Ionizing Radiation Techniques for Explosives Detection in Air Cargo

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DHS Explosive Detection Workshop
University of Rhode Island
October 9, 2009

PNNL-SA-68923

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Screening Challenges

- 0.5x0.5x1m^3
- Detect small amounts of explosives
- Low-energy x-ray (80-160kVp)

- 1.6x2.2x3.2m^3
- Detect small amounts of explosives
- *???*

- 2.4x2.4x12m^3
- Detect high-Z threats
- High-energy x-ray (3-10MeV)

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Ionizing-Radiation Options

- X-Ray / Gamma-Ray
  - Transmission Radiography – create 2D projection(s) of 3D contents
    - requires higher penetration than luggage-screening, lower than cargo-container screening
  - Compton Backscatter – 2D image of low-Z material
    - Lower resolution than transmission imaging, higher sensitivity to low-Z material
  - Computed Tomography – 3D (volume) imaging
    - Higher potential for object discrimination than radiography, costlier in time, equipment, and complexity
  - X-ray Diffraction – elemental characterization
    - Lower-energy implies insufficient penetration for size / content of air cargo
  - Nuclear-resonance fluorescence – localized probe of elemental content
    - Requires beam ~10MeV
- General Observations
  - COTS
  - Poor at material ID (anomaly detection systems)

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Ionizing-Radiation Options

- Neutrons
  - Radiography – similar to x-ray radiography
  - Neutron capture – elemental characterization by analysis of gamma-ray emission
    - Requires thermal source (or thermalization in the container)
  - Resonant absorption – image(s) of elemental content
    - Polychromatic beam, image at resonant peaks of elements
  - Inelastic scatter – analysis of gamma-ray emission after scatter
    - Can be performed with high-energy source
  - Elastic scatter – scatter angle varies with Z
    - Has this ever left the lab?
- General Observations
  - More material-specific than x-rays
  - Hard to generate, hard to detect

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Solution Likely to Involve Multiple Modalities

- Likely solution to air-cargo screening integrates multiple interrogation techniques
  - Transmission radiography and backscatter
    - Surface detection of thin explosives by backscatter relaxes detection criteria for transmission imaging
  - Radiography / CT (primary) and elemental characterization (secondary)
    - Allow longer examination time for neutron-based secondary
  - Combined neutron / x-ray radiography
    - Neutrons and photons have different interaction mechanisms
    - Ratio of neutron attenuation coefficient to x-ray attenuation coefficient provides discrimination between materials

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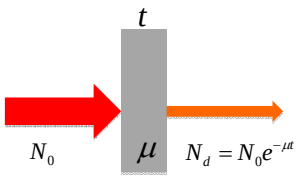
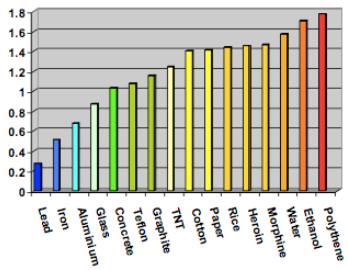
Ration of Attenuation Coefficients – "R-Value"

- Ratio of normalized transmission through material eliminates thickness ambiguity
- R-value discriminates between benign and threat materials
- What about overlap regions, image complexity (clutter)?
- Is there an optimal energy for the neutrons and photons?



$$R = \frac{\ln\left(\frac{N_0}{N_d}\right)_{neutrons}}{\ln\left(\frac{N_0}{N_d}\right)_{photons}} = \frac{\mu_n}{\mu_p}$$



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- Ratio of normalized transmission through material eliminates thickness ambiguity
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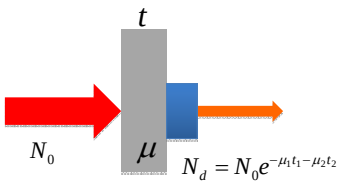
- What about overlap regions, image complexity (clutter)?
- Is there an optimal energy for the neutrons and photons?
- How is the R-value discriminant affected by bremsstrahlung source?



$$R = \frac{\ln\left(\frac{N_0}{N_d}\right)_{neutrons}}{\ln\left(\frac{N_0}{N_d}\right)_{photons}} = \frac{\mu_{n,1}t_1 + \mu_{n,2}t_2}{\mu_{p,1}t_1 + \mu_{p,2}t_2}$$

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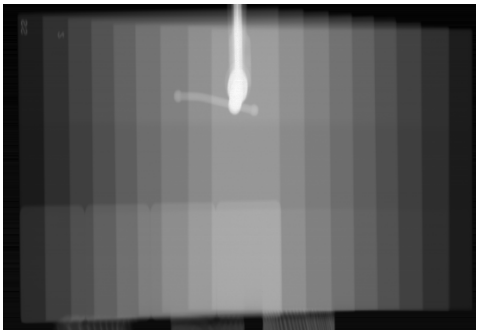
Contrast Metric

- Calculate minimum thickness of threat to change signal through benign material by 10%
- Necessary but not sufficient condition for detection
  - Deployed methods use scene-segmentation techniques for analysis



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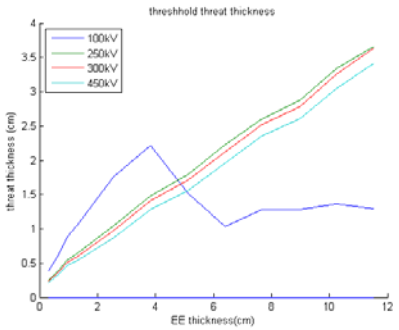
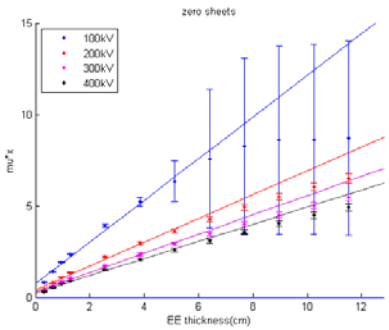
X-ray Contrast Metric



- Minimum thickness of (simulated) threat to change detected signal by 10% as a function of commodity thickness



- Log-corrected attenuation of beam
- Error bars are standard deviation of pixel intensities in ROI

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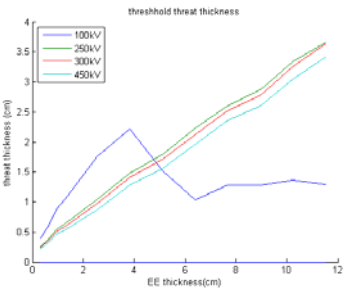
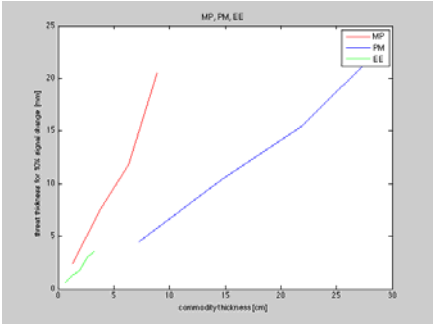
X-ray and Neutron Contrast Metric





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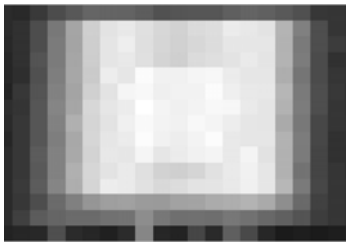
Simulated Electronics Cargo

- Simulated EE commodity has density and approximate Z_{eff} as generic "computer parts"
- Composed of sheets of metal and glass to provide limited spatial heterogeneity (and allow modeling / simulation

X-ray Radiograph

Neutron Radiograph



contrast metric 1: % change in signal due to threat
- neutron contrast (avg. pix. 58-68): 15.690305
- x-ray contrast (avg. pix. 260-310): 7.826237

contrast metric 2: (max-min)/(max+min)
- neutron contrast (avg. pix. 58-68): 0.072745
- x-ray contrast (avg. pix. 260-310): 0.037658

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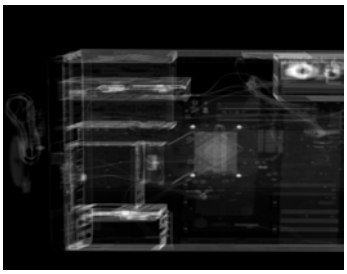
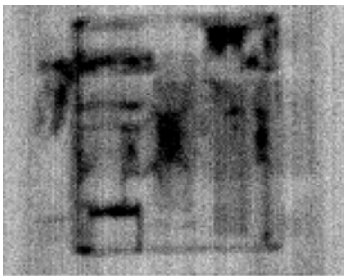
Electronics Example

X-ray Radiograph



Neutron Radiograph



2 sheet simulants

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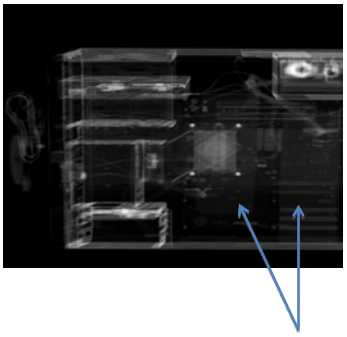
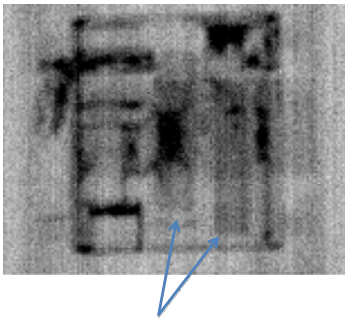
Electronics Example

X-ray Radiograph



Neutron Radiograph



2 sheet simulants

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What Do the Neutron / Photon Correlated Radiographs Tell Us?

- Can show that neutron interrogation improves the minimum detectable thickness for some threat/commodity combinations
- Low count rates limit SNR and spatial resolution (i.e., inadequate neutron generator capabilities)
- Implementation
  - High-resolution, low-noise x-ray image
  - Low-resolution, high-noise image
  - What are the limits (time, etc.) for practical implementation
- What is the best neutron system to use?
  - Electronic collimation using associated alpha particle (nAPI)?
- What is the best way to combine these data?
  - The air-cargo initiative has a data-exploitation task that is exploring this question

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Conclusions

- Multi-pronged approach will be necessary to improve explosives detectability
- Registered neutron / photon radiography is a promising approach
- Framework to determine optimal energies / sources

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Air-Cargo Screening Initiative – Credits

- This research was conducted under a Stevenson-Wydler (15 USC 3710) Cooperative Research and Development Agreement (CRADA) number NFE-07-01081 (a funds-in CRADA sponsored by Battelle Memorial Institute.)
- CRADA partners include:
  - Battelle Memorial Institute
  - Brookhaven National Laboratory
  - Idaho National Laboratory
  - Oak Ridge National Laboratory
  - Pacific Northwest National Laboratory

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