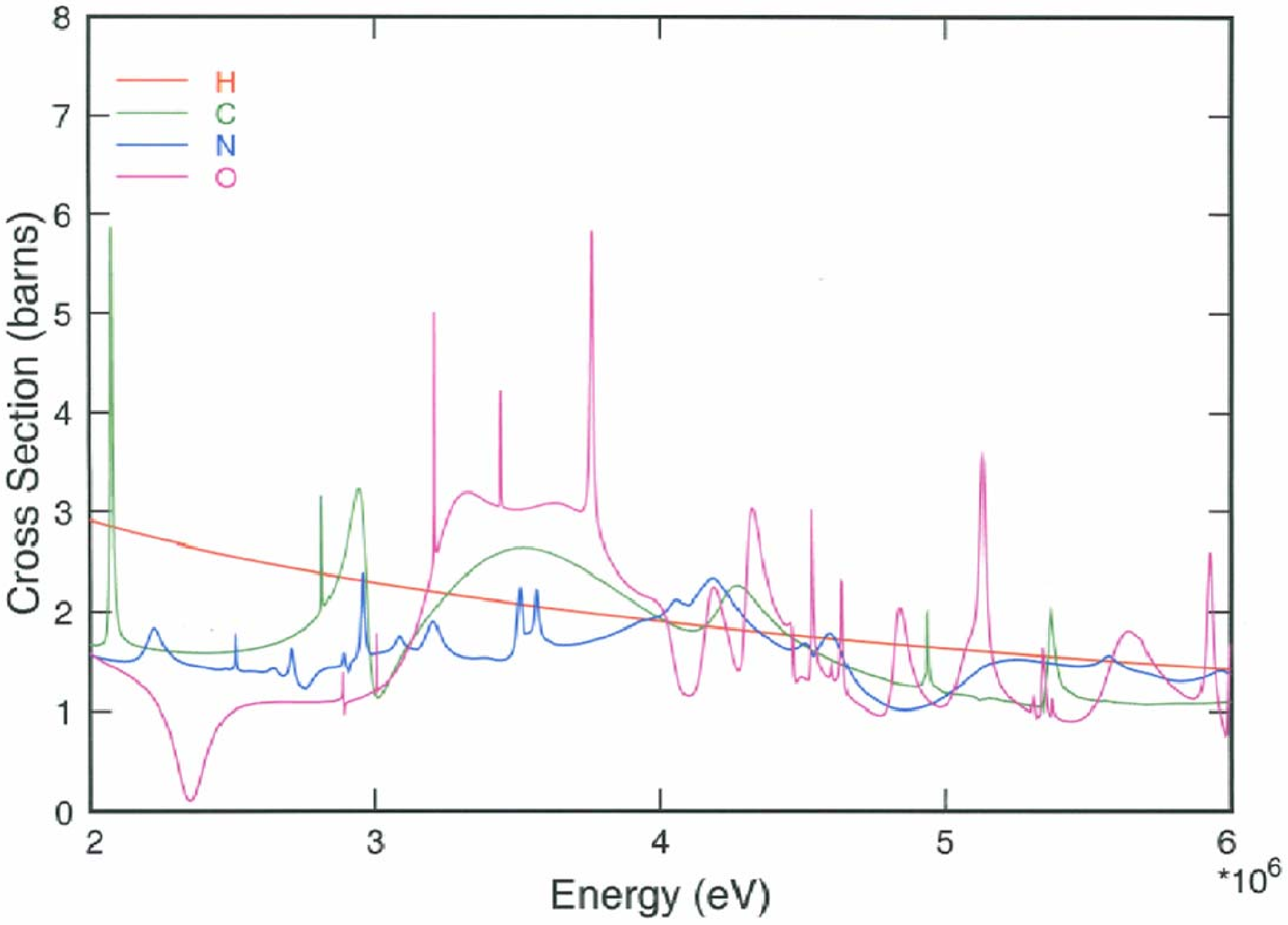
Solar cycle $p + p \longrightarrow {}^2H + e^+ + \nu_e$

$$p + p + e^- \longrightarrow {}^2H + \nu_e \quad \text{etc.}$$

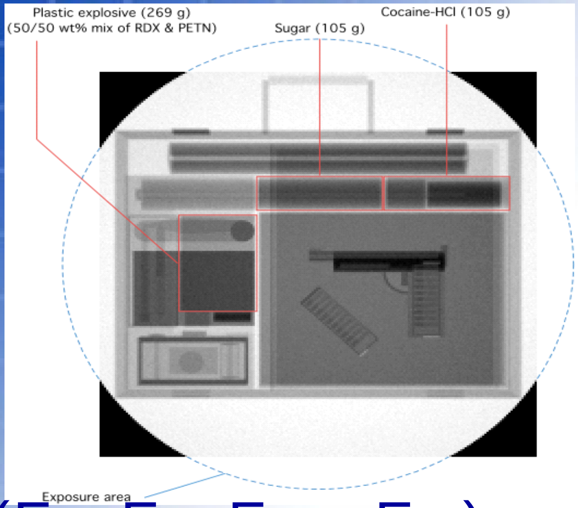
Neutron star formation $p + e^- \longrightarrow n + \nu_e$

This single decay mode can be inhibited by energy conservation or by unavailable quantum states for the decay products. Thus the neutron is stable in certain atomic nuclei and neutron stars.

Neutron Cross Sections (σ) are Unique for Low Z Elements.

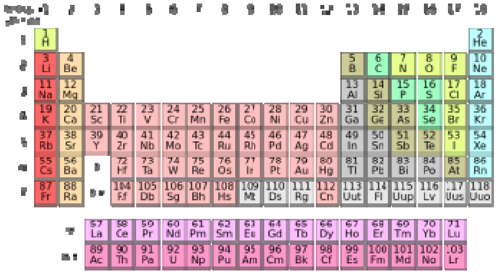


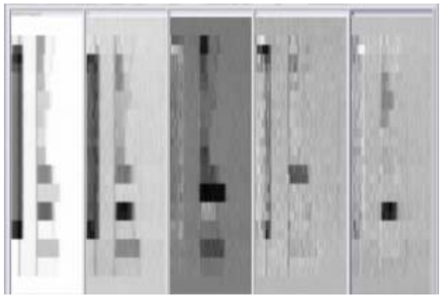
Neutron Resonance Radiography Steps



$(E_1, E_2, E_3, \ldots E_N)$

$$\begin{pmatrix}\sigma_a^1 & \sigma_b^1 & \sigma_c^1 & \sigma_d^1\\ \sigma_a^2 & \sigma_b^2 & \sigma_c^2 & \sigma_d^2\\ \sigma_a^3 & \sigma_b^3 & \sigma_c^3 & \sigma_d^3\\ \sigma_a^4 & \sigma_b^4 & \sigma_c^4 & \sigma_d^4\\ \sigma_a^5 & \sigma_b^5 & \sigma_c^5 & \sigma_d^5\\ \sigma_a^6 & \sigma_b^6 & \sigma_c^6 & \sigma_d^6\end{pmatrix}\cdot\begin{pmatrix}\chi_a\\ \chi_b\\ \chi_c\\ \chi_d\end{pmatrix}=\begin{pmatrix}b^1\\ b^2\\ b^3\\ b^4\\ b^5\\ b^6\end{pmatrix}$$





1) Take a series of neutron images at different energies
2) Do some math
3) Generate images indicating presence of basis elements – elemental maps.

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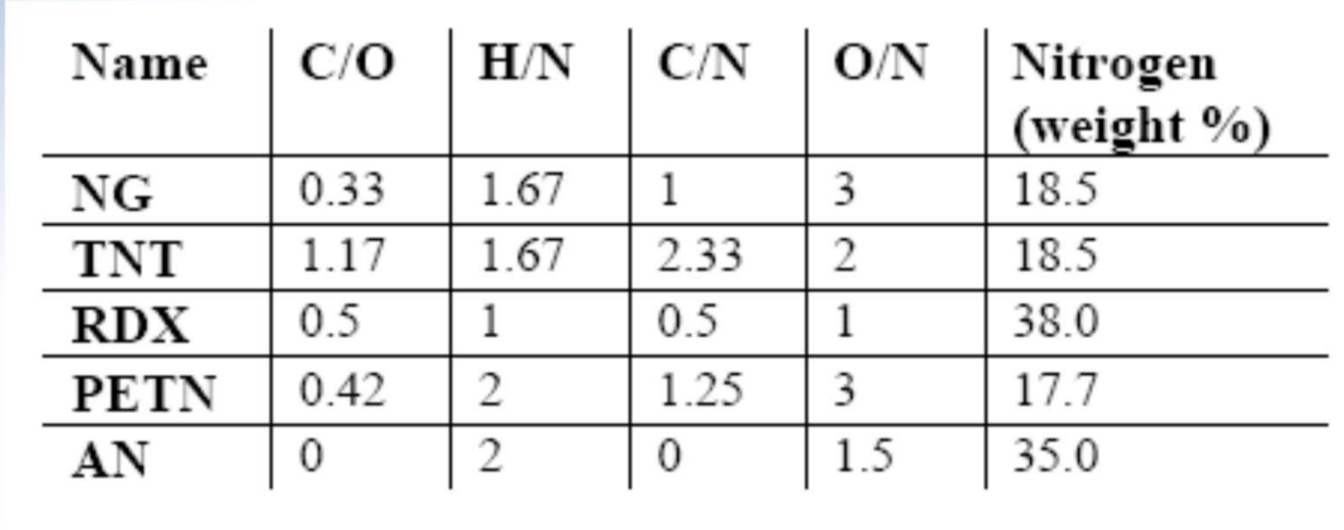
Advantages Of Using Neutron Resonance Radiography

- Multiple Element (H,C,N,O +) mapping for 2-6 MeV neutrons yields many potential discriminants for explosives detection.



Name	C/O	H/N	C/N	O/N	Nitrogen (weight %)
NG	0.33	1.67	1	3	18.5
TNT	1.17	1.67	2.33	2	18.5
RDX	0.5	1	0.5	1	38.0
PETN	0.42	2	1.25	3	17.7
AN	0	2	0	1.5	35.0

- Proof Of Concept Application
  - **Separation Of Diamonds (Carbon) From Kimberlite Rock.**
- Sensitivity scales as $1/R^2$ rather than $1/R^4$
  - **TNA or PFNA detect excited gammas which adds another factor of $1/R^2$ for overall scaling of $1/R^4$**

Key NRR Challenges

- NRR requires a variable energy, effectively monochromatic neutron source. Neutron beam energy spread needs to be minimized. Accelerator production is the only option (10^8-10^10 n/sec)
- NRR requires good neutron detection and photon rejection. The overall presence of photons must be minimized as they contaminate cross section measurements.
- In order to perform NRR you must first measure neutron cross sections for all basis elements, and determine which neutron energies to use.

NRR Key Concepts - Neutron Source

- D(d,n)^{3}He allows production of variable energy neutrons from a single deuteron beam energy into deuteron target.
- Source is accelerator based and does not use radioactive materials. In this application the accelerator energy does not change.
- The angle with respect to the incoming deuteron beam defines the neutron energy

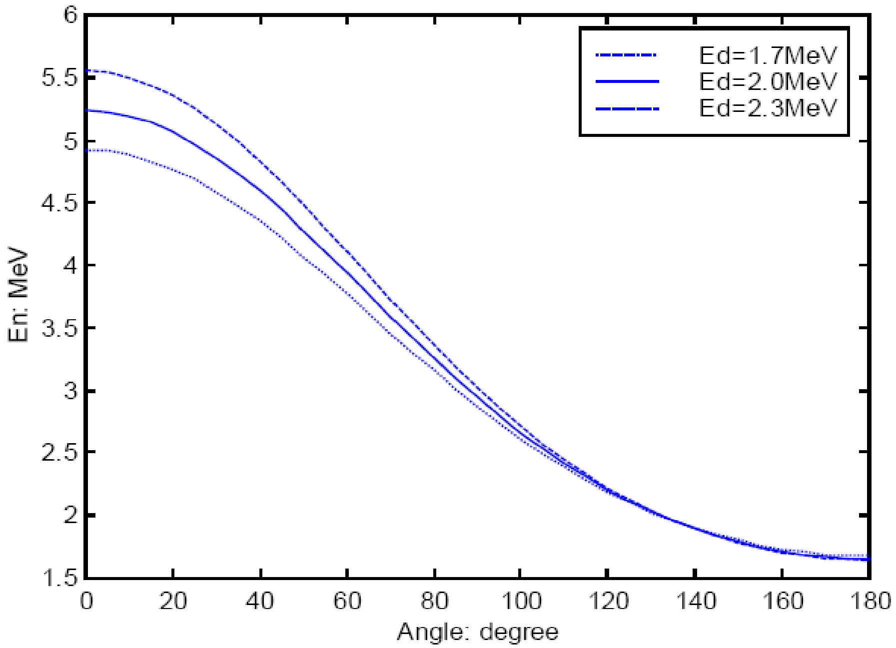
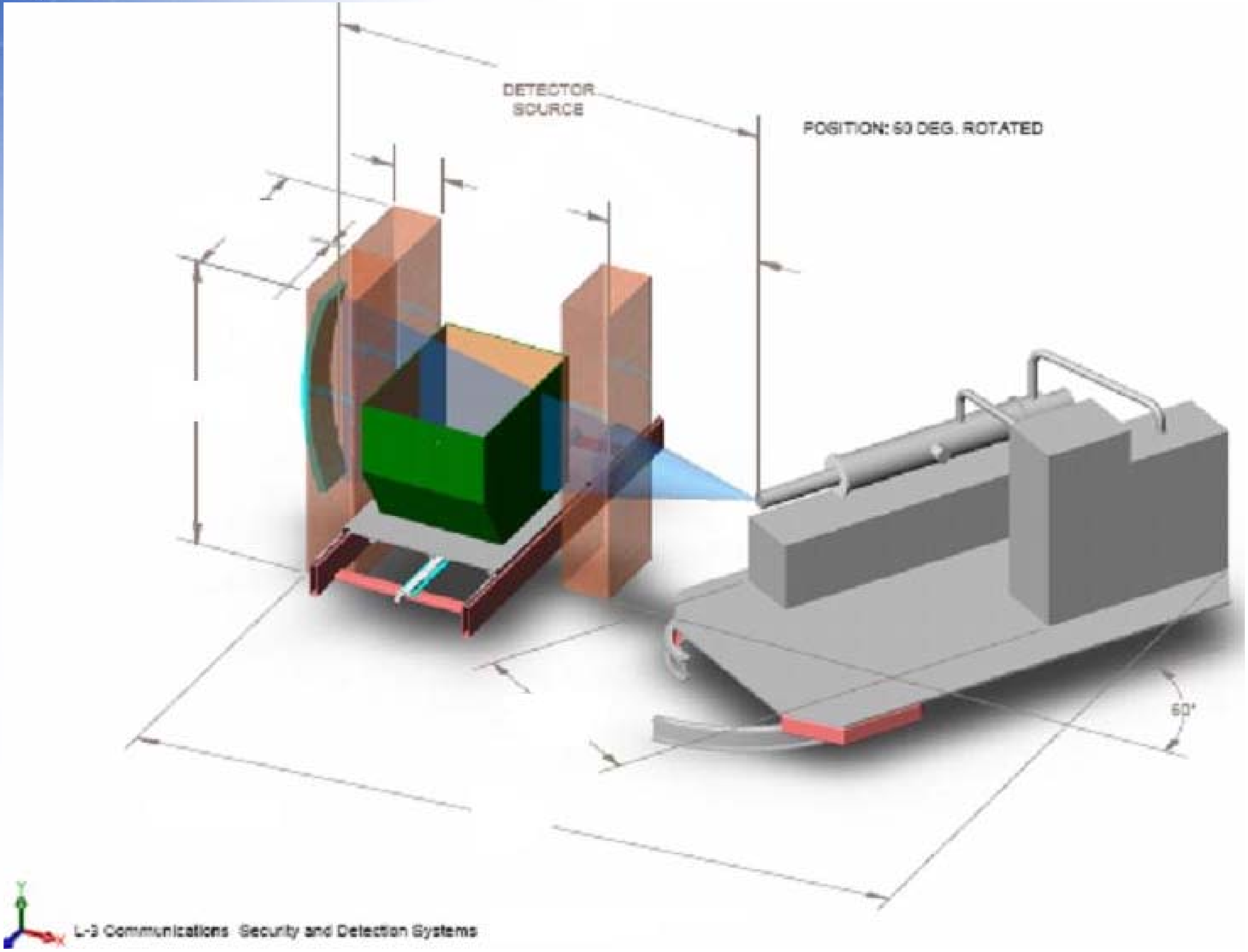


Figure 4.1 DD neutron energy as a function of angle

System Components

- Deuteron accelerator generates incoming single energy deuteron beam. Beam transport system focuses beam onto deuterium gas target to make neutrons. Commercial accelerator. MIT/LLNL gas target.
- Rotation of accelerator and adjustable collimator allows variation of neutron energies. L-3/MIT
- Neutron detection via plastic scintillator and photomultiplier tube. Commercial Detectors.
- Detector electronics / data acquisition system provides experimental control and data recording. L-3 custom electronics and DAS.
- Detection Algorithm – L-3.

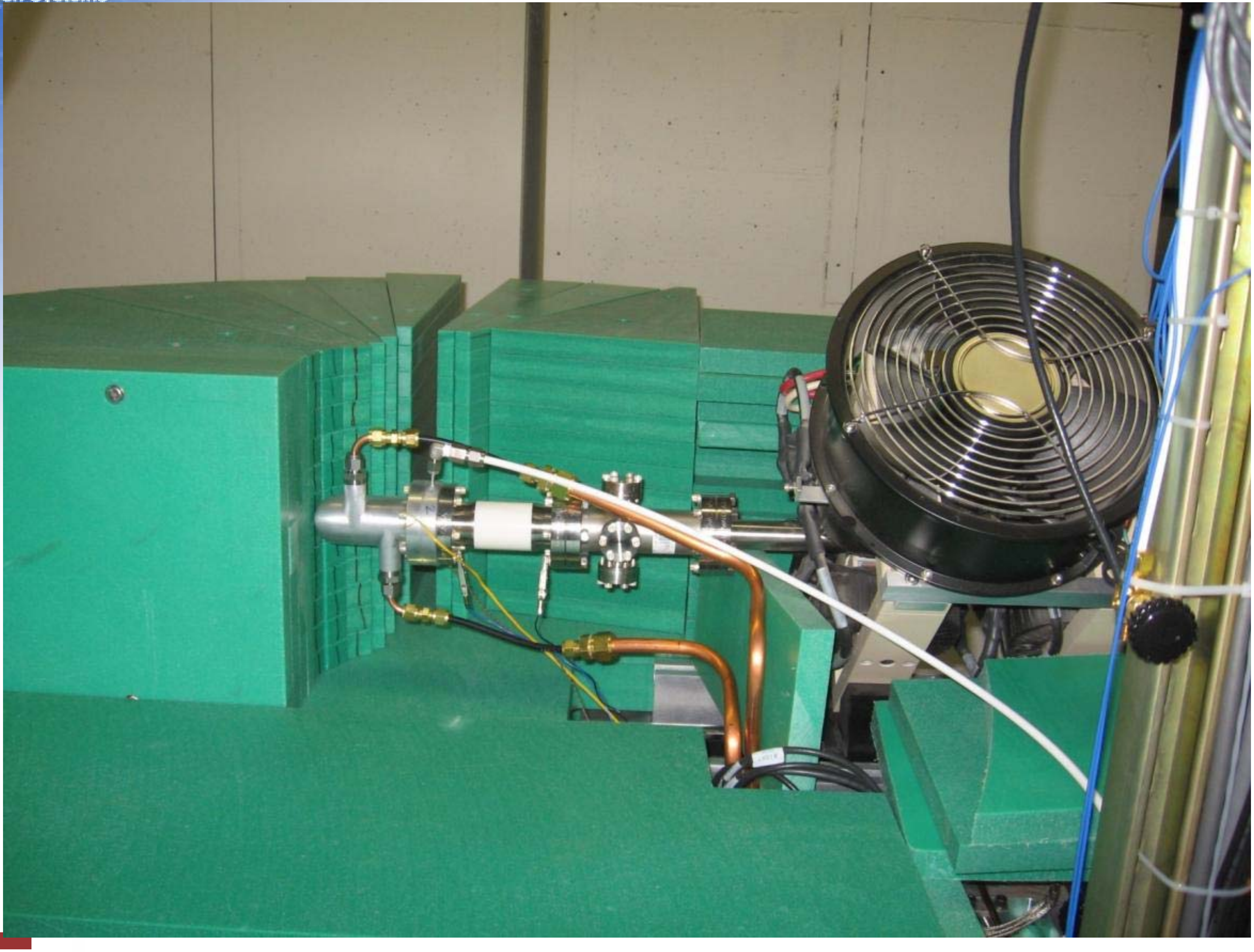
NRR Prototype Concept. Accelerator Rotates To Vary Neutron Energy



Accelerator At 90 Degrees

Accelerator At 90 Degrees Rear View

Deuterium Gas Target



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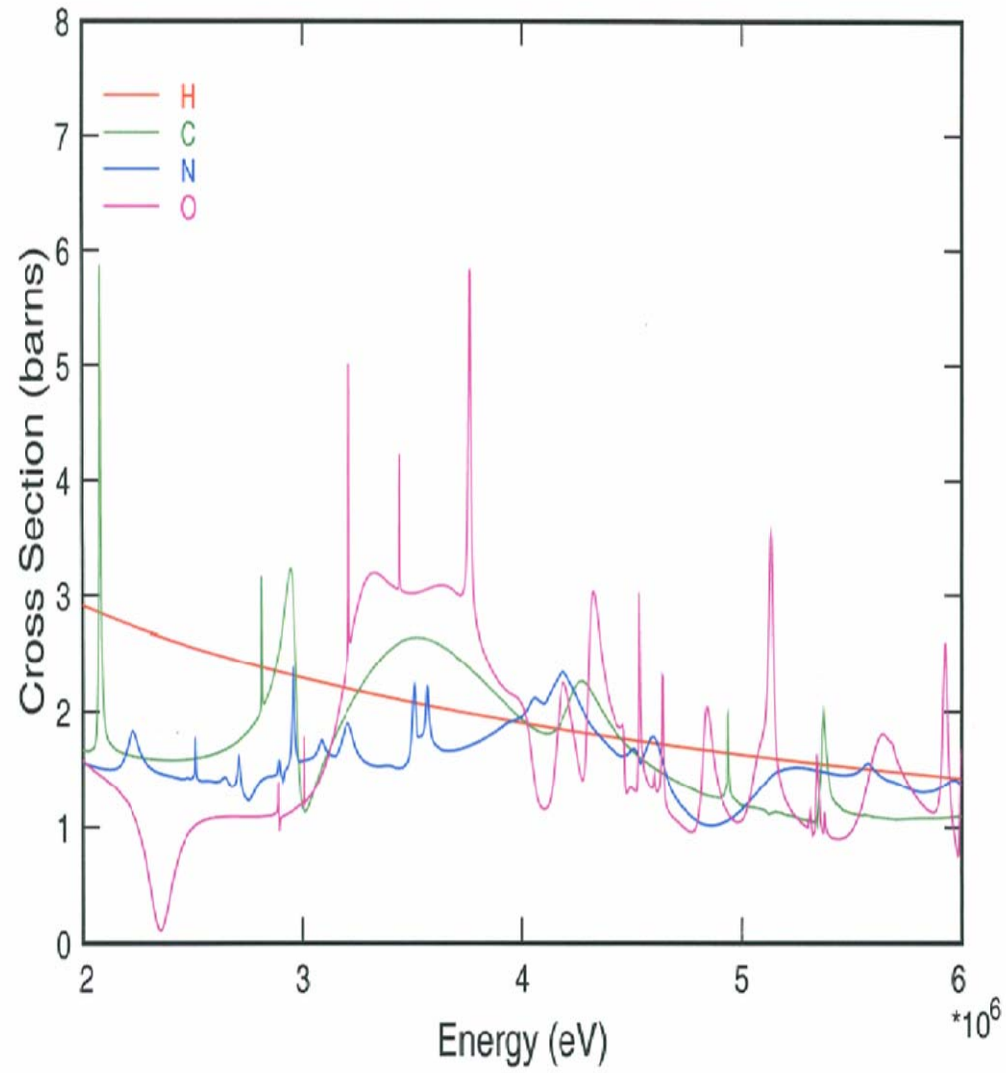
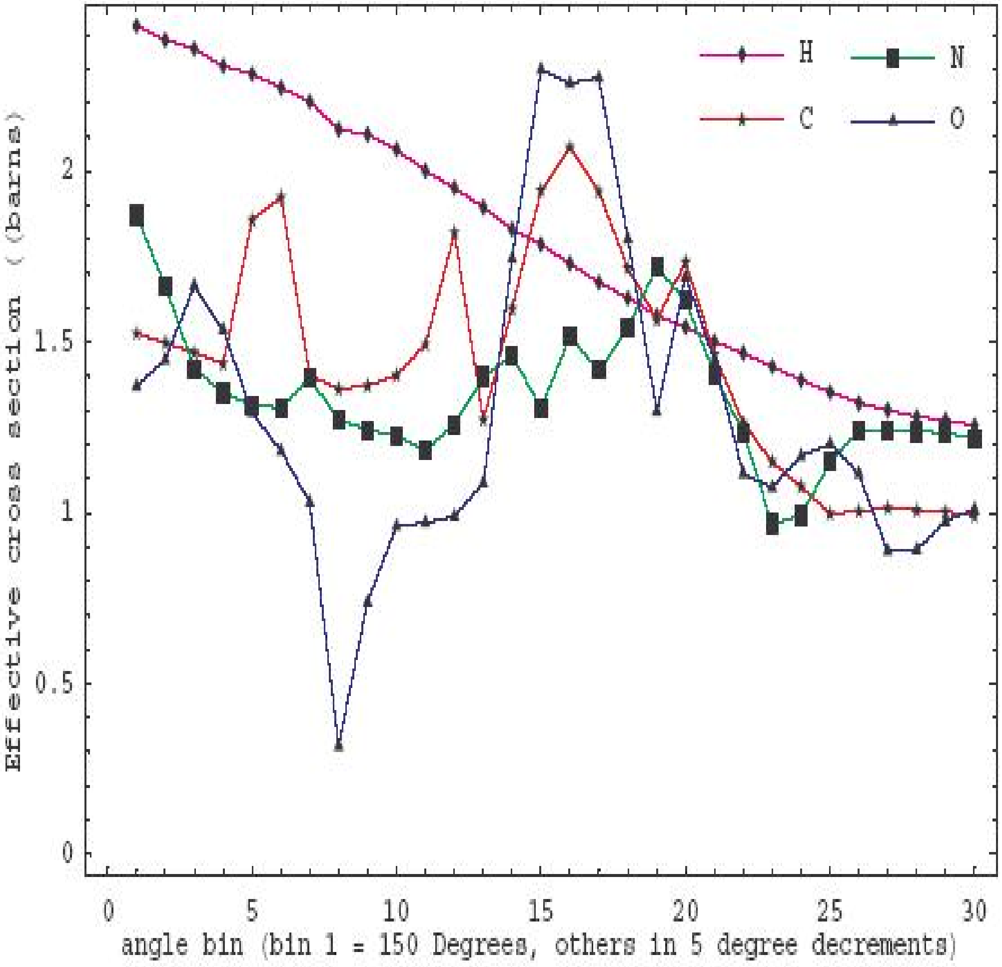
Experimental Results

- Cross section measurements – key to project
- Elemental composition
- Elemental maps
- Results generated by taking images at 7 neutron energies and fitting for basis elements Hydrogen, Carbon, Nitrogen, Oxygen, and Silicon

MCNPX Modeling Shows Impact Of Energy Resolution On Cross Section Measurements.

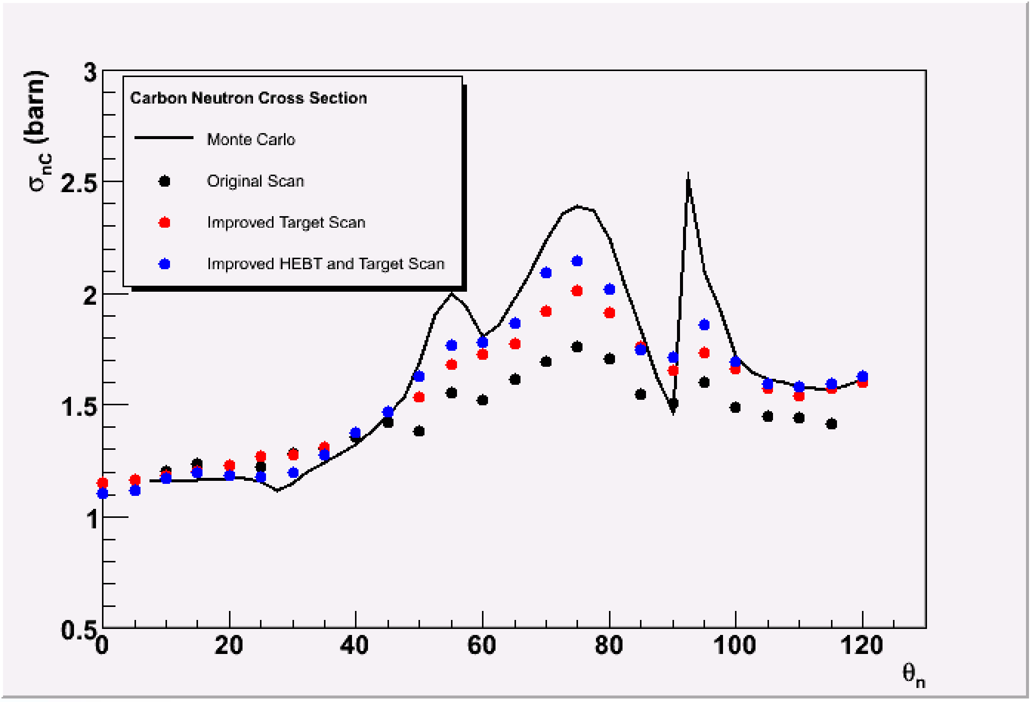


Theory



Simulation

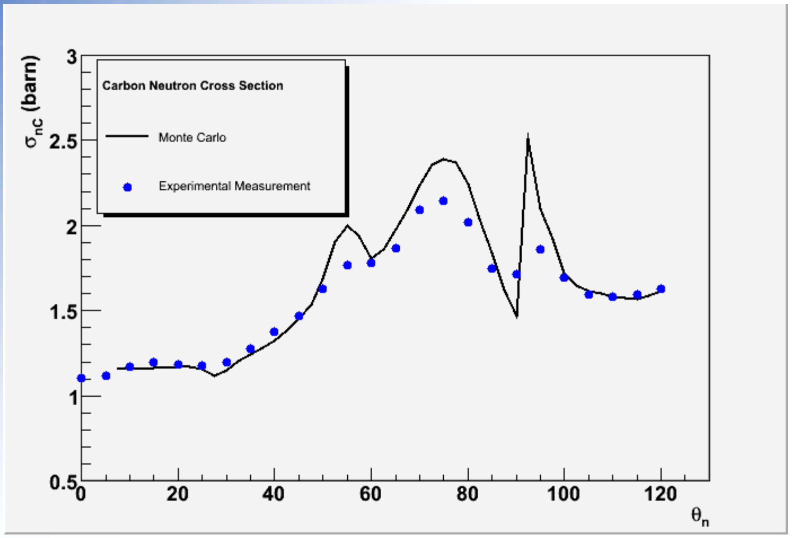
Carbon Cross Section Measurement



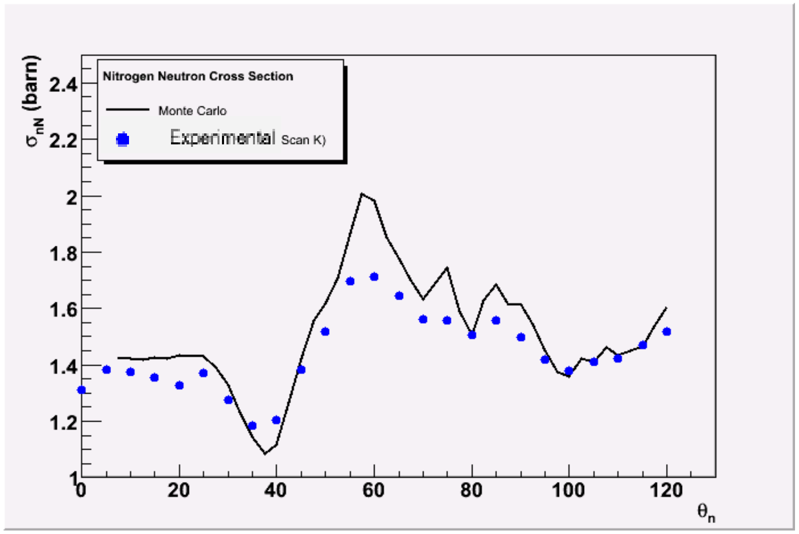
- Initial measuremnt had significantly lower cross section due to high photon background, photon-to-neutron ratio was 1.5
- Target was modified photon-to-neutron ratio was 0.6
- Beam transport modified photon-to-neutron ratio is currently 0.15

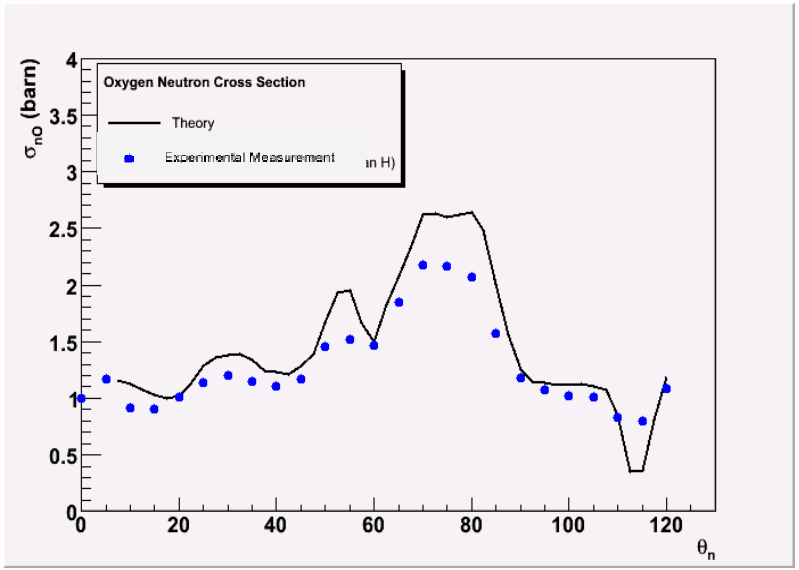
Elemental Cross Sections-Monte Carlo vs. Measurement as a Function of D Beam Angle

Carbon

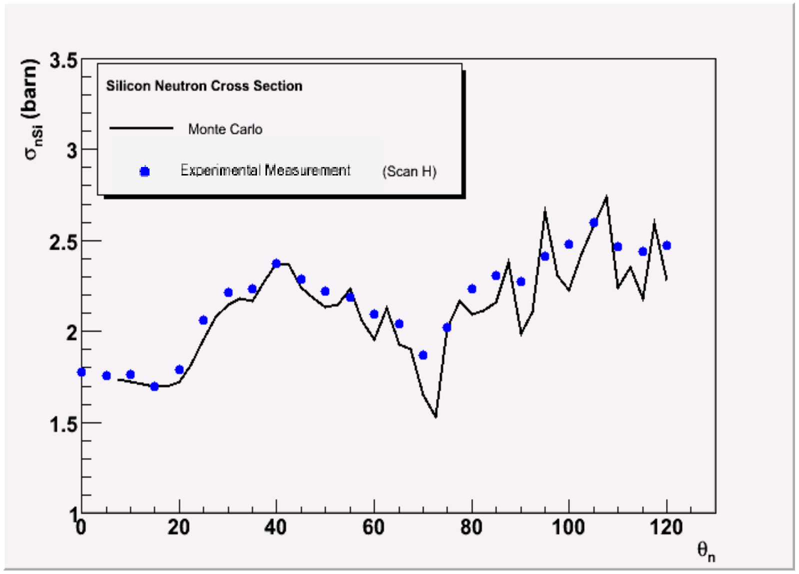


Nitrogen





Oxygen



Silicon

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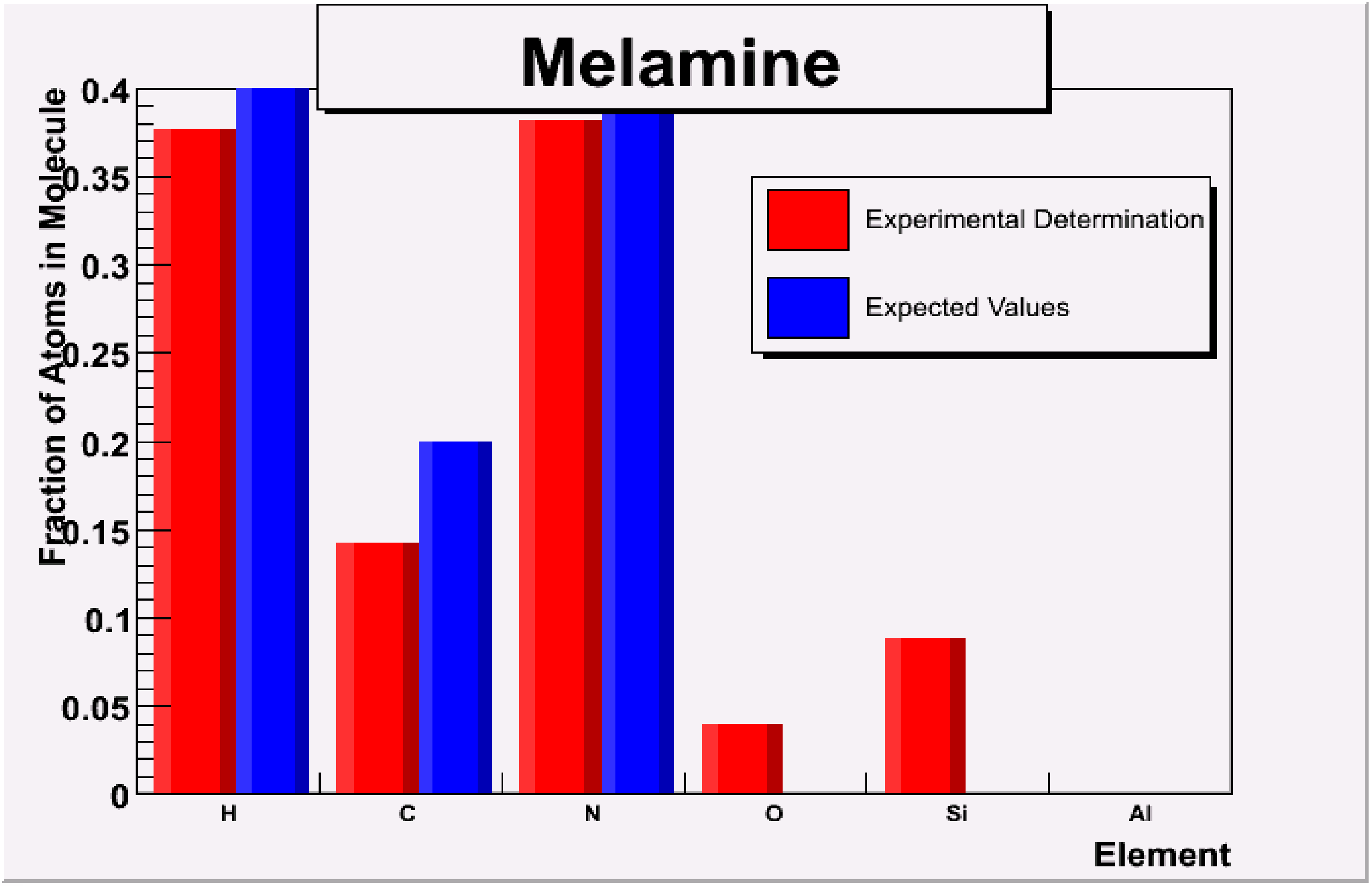
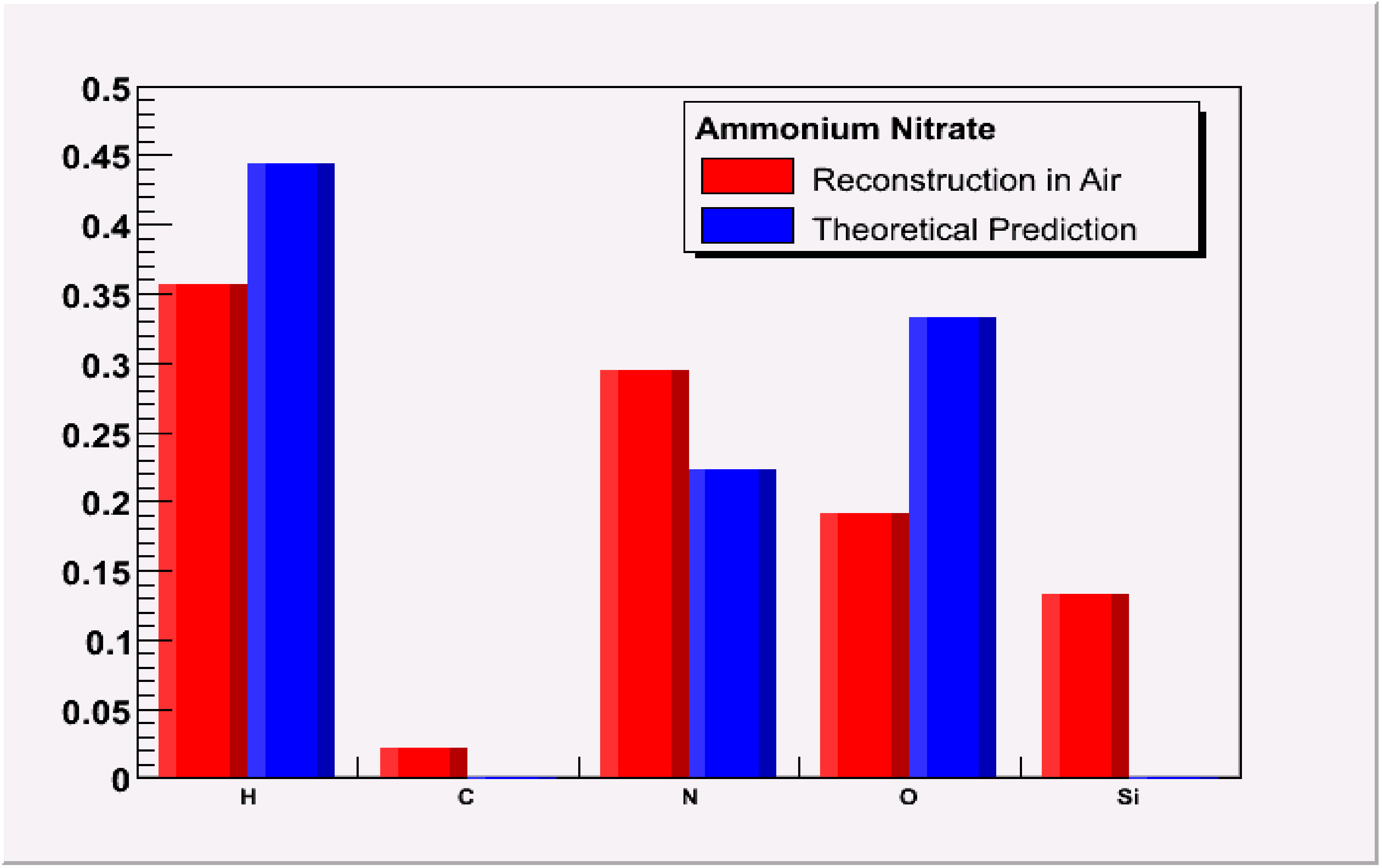
Results of Elemental Calibrations- Measurement of Melamine Chemical Composition (Optimized By Angle Selection)



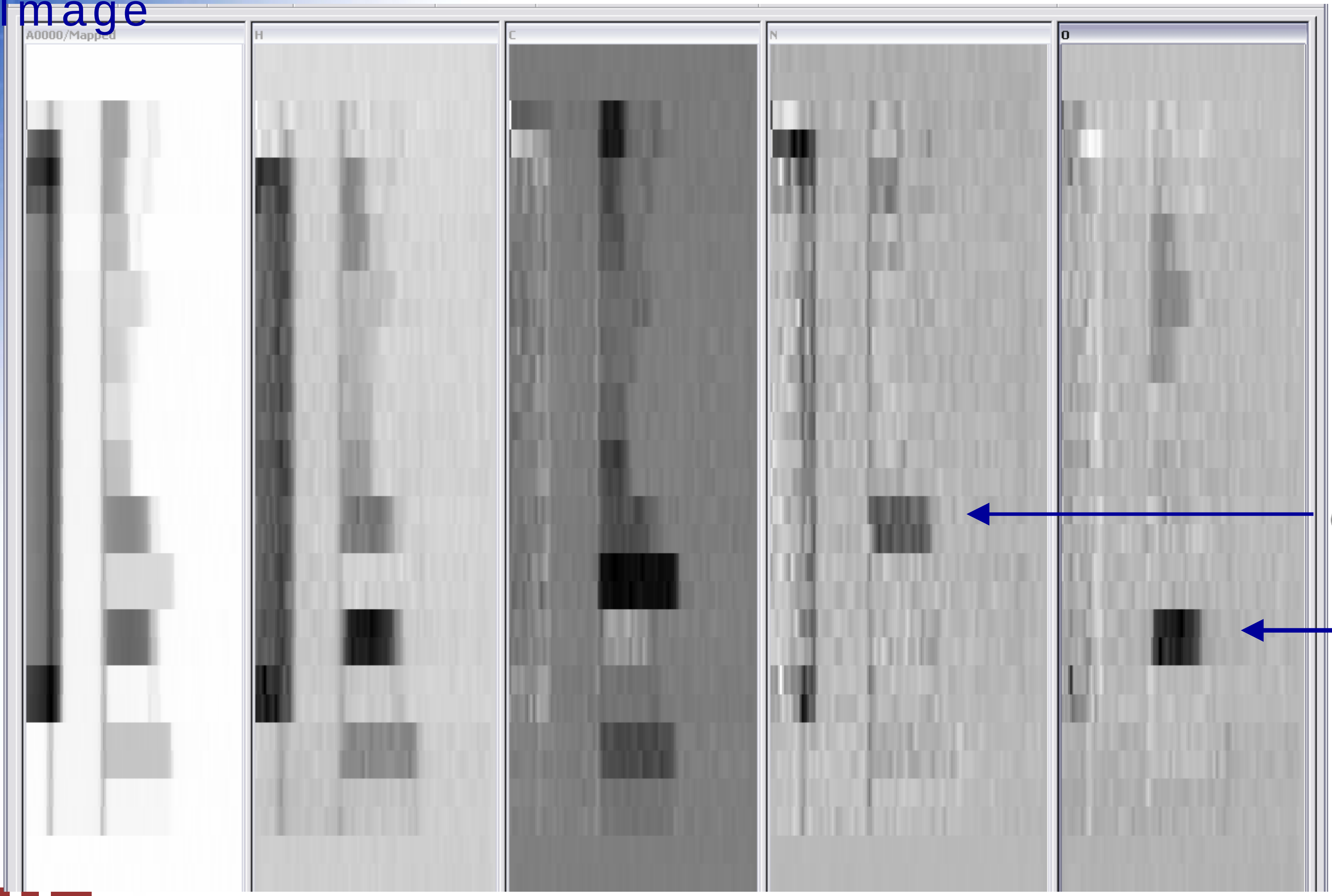
Results of Elemental Calibrations- Measurement of Ammonium Nitrate Chemical Composition (unconstrained)



Elemental Maps

Attenuation Image

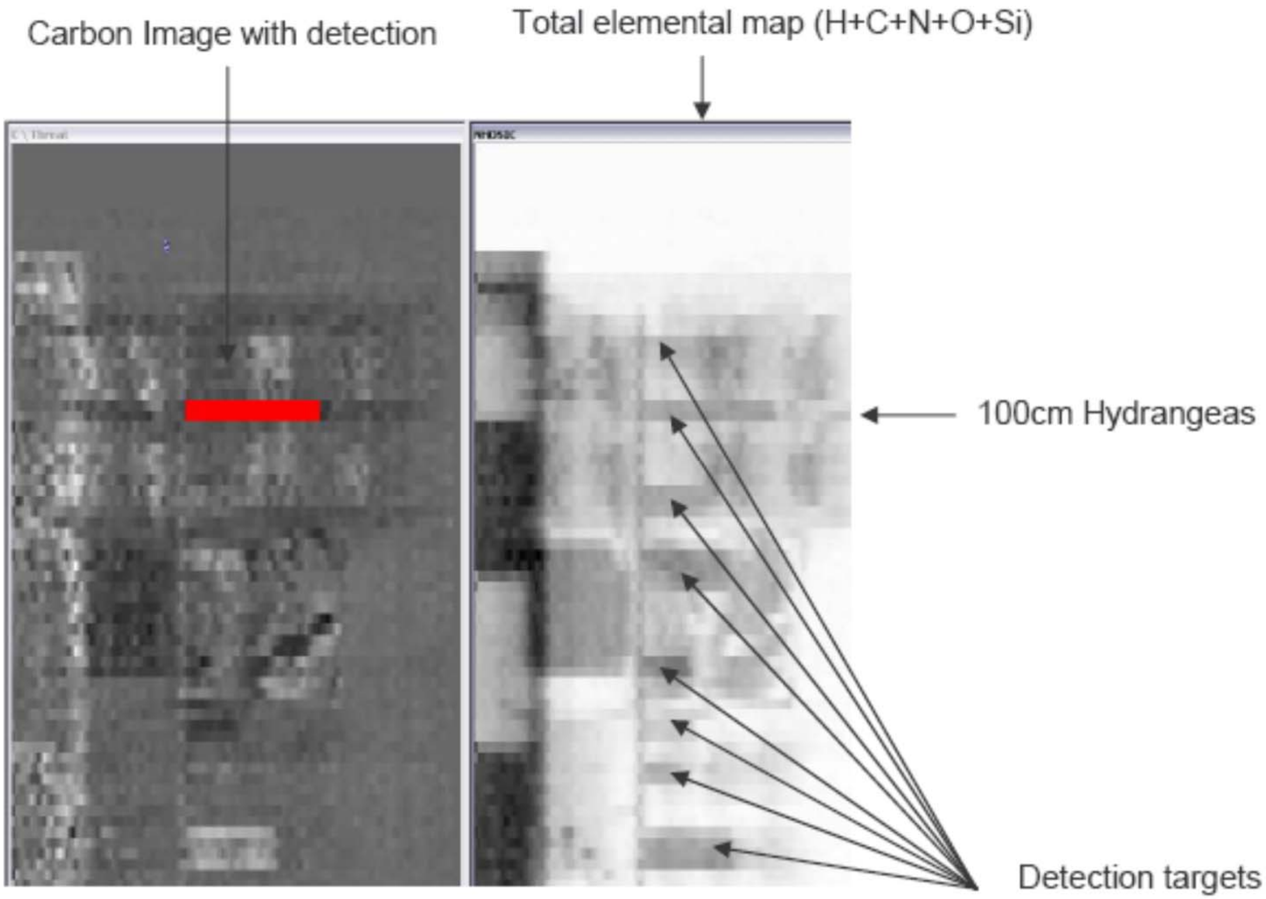
H C N O



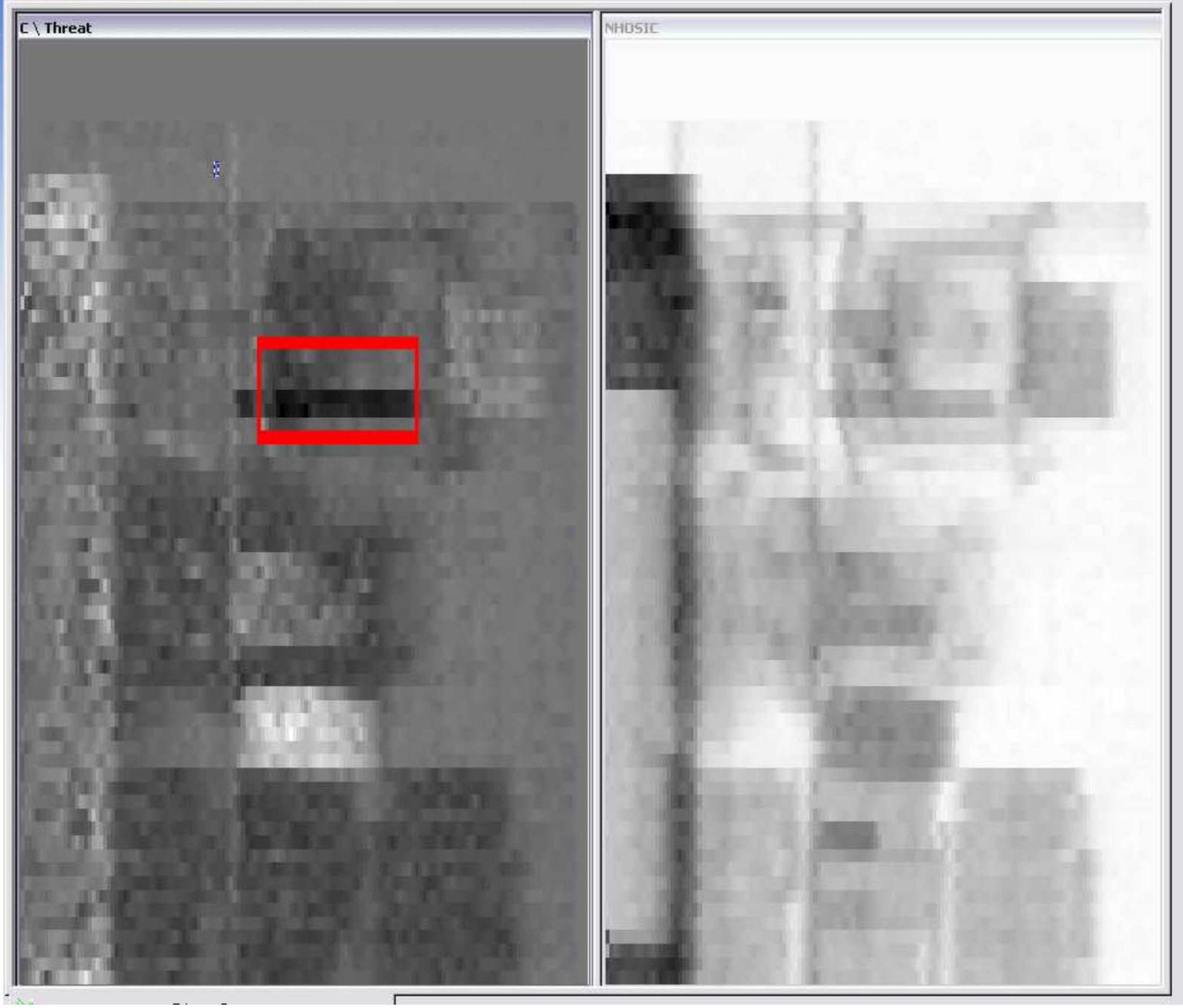
$C_3H_6N_6$

H_2O

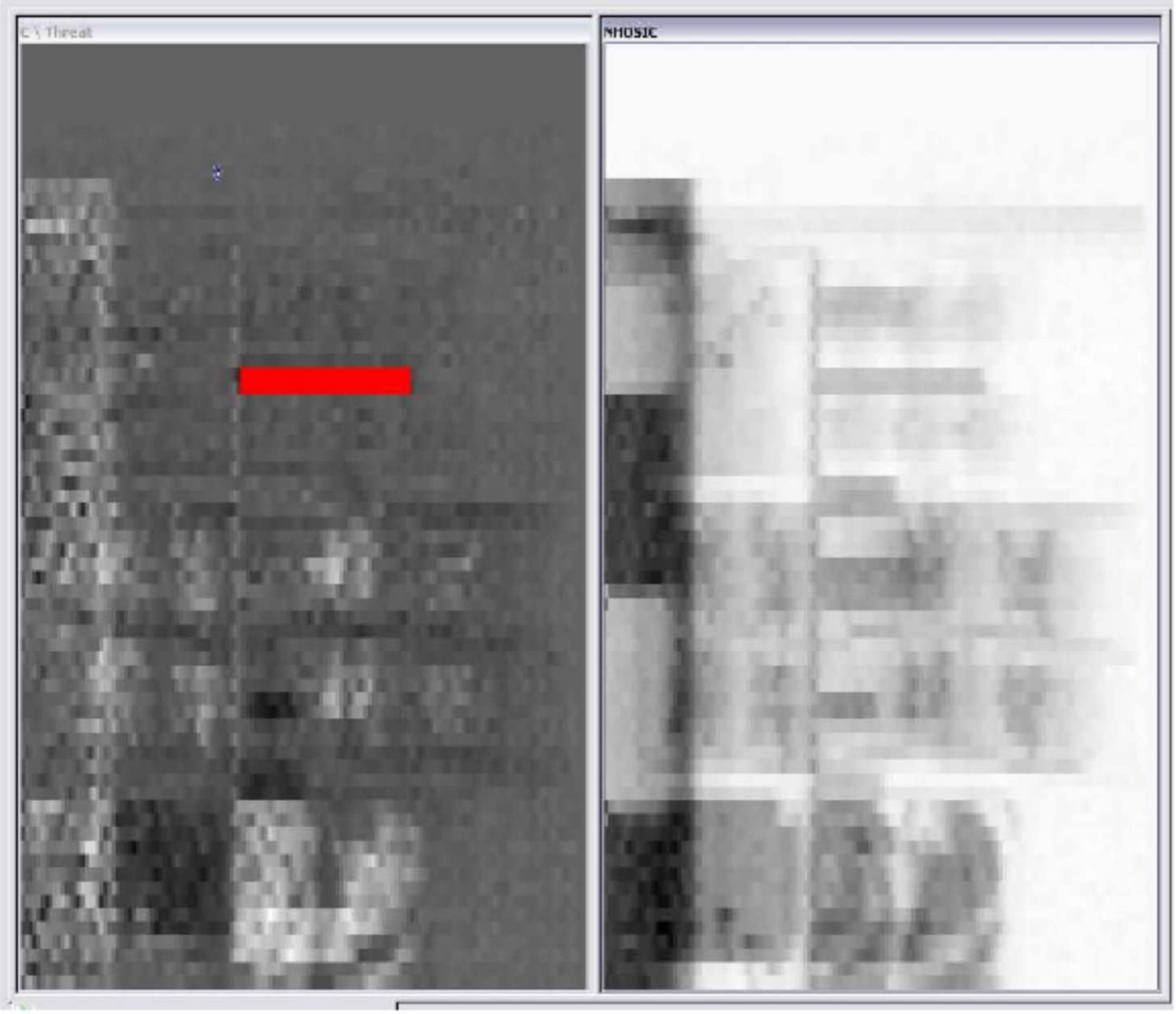
Carbon Detection in Flowers. Target Correctly and Automatically Detected in Typical Air Cargo Background.



Carbon Detection in Electronics. Target Correctly Detected in Typical Air Cargo Background.



Carbon in Produce



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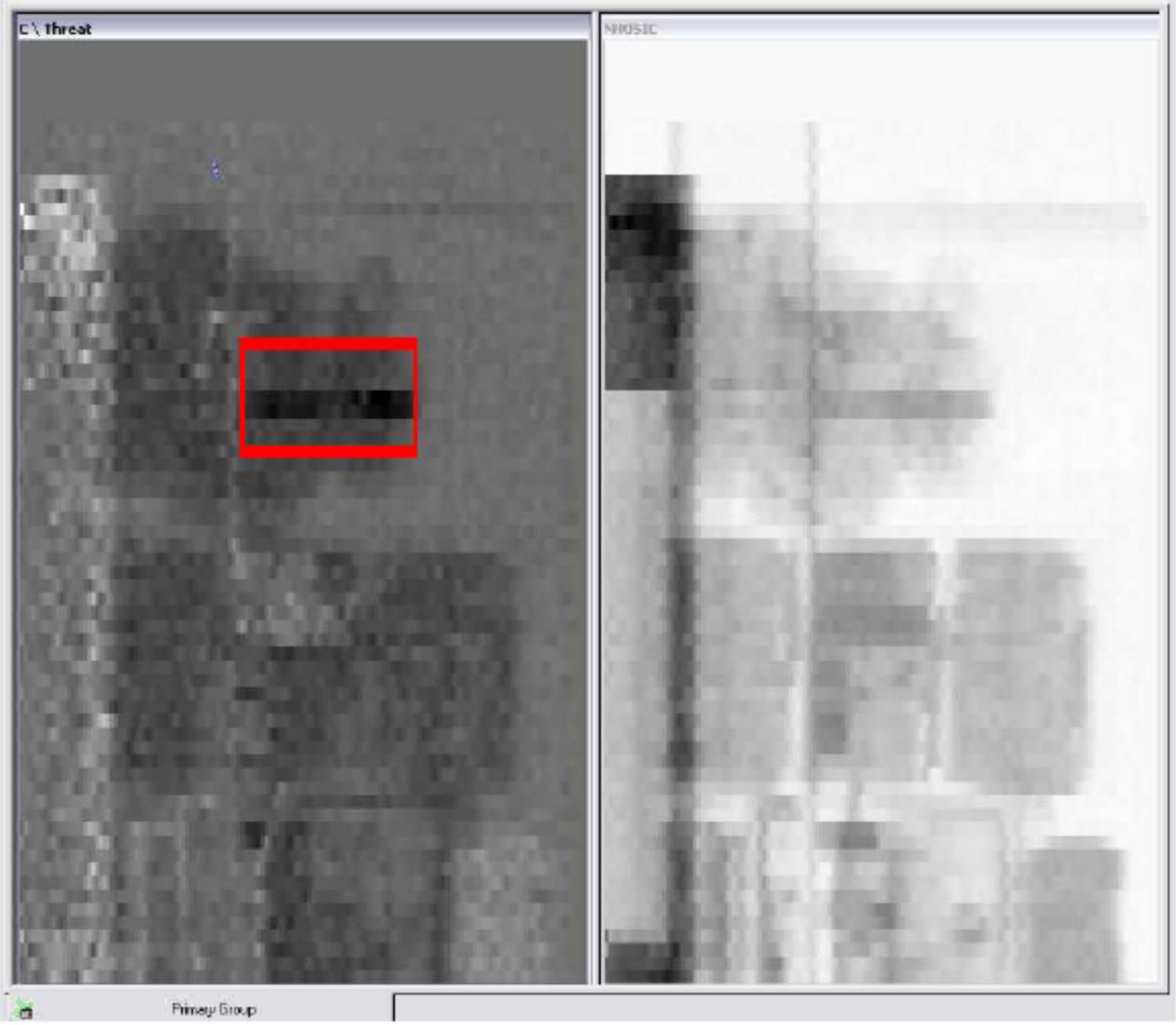
Carbon in Clothes



NRR Performance

- Detected carbon blocks in 17/22 scans in 7 cargo types with preliminary algorithm.
- Because of the short duration of the first phase of this program (2 years) we did not plan to take data at TSA Tech center in Atlantic City. TSA did not supply us with explosives or validated simulants, which made algorithm development very difficult.
- We were able to collect some explosive data at the end of the program and demonstrate explosives detection in LD-3 containers.
- The program was not extended to 5-7 years as initially planned and no further funding was forthcoming.

General Comments On Using Neutrons

- Neutrons are strongly under represented in explosive detection market as compared to photons. This makes them a tough sell to management.
- Residual radioactivity at the source can increase the mean time to repair in some circumstances.
- Shielding requires a large exclusion zone and willingness to wear badges.
- Modeling requires special purpose LANL MC code (MCNP) which DOE may or may not be willing to sell you at a high price.
  - Both models and simulants require knowledge of atom densities.
- All components (except the gas target) demonstrated to function in an airport environment.

Summary

- Measurements conducted on full scale NRR prototype conclusively show multi-element discrimination possible with NRR.
- Capability to measure rough chemical formulas demonstrated.
- Automated detection based on elemental maps in air cargo sized objects demonstrated.

Acknowledgements/References

- MIT Bates Accelerator Laboratory staff
- L-3 Communications Security and Detection Systems staff
- LLNL
- References…..

  - D. Perticone[1,2] , B. W. Blackburn[1], G. Chen[2], W. A. Franklin[1], E. E. Ihloff[1], G. E. Kohse[1], R. C. Lanza[1], B. McAllister[1], and V. Ziskin[1,2], “Fast Neutron Resonance Radiography for Elemental Imaging: First Results (Unpublished).
  - B. W. Blackburn[1], G. Chen[2], W. A. Franklin[1], E. E. Ihloff[1], G. E. Kohse[1], R. C. Lanza[1], B. McAllister[1], D. Perticone[1,2], and V. Ziskin[1,2], “Fast Neutron Resonance Radiography (NRR) for Homeland Security”, 2007 IEEE Nuclear Science Symposium – Honolulu.

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