Imaging and Identification Technologies for Homeland Security

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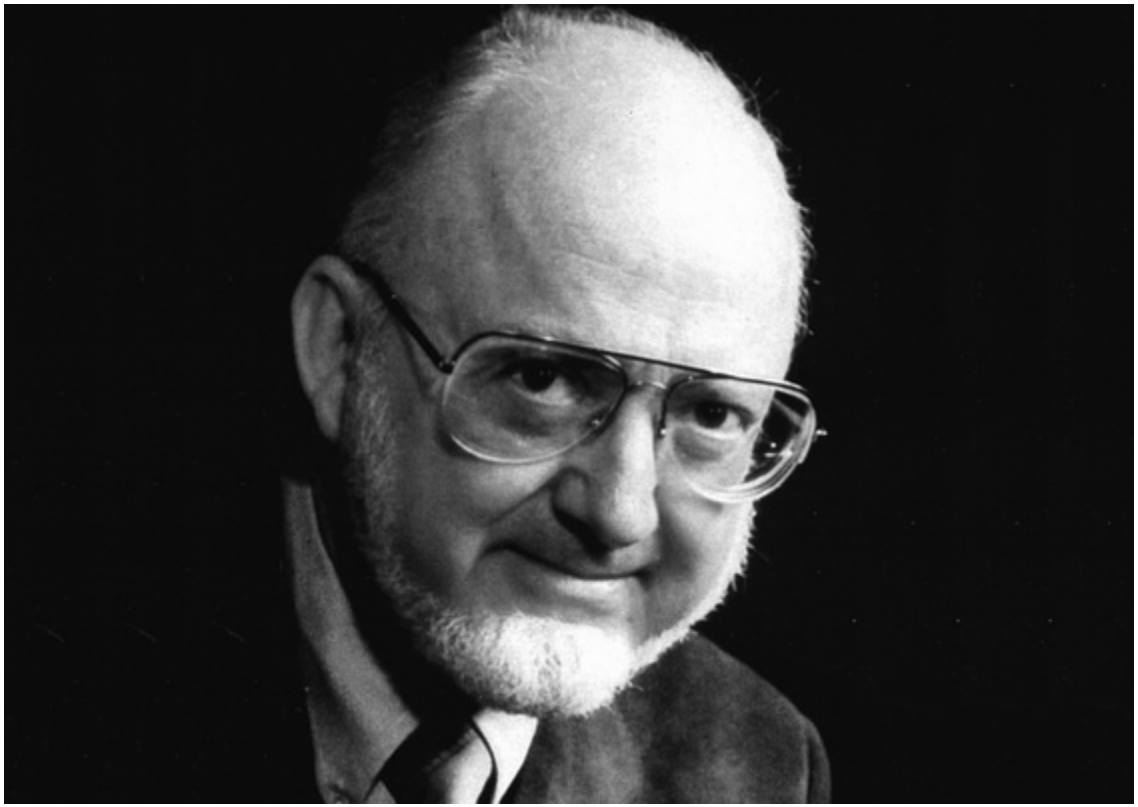
AS&E®

Jack C. Greene 1921 - 2001



Health Physics 82(4):551-552, April 2002

The Big Question: What is in the Box?

Ships with 7,000 TEU capacity are now in service
Ships with 12,000 TEU capacity expected by 2011

Detection and Interdiction Is a Big Job…

- 95,000 miles of shoreline and navigable waters
- Each year, >360 ports handle
  - 9 million cargo containers
  - nearly 200 million passengers
- Each day, >500 airports handle
  - 30,000 flights and
  - 2 million passengers
- Each year, land border crossings deal with
  - >500 million people
  - 130 million vehicles
  - 2.5 million rail cars

--Investors' Business Daily, 28 June 2004

The Threat

- Explosives, weapons
- Terrorist infiltration via sea containers, trucks
- WMD
- Other contraband
  - drugs
  - high-tariff materials

Technologies for Imaging and Identification

- Intelligence reports
- Cargo tracking technology
- Manual search techniques
- Canine detection
- Trace detection technologies
- Bulk detection technologies

Manual Search Techniques

- General Features
- People
- Hand-Carried Items
- Mailed or Shipped Items
- Vehicles
- Buildings and Property

Canine Detection

- Substances Detected
- Strengths
- Limitations
- Costs
- Training

Trace Detection Technologies

- Chemical, Drug, and Explosive
  - Ion Mobility Spectrometry (IMS)
  - Field Ion Spectrometry (IMS)
  - Surface Acoustic Wave (SAW) Sensors
  - Mass Spectrometry
  - Raman Spectroscopy
  - Gas Chromatography/Surface Ionization Detection
- Radiation Detection
  - Passive
  - Active

Bulk Detection

- Detection not from residual contamination but by the actual, macroscopic mass of the substance
- Simplest form: manual search
  - based upon visual discovery by a human
- Technology-based bulk detection
  - the item to be screened is irradiated with some sort of incident radiation
  - radiation that is transmitted, backscattered, or emitted from the contraband material is subsequently collected and analyzed

Bulk Detection Technologies

- Ultrasound
- Eddy Current Testing
- Millimeter Wave and Microwave Imaging
- Transmission X-ray Systems
- Backscatter X-ray Systems
- Dual Energy X-ray Systems
- Computed Tomography (CT) X-ray Systems
- X-ray fluorescence
- Muon scattering
- Thermal Neutron Activation (TNA)
- Pulsed Fast Neutron Analysis (PFNA)

Ultrasound

Ultrasound Imaging and Detection

- one and two-dimensional imaging
- medical ultrasound imaging available for years
- material signatures
- discrimination of contents of sealed containers

PNNL's Ultrasonic Pulse Echo

- a hand-held gun
- transmits ultrasonic pulses
- detects return echoes
- can determine the contents of a sealed container
- sensitive enough to distinguish between diet and regular Coca-Cola
- helps users find objects or compartments in liquid-filled containers and solid materials, including
  - shipping drums
  - metal ingots

http://www.pnl.gov/breakthroughs/win-spr02/special4.html

Ultrasonic Pulse Echo instrument

- originally developed inspect chemical weapon stockpiles in Iraq following the 1991 Gulf War
- sensor is positioned on the outside wall of the container
- sound waves are transmitted
- return echoes bouncing off the other side of the container are analyzed for
  - time-of-flight
  - amplitude decay
- identify the characteristics of the contents and compare those features against information in the data library
- can measure how full a container is
- find cavities or hidden packages within the container that might hold drugs or other smuggled goods

Eddy Current Testing

Eddy Current Material Identification

- Most metals are similar in appearance
- hard or impossible for border inspectors to visually determine whether a metal is what it's purported to be
- PNNL developed the Materials Identification System (MIS)
- touch a piece of metal with a probe
- compare it with a database of known materials

PNNL's Materials Identification System (MIS)

- MIS can identify material that may be used for nuclear weapons applications
- system
  - a laptop computer
  - a plug-in instrument card
  - a hand-held probe
- probe passes over a piece of metal
- instrument card measures the flow of electrical currents through the metal
- ease of flow--or, alternately, resistance--varies from one metal to another

Materials Identification System (MIS)

- compare and reconcile against an extensive U.S. Customs database
- determines whether the metal is what is declared or purported to be
- also indicates the most likely identity of the metal
- may search database for additional information including the classification of the metal and regulations that apply

Materials Identification System (MIS)

- MIS helps border inspectors determine if a shipment of metals has been labeled fraudulently to avoid a higher duty fee
- both MIS and the ultrasound system excel at picking out commingled items, a common smuggling approach
- Other applications
  - used at Hanford to inspect excessed equipment
  - identify items that may impose special export controls requirements
- http://www.pnl.gov/news/1997/bnw97_26.htm

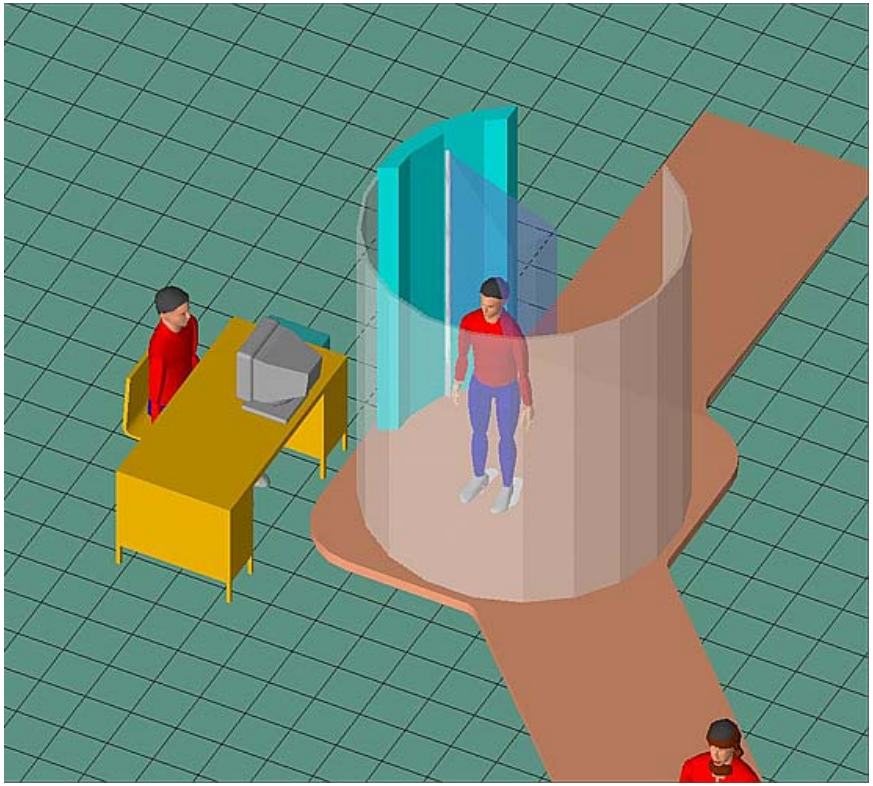
Radiofrequency (RF) Imaging

Millimeter Wave and Microwave Imaging

- Concealed weapons made of plastic, ceramics and metal can be detected with a holographic imaging system
- http://availabletechnologies.pnl.gov/securityelectronics/scanner.stm
- wideband mm-wave holographic imaging system
- developed for TSA to screen airline passengers for weapons
- could be used to secure
  - other mass transit systems including subways and trains
  - government buildings, courtrooms, embassies, offices and prisons
  - nuclear sites
  - public gathering places such as concert and sporting arenas and religious shrines
  - companies concerned about theft prevention

PNNL's Personal Security Scanner

- identifies metal, plastic and ceramic weapons concealed under clothing
- emits millimeter radio waves that penetrate clothing, but bounce off the body and other objects
- reflected waves picked up by a transceiver
- digitized
- 3-D holographic image-processing forms high-resolution radar images of the person under surveillance along with any associated body-worn concealed object



Personal Security Scanner

- Privacy algorithms based on neural networks and other image processing techniques are used to locate and segment the concealed objects and place any detected object on a gender-neutral wire frame mannequin or human silhouette
- A security guard who responds to the alarms generated by the privacy algorithms can easily spot the segmented threats and their locations

Advantages or RF Imaging over Metal Detectors or X-ray Imaging

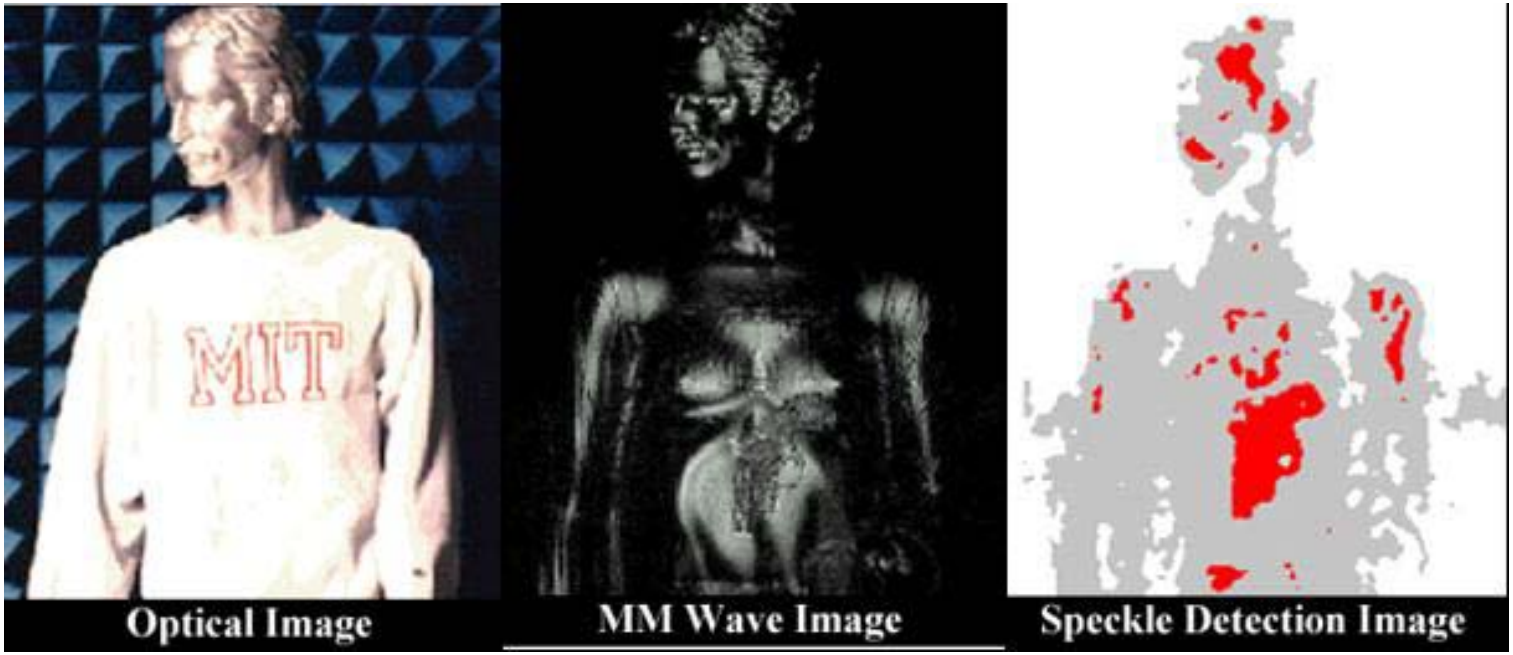
- metal detectors cannot screen for plastic or ceramic weapons
- RF holographic imaging system can identify metallic and nonmetallic guns concealed under clothing
- has potential for detecting plastic explosives
  - backscatter x-ray systems are excellent at this, too

Personal Security Scanner Benefits

- non-ionizing mm waves are not harmful to humans at these intensities
  - no deterministic effects
  - well below threshold for stochastic effects
- elimination of privacy concerns
- not physically invasive
- high speed detection that facilitates crowd movement and decreases congestion in high traffic public areas

Personal Security Scanner Benefits

- speckle detection can be displayed
- visible light, millimeter RF, and speckle detection images
  - Note the clear outline of the gun in the speckle detection image that is harder to discern in the millimeter RF image



Transmission X- and Gamma-Radiation Systems

X-ray Imaging Technology

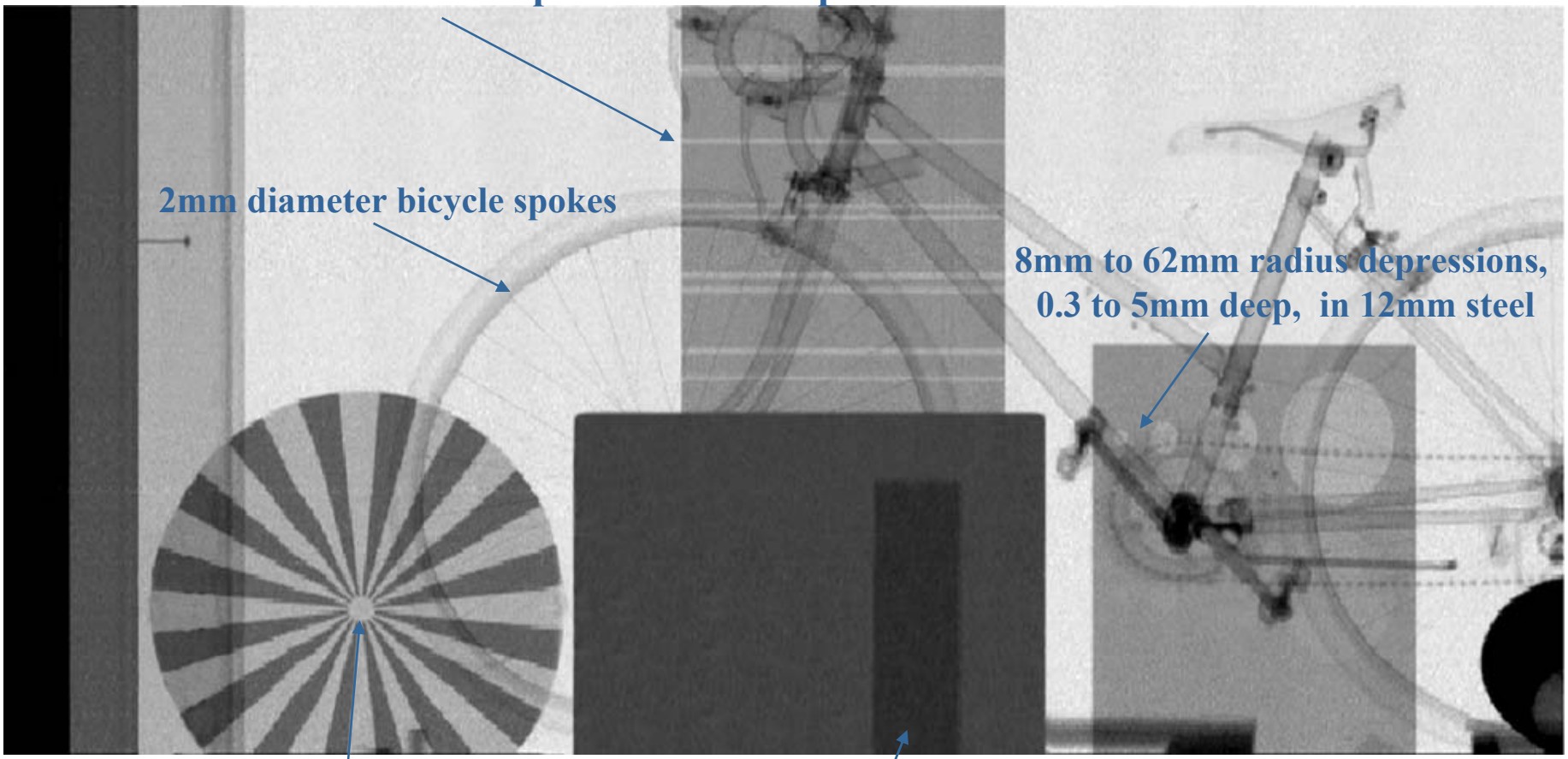
- Light and moderately-loaded cargoes can be inspected by x rays and gamma rays with relatively low energies
  - X rays can be tube-generated up to 500 keV, several kilowatts
  - Gamma rays from ^{137}Cs at 662 keV or ^{60}Co at approximately 1.2 MeV (typically 37 GBq (1 Ci) source strength)
- Heavily loaded cargoes require penetrating radiation in excess of 2 MeV
  - Linear Accelerator (LINAC) sources

Shaped Energy

Shaped Energy - A Family of Systems

- ***Technology for combining high energy transmission with backscatter***
  - ***3.8 MeV LINAC, 3.6 m from container***
  - ***Low dose***
  - ***High resolution***
  - ***High penetration (up to 30 cm steel equivalent) for dense cargo interrogation***
  - ***Broad versatility***
    - ***Backscatter can be from 1 or 2 sides, or from above for orthogonal view***
  - ***Moderate cost compared to other high energy systems***

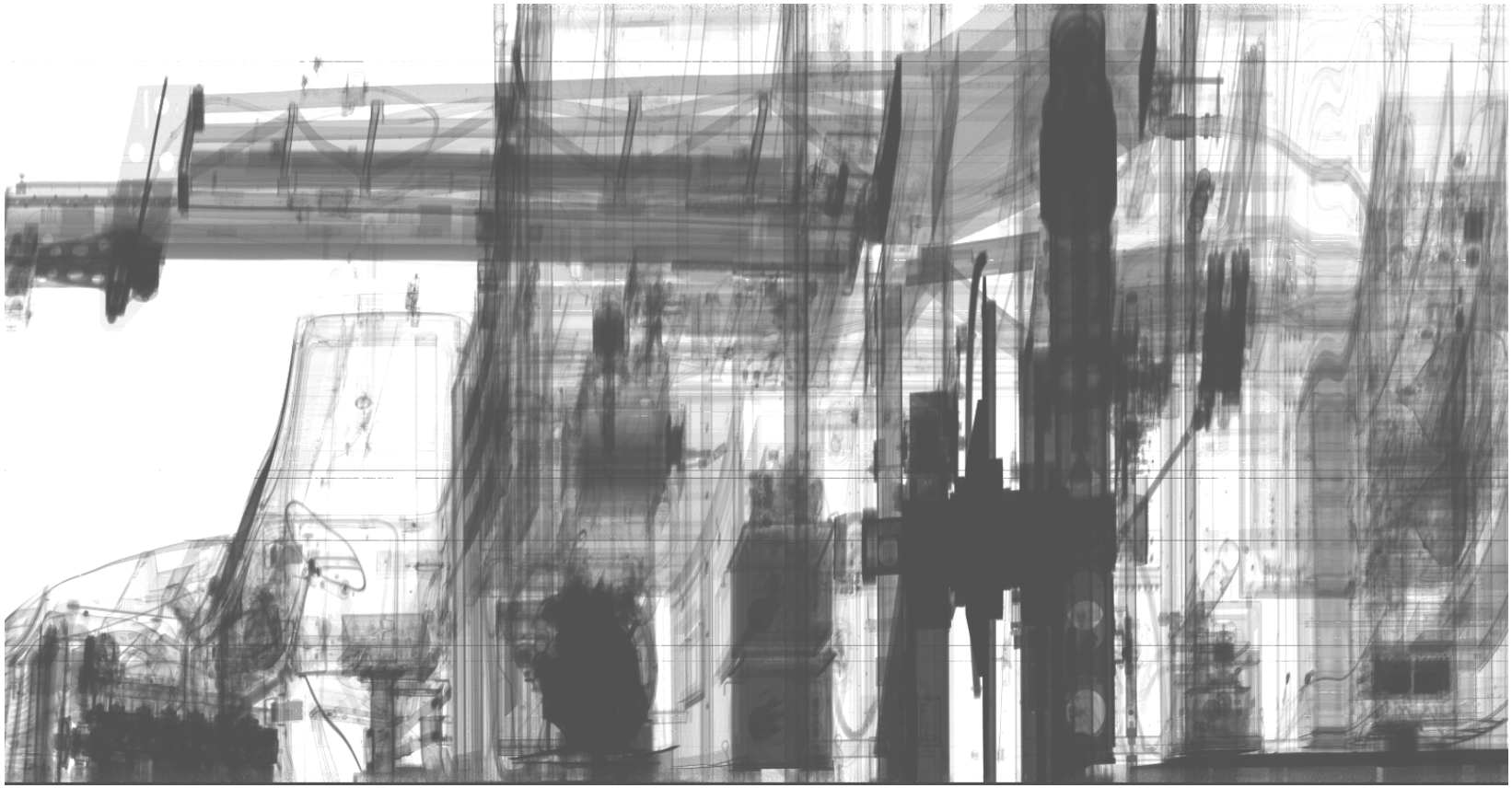
Shaped Energy Image



Resolution phantom
16 distinguishable segments in
25mm diameter center region

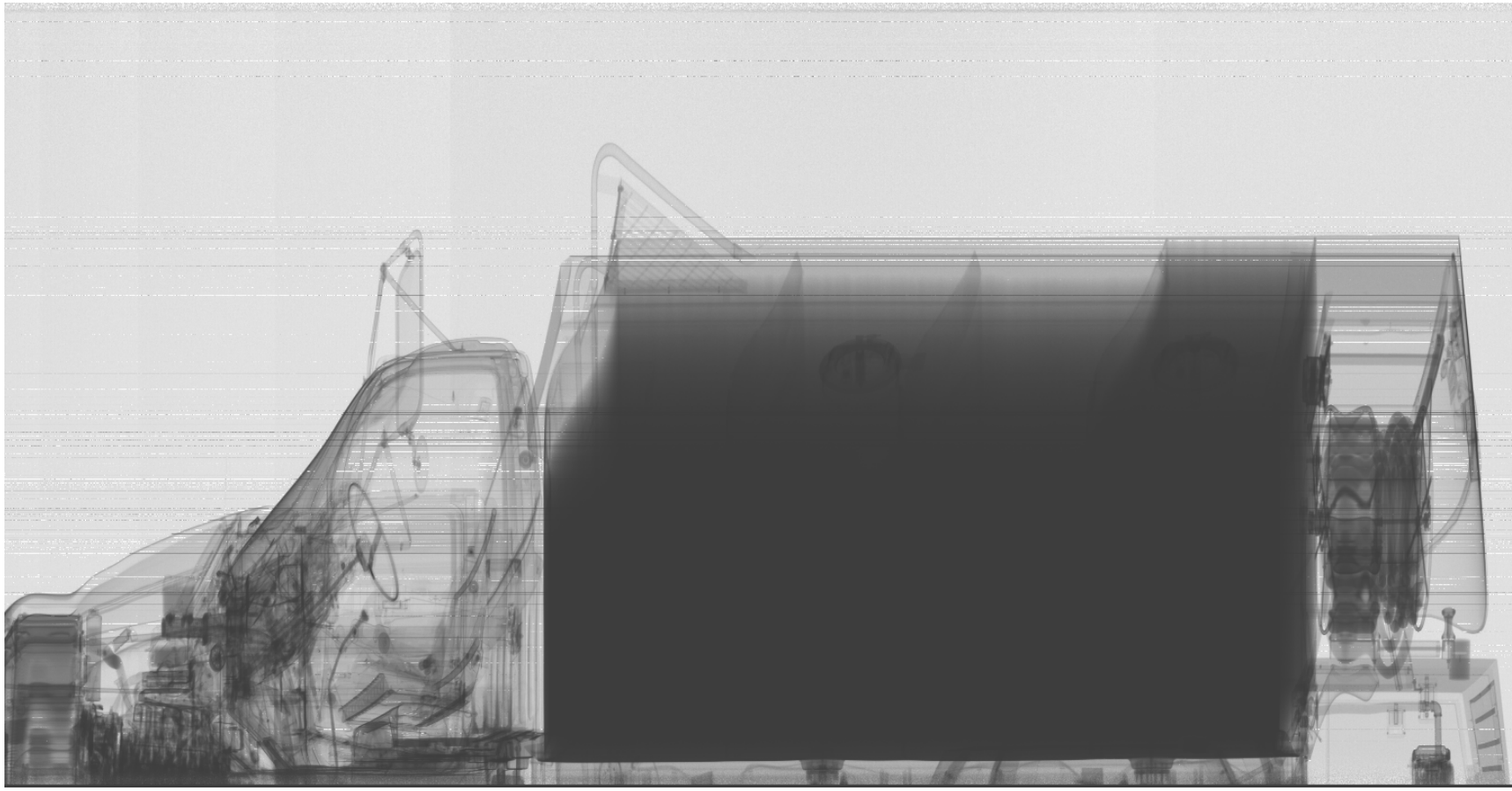
Lead brick seen through 250mm steel
("Density Expand" was applied to this region)

MobileSearch, Imaged with Shaped Energy



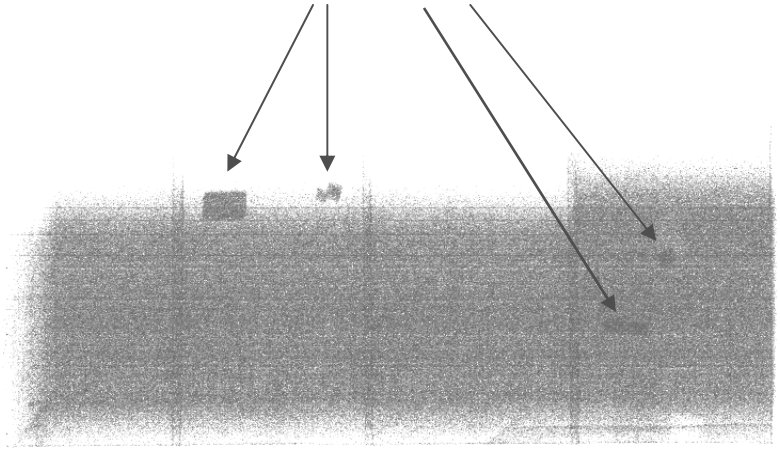
Bottom of X-ray Beam 1.1meter from ground, 45 degree opening angle

Oil Tanker, SE Image, As Scanned



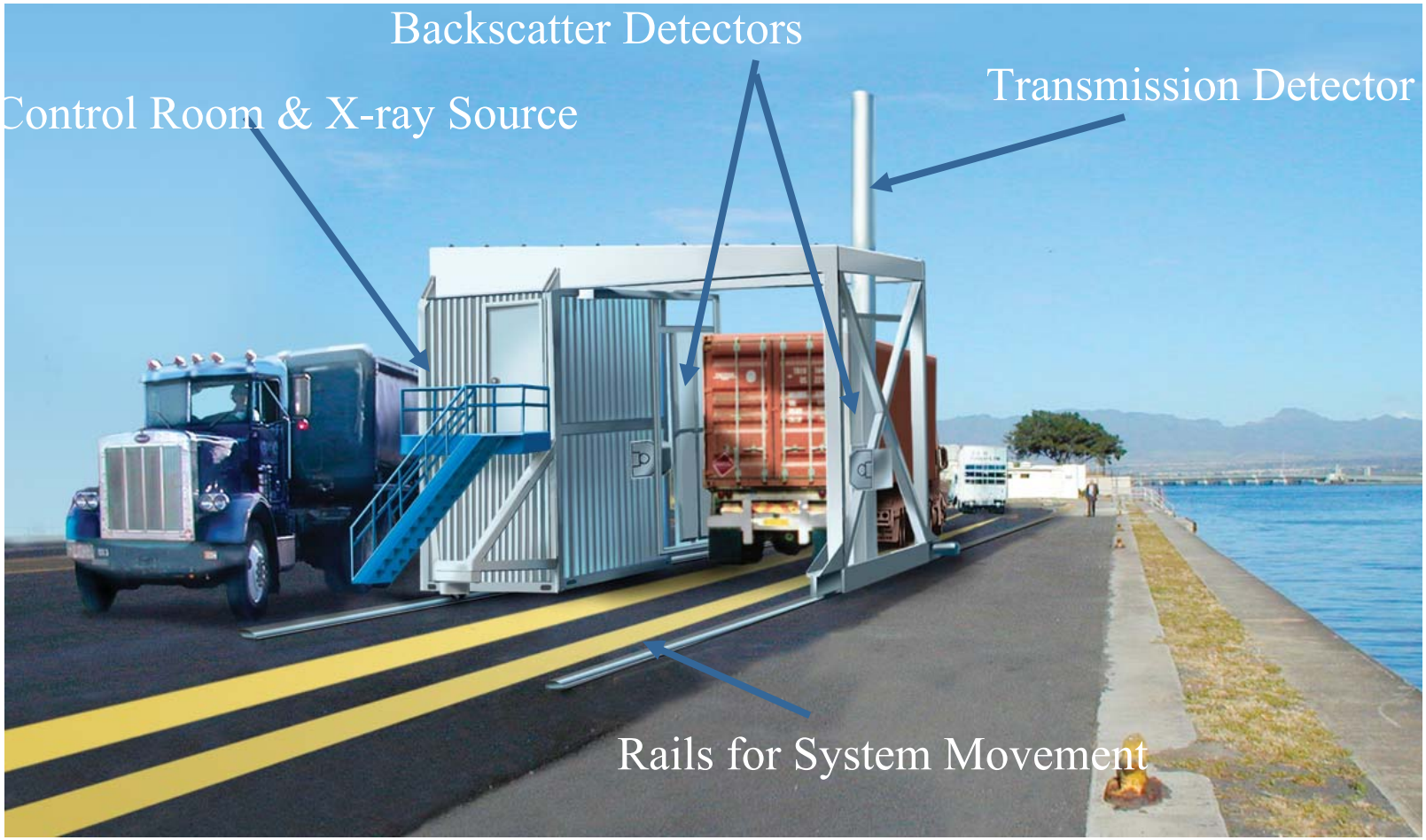
Oil Tanker, SE Image, Windowed

High Density Objects in Oil



Dense objects can be seen through 240 cm oil

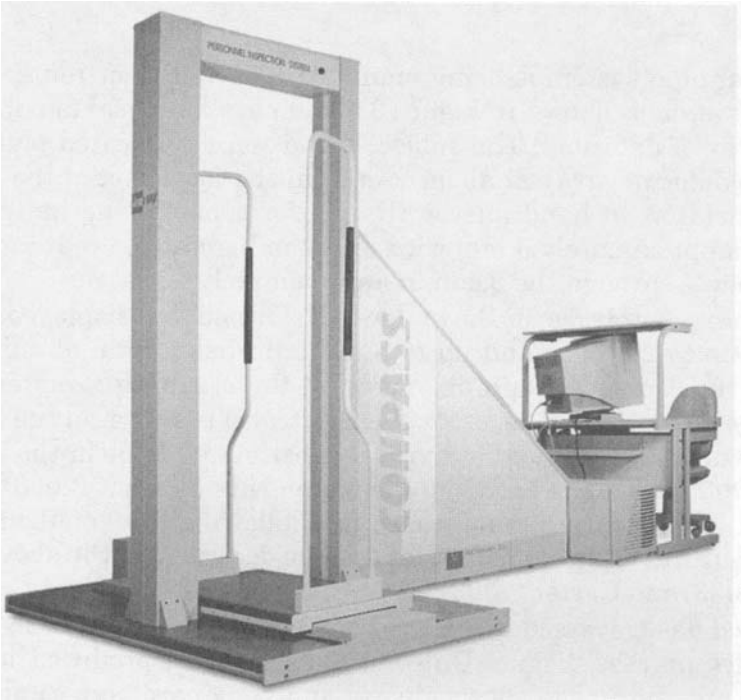
Shaped Energy Gantry System with Dual Sided Backscatter



Shaped Energy Attributes

- High penetration transmission with multiple view backscatter options
- Variety of scanning options
  - Cargo can be transported past fixed x-ray system on platen, rails, or with tug vehicle
  - Alternatively, x-ray system can move on rails past cargo container
- Option to include radioactive threat detection
- Dose to cargo less than 20 μSv

Conpass Transmission System

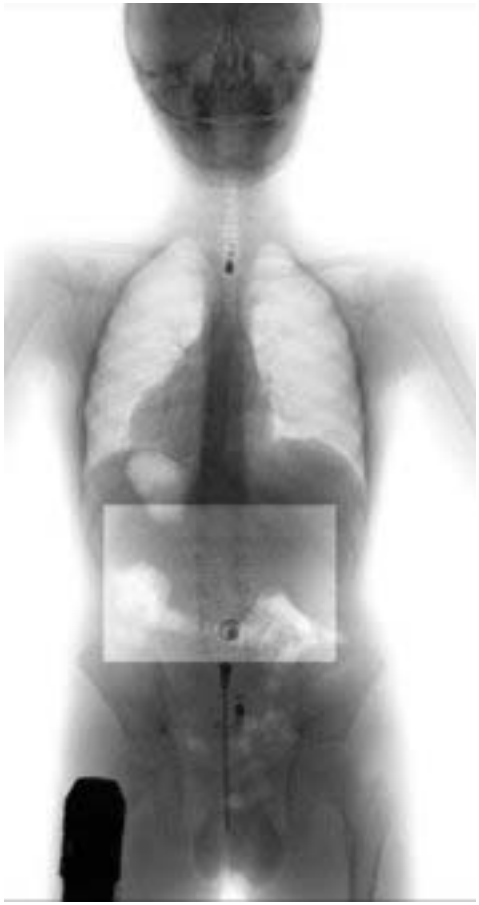


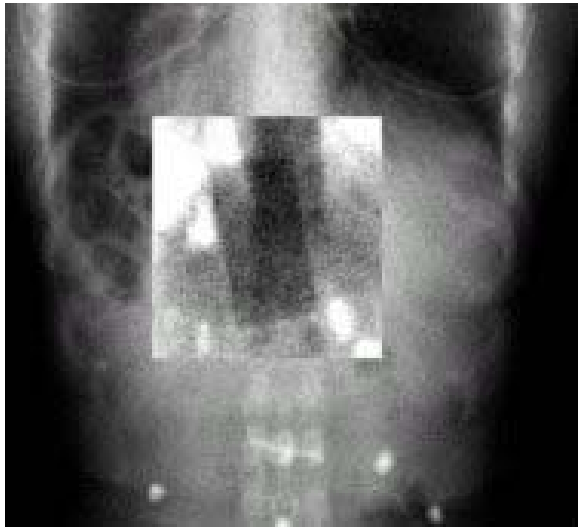
- full body analysis within 20 s
- 10 s scanning time
- 1280 detectors
  - linear array
  - 1.5 mm pitch
- 3-5% contrast resolution
- 500 x 1280 image elements
- 160-200 kV with 10 kV step
- Dose to a passenger = 2.4 μSv per scan
- < 0.6 μSv/hour at 100 cm from housing
- http://www.americansecurity.net/products/conpass/conpass.html

Transmission X Ray Imaging for Security

M.M.C. International B.V. CONPASS x-1280

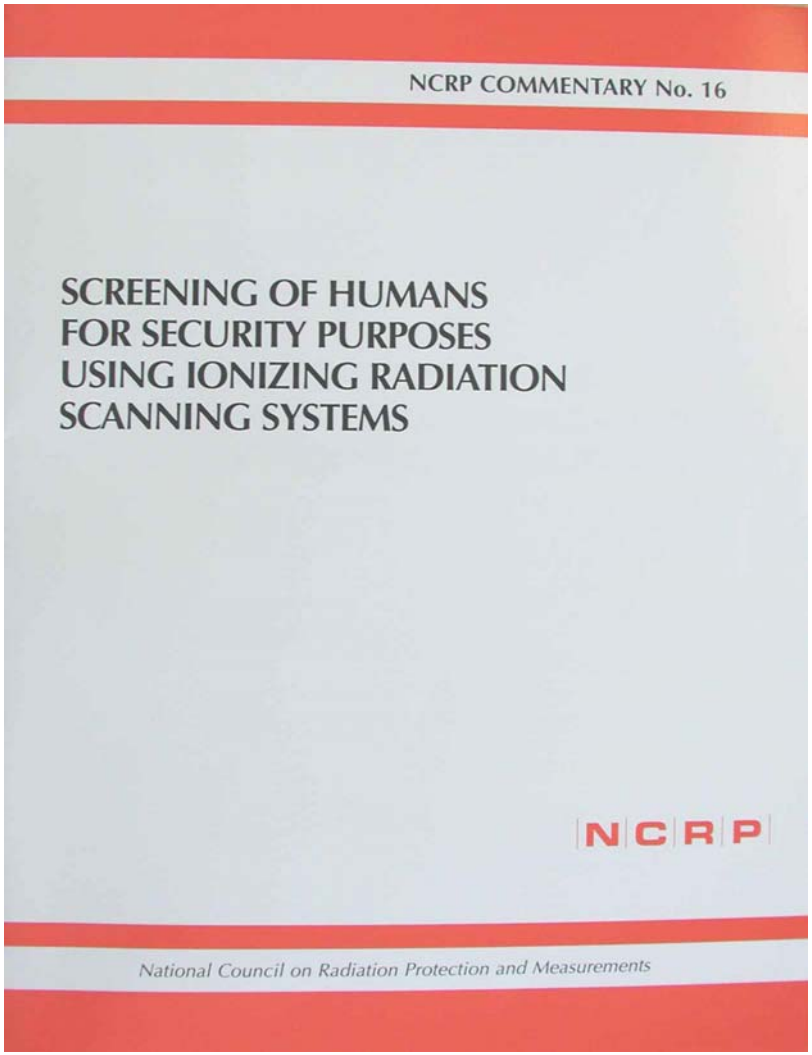
http://www.mmcinter.com/





Radiation Issues: Doses to People, Cargo

- "General_Use Systems": NCRP recommends 0.1 μSv/ scan
  - to make it unlikely that an individual will exceed 0.25 mSv/y for a single source or set of sources at a given venue
- "Limited-Use Systems: 10 μSv/scan
- Low dose-to-cargo also an important criterion
- Concern for stowaways, radiation-sensitive products
  - CT scanners don't meet this criterion
  - Neutron systems are iffy



Doses from Cargo Scanners

System or modality	Dose equivalent used for calculation (nSv)	Number of passes for 1 mSv (rounded)
RailVACIS	25	40,000
Mobile Truck Gamma Ray	40	25,000
VACIS-II	50	20,000
Truck X-Ray	400	2,500
Mobile Truck X-ray -- Wide Eye	530	1,887
Mobile Truck X-ray -- Low Under Carriage	2,300	43
Container X-ray -- 6 MeV	115,000	9
Pulsed Fast Neutron Analysis	315,000	3

Adapted from Khan SM, PE Nicholas, and MS Terpilak. 2004. "Radiation dose equivalent to stowaways in vehicles." Health Physics 86(5):483-492.

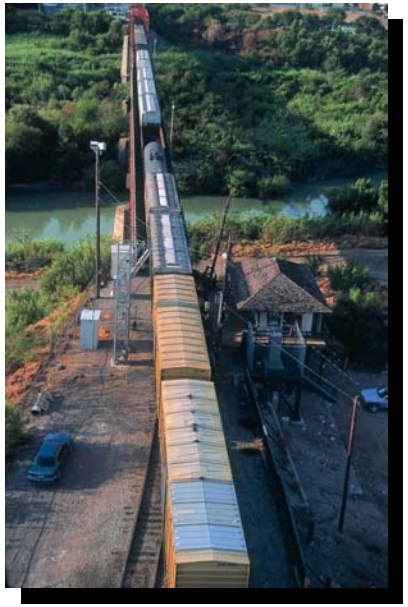
Radioactive Sources
(Gamma Ray Sources)

SAIC's VACIS
Vehicle and Cargo Imaging System

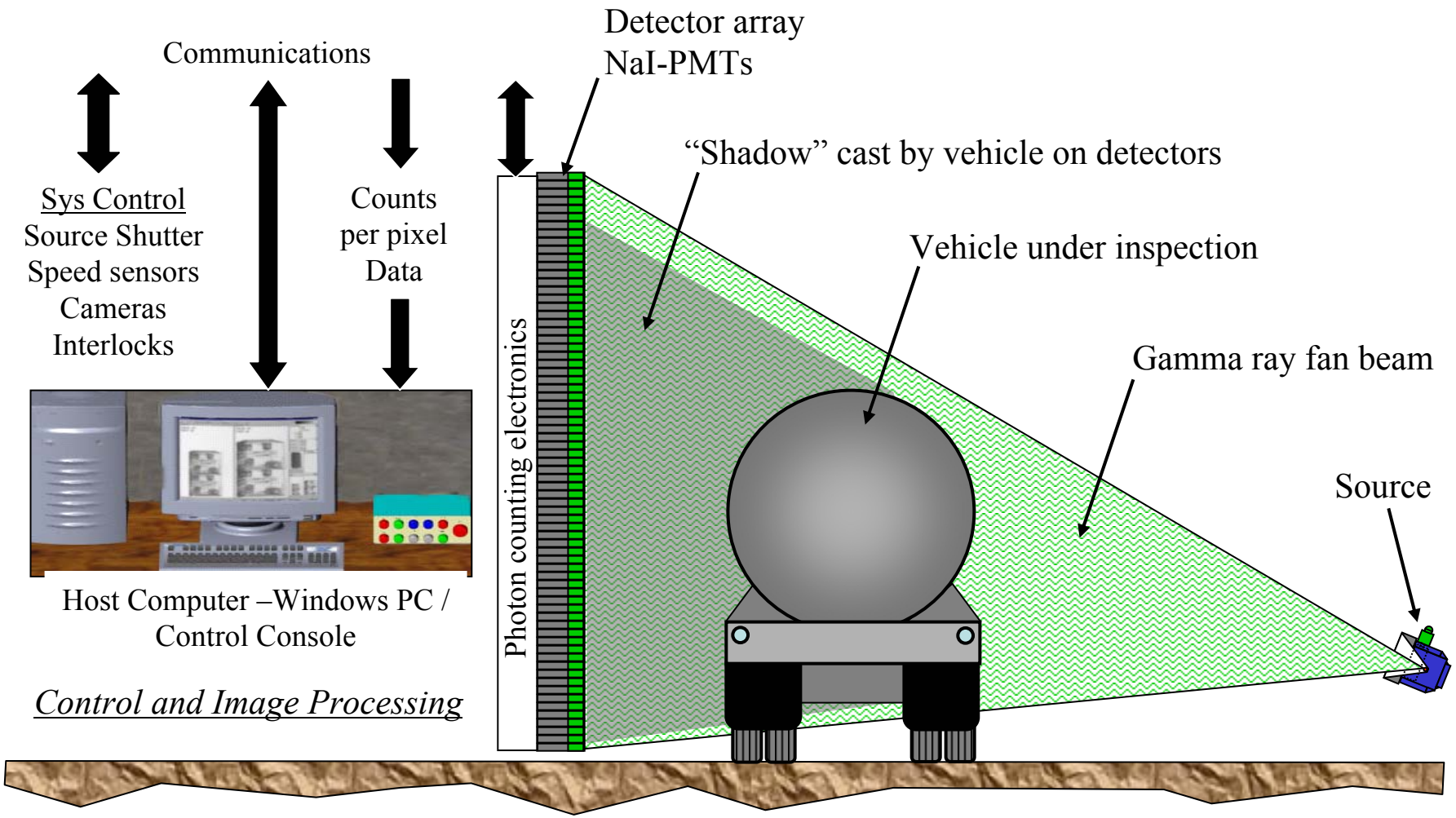
Slides Courtesy Monica Humphrey

www.saic.com

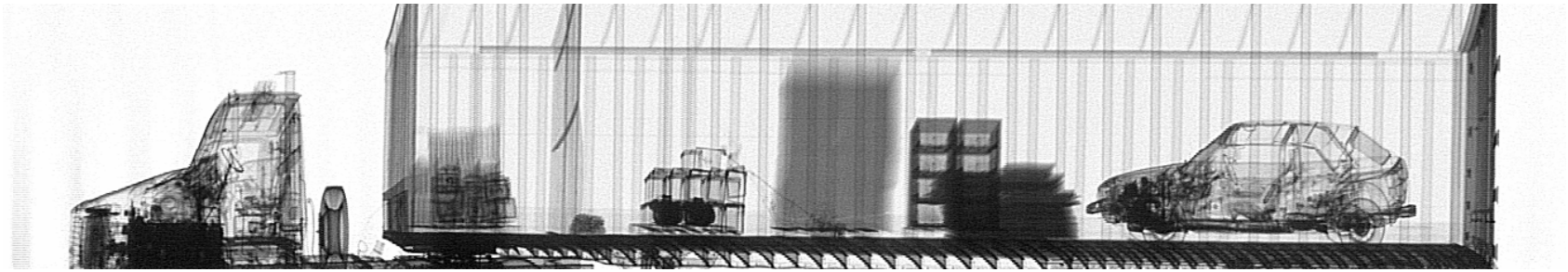
Various Gamma Gauge Applications

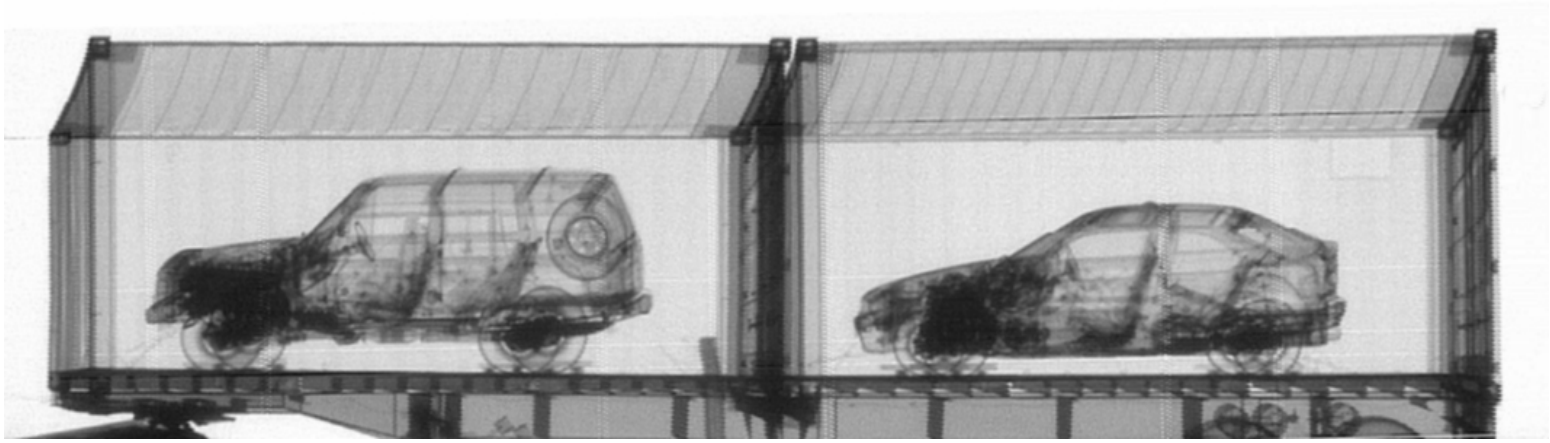


General Components



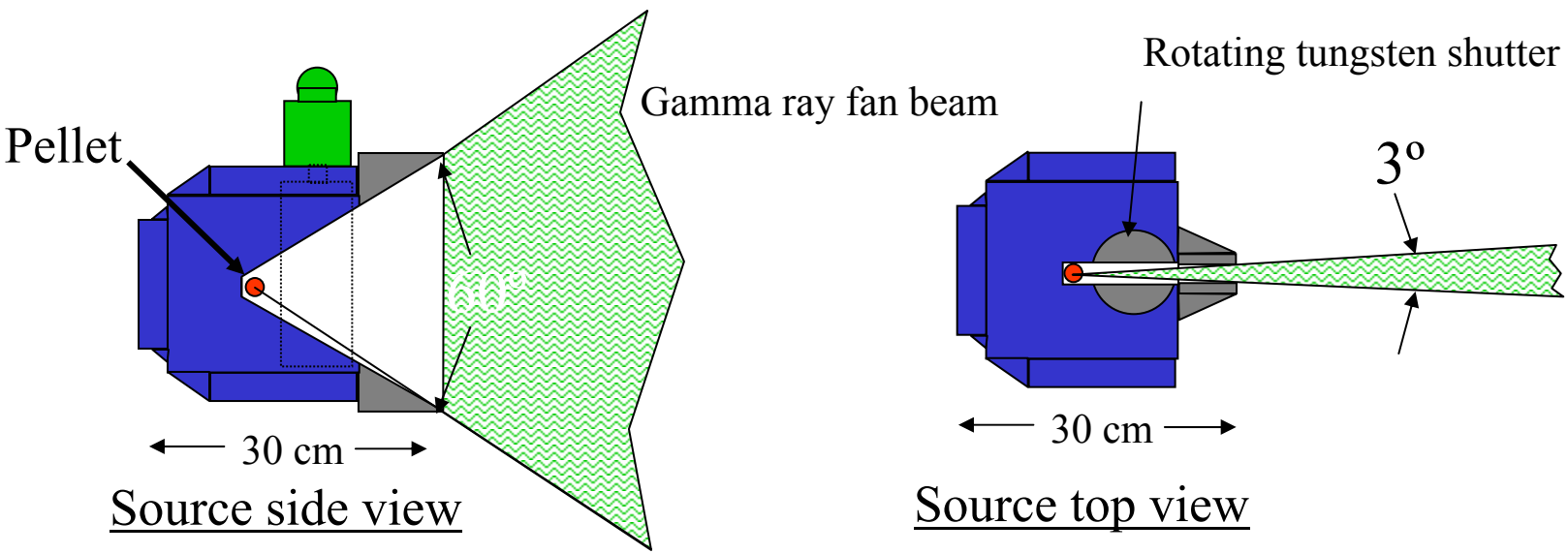
Typical Images





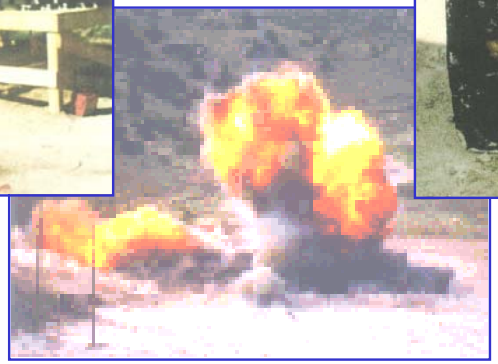
Gamma Gauge Source

- Similar to conventional medical/ industrial x-ray scanning machines, except the x-ray tube is replaced with a gamma ray source.
- A small pellet (a few millimeters in diameter) provides the gamma rays
- The pellet is installed in a shielded (steel and tungsten) housing equipped with a shutter.
- Minimum ANSI N538-1979 classification of 34-343-343-R2



VACIS Source Holders Proven to Withstand Extreme Conditions

- **Bomb-tested:** With 7,500 lbs. (3,400 kg) of TNT-equivalent explosive.
- **MYTH:** Placing a VACIS near an explosion will cause the source to become a radiological dispersal device (RDD).
- **FACT:** SAIC's test shows that this is virtually impossible.

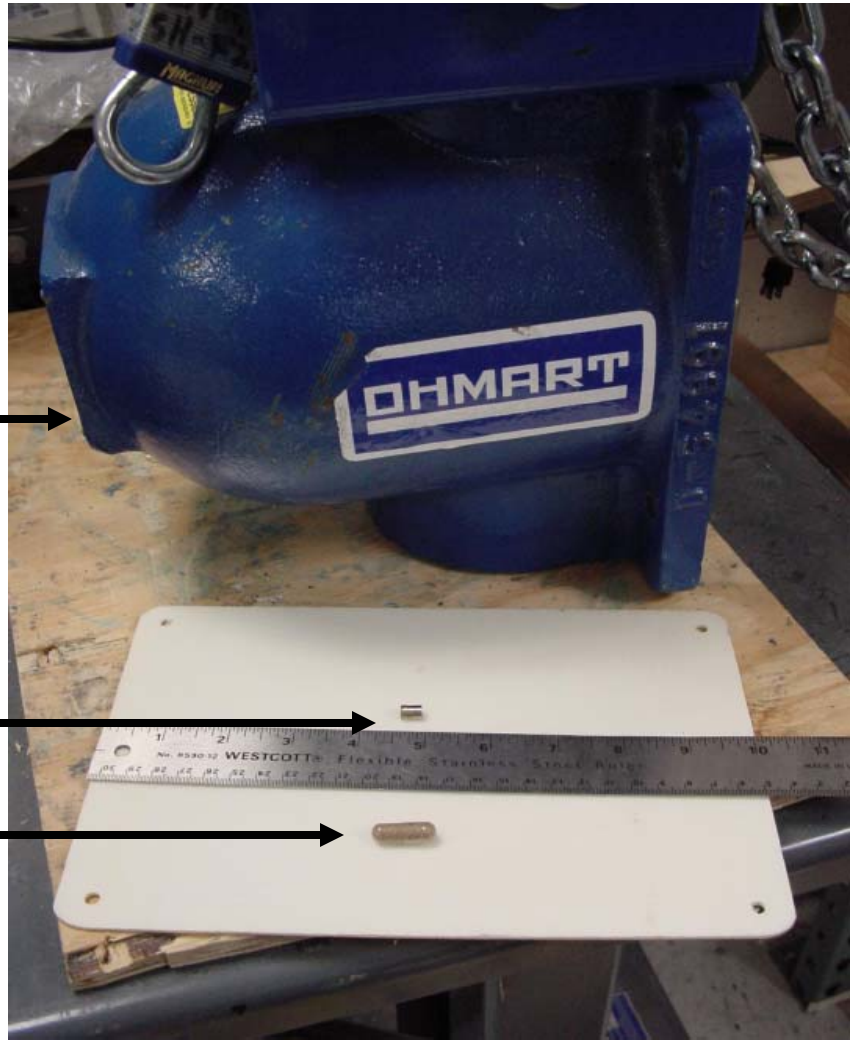


Relative Size of the Cesium or Cobalt Capsule

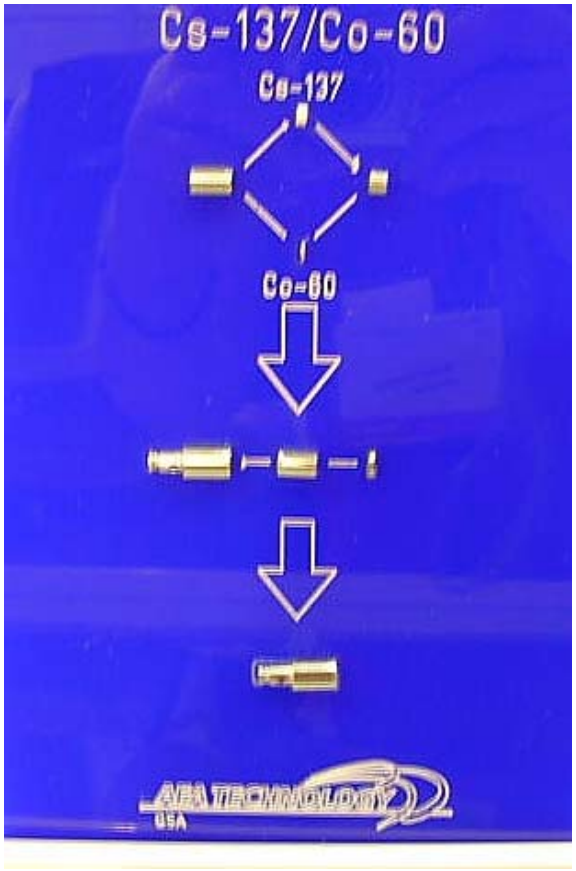
Source holder

Source Capsule

Multivitamin



AEA Technology Source Capsule Cs-137 & Co-60

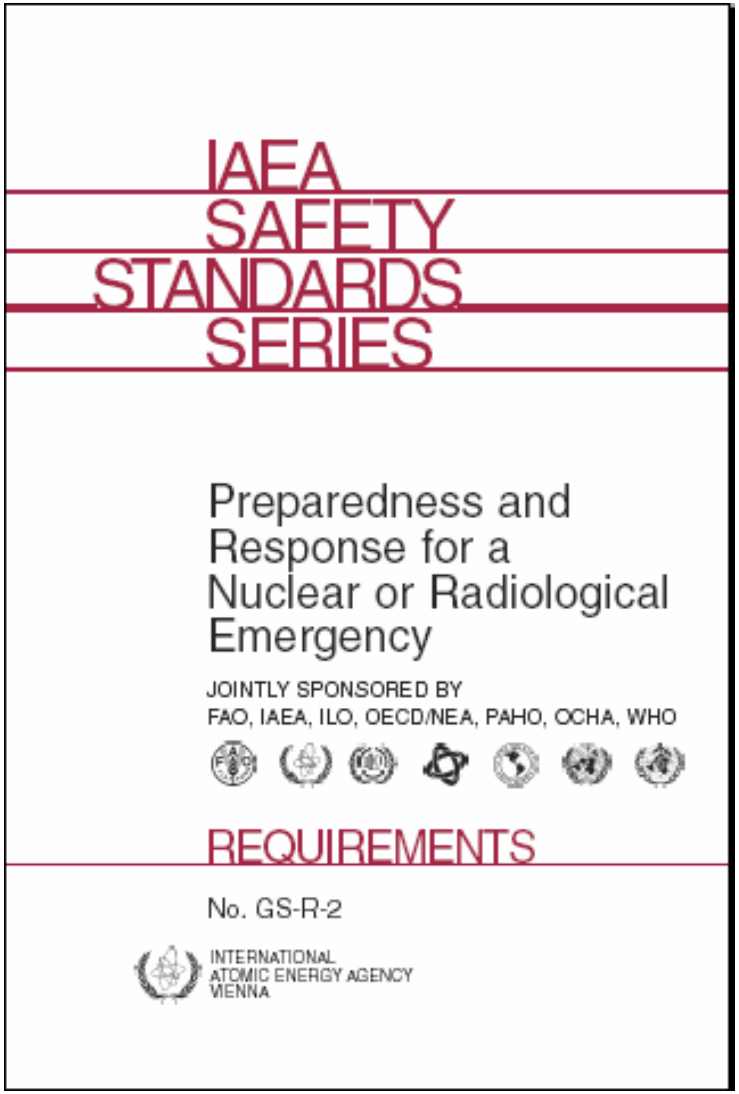


Radionuclide Source

- Most commonly used in radiography

Radionuclide	Half-life (years)	Photon energies (MeV)
^{60}Co	5.27	1.17, 1.33
^{137}Cs	30.1	0.66
^{192}Ir	0.20	0.30 – 0.61

The “dangerous source” concept



- “A source that could, if not under control, give rise to exposure sufficient to cause severe deterministic effects, i.e., effects that are fatal or life threatening or result in a permanent injury that decreases quality of life.”
- sources with an activity greater than ‘D’ have the potential to cause severe deterministic effects

International Atomic Energy Agency (IAEA). 2004. Preparedness and Response for a Nuclear or Radiological Emergency. Requirements. IAEA Safety Standards Series GS-R-2. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1133_scr.pdf, International Atomic Energy Agency, Vienna.

Reference doses for D-values

Tissue	Dose Criteria
Bone marrow	1 Gy in 2 days
Lung	6 Gy in 2 days from low LET radiation
	25 Gy in 1 year from high LET radiation
Thyroid	5 Gy in 2 days
Skin/tissue (contact)	25 Gy at depth of 2 cm for most parts of the body (e.g., from a source in a pocket) or 1 cm for the hand for a period of 10 hours
Bone marrow	1 Gy in 100 hours for a source that is to big to be carried

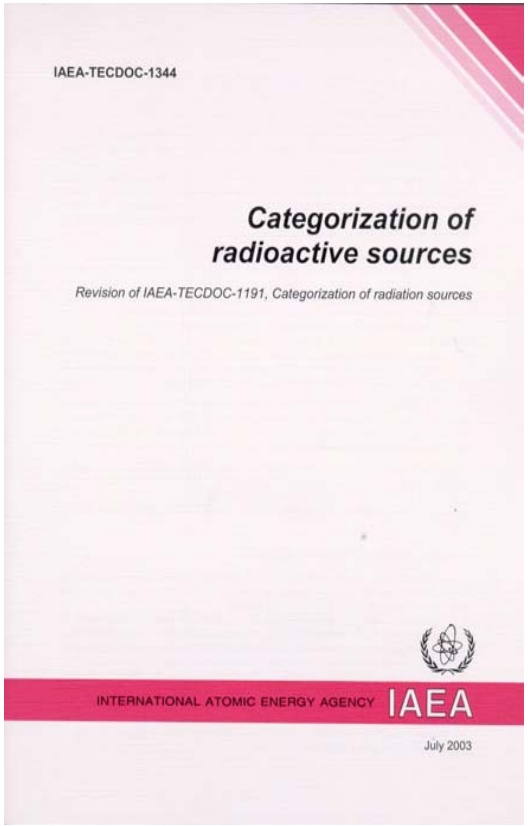
D-values for Selected Radionuclides

	TBq	Ci
^{60}Co	0.03	0.8
$^{90}Sr(^{90}Y)$	1	30
^{99}Mo	0.3	8
^{131}I	0.2	5
^{137}Cs	0.1	3
^{192}Ir	0.08	2
^{226}Ra	0.04	1
^{241}Am	0.06	2
Pu	0.06	2

Categorization of radioactive sources IAEA TECDOC-1344 (July 2003)

Increasing Risk

Category	Practice	Activity Ratio A/D
	Radioisotopic Thermoelectric Generators (RTGs); Irradiators; Teletherapy; Gamma Knife	A/D ≥ 1000
	Gamma radiography; Brachytherapy (high dose rate (HDR) or moderate dose rate (MDR))	1000>A/D≥10
	Fixed industrial gauges (e.g.: level, dredger, conveyor gauges) Well logging	10>A/D≥ 1
4	Brachytherapy (low dose rate (LDR) except eye plaques & permanent implants) Portable gauges; Static eliminators; Bone densitometers	1>A/D≥ 0.01
5	Brachytherapy (eye pl. & perm implants); X-ray fluorescence (XRF); Electron capture detectors (ECDs)	0.01>A/D≥ Exempt/D



Dodd, B. International Efforts in Countering Radiological Terrorism. NCRP Annual Meeting, 15 April 2004.

Radiation Issues: Security

- Vulnerability of system itself to terrorism, vandalization, accidents
  - Gamma sources present potential for problems if improperly guarded and controlled
  - NAS recommendation, October 2002, "…licensees possessing large sources should be encouraged to substitute non-radioactive sources… when economically feasible"
- The radiation protection principle of **Justification** in the aftermath of 9/11/2001: consider terrorist or criminal diversion of source
  - Lubenau and Strom (2002) Health Phys 82(2):155-164
  - IAEA TECDOC 1355 (draft of June, 2003)

IAEA-TECDOC-1355
Security of radioactive sources

- The Regulatory Authority should require that those who intend to manage radioactive sources seek an authorization, unless exempted or only notification is used.
- The Regulatory Authority should establish a formal, documented process to evaluate applications requesting the possession and use of radioactive sources.
- Since those with malevolent intent may attempt legal purchases, it is important from a security viewpoint to be assured that requests for authorization have validity.

IAEA-TECDOC-1355
Security of radioactive sources

- Hence, prior to issuing any authorizations, including any authorization to purchase or sell sources, the Regulatory Authority should verify that the applicant has legitimacy, that there is an ***adequate justification for the management of the radioactive source as well as an adequate justification for the types and quantities of the radioactive sources requested***.
- This procedure should be seen as an important principle applicable to the management of all kinds of radioactive sources.

IAEA-TECDOC-1355
Security of radioactive sources

- Depending on the security group, the Regulatory Authority should be proactive in obtaining all relevant information and require that those who intend to use radioactive sources submit an assessment of the security of the source and/or the facility in which it is to be managed.
- The security assessment should demonstrate the balance needed between security measures and the need to use the sources.

IAEA-TECDOC-1355
Security of radioactive sources

- The assessment should take into account the risk posed by the possession and use of the radioactive source.
- The assessment should be more comprehensive for sources in the higher groups.
- Detail which security measures would be implemented and how the trustworthiness of individuals would be ensured.

Radiation Issues: Radioactive Waste Disposal

- Unique to RAM sources, not accelerators and x-ray machines
- In 2008, because of compact restrictions, users in 35 states will not have a viable disposal path for unwanted sources if manufacturers no longer accept their return
  - e.g., accident in Thailand
- Several countries world wide exclude RAM sources for cargo containing radiography

X-Ray Sources

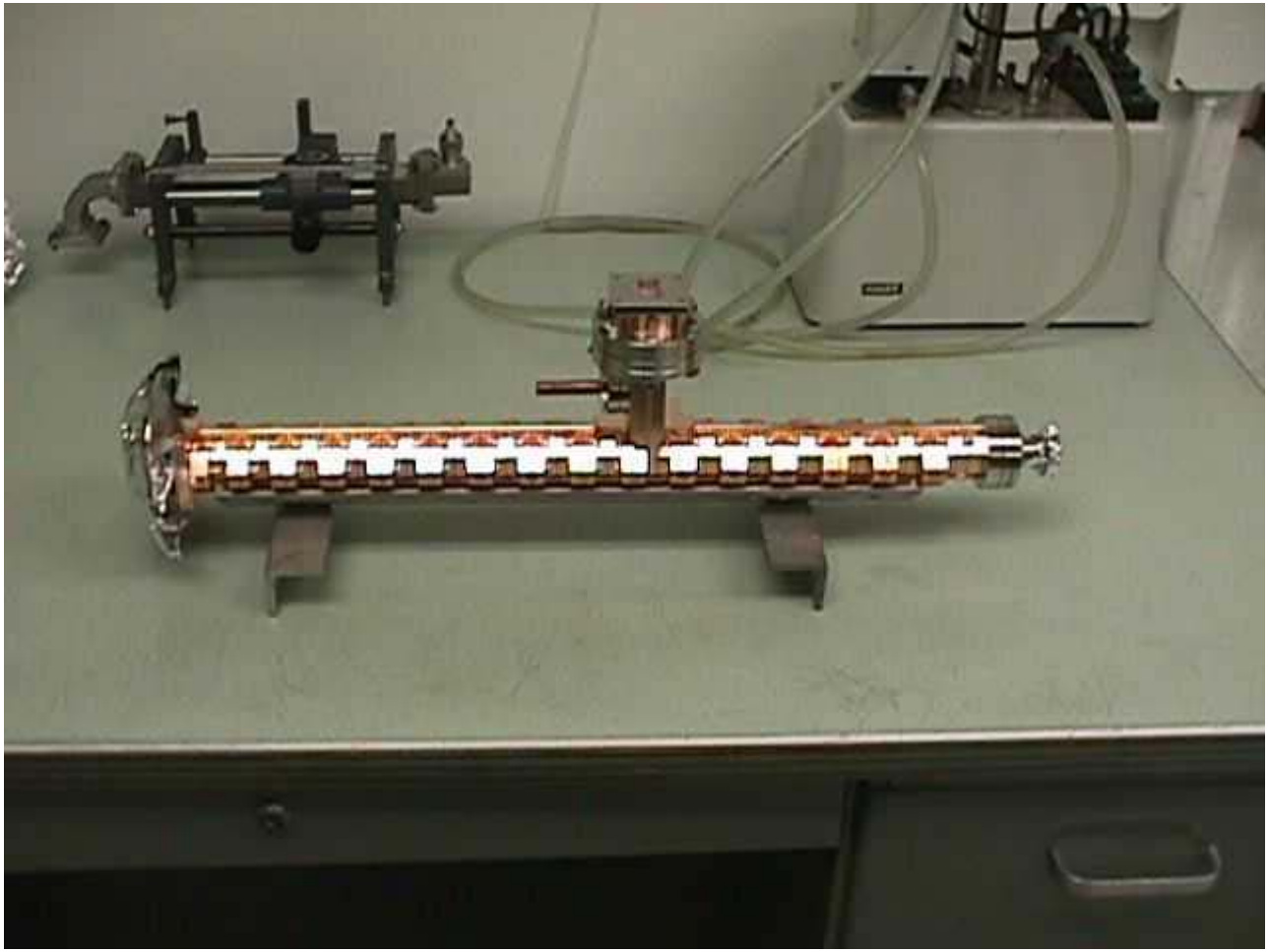
X-ray Tubes

- Most common source of x-rays for industrial and medical applications
- Limited to ~ 500 keV maximum energy
- Tube power generally limited by target heat dissipation
- X-ray Inspection systems for :
  - Package and parcel inspection
    - Use tubes with voltages between 120 and 225 kV
      - 5 – 13.3 mA
      - Powers up to 3 kW
  - Cargo Inspection
    - Light to medium loads up to 450 kV
      - 5 -10 mA
      - Powers up to 5 kW

Linear Accelerators

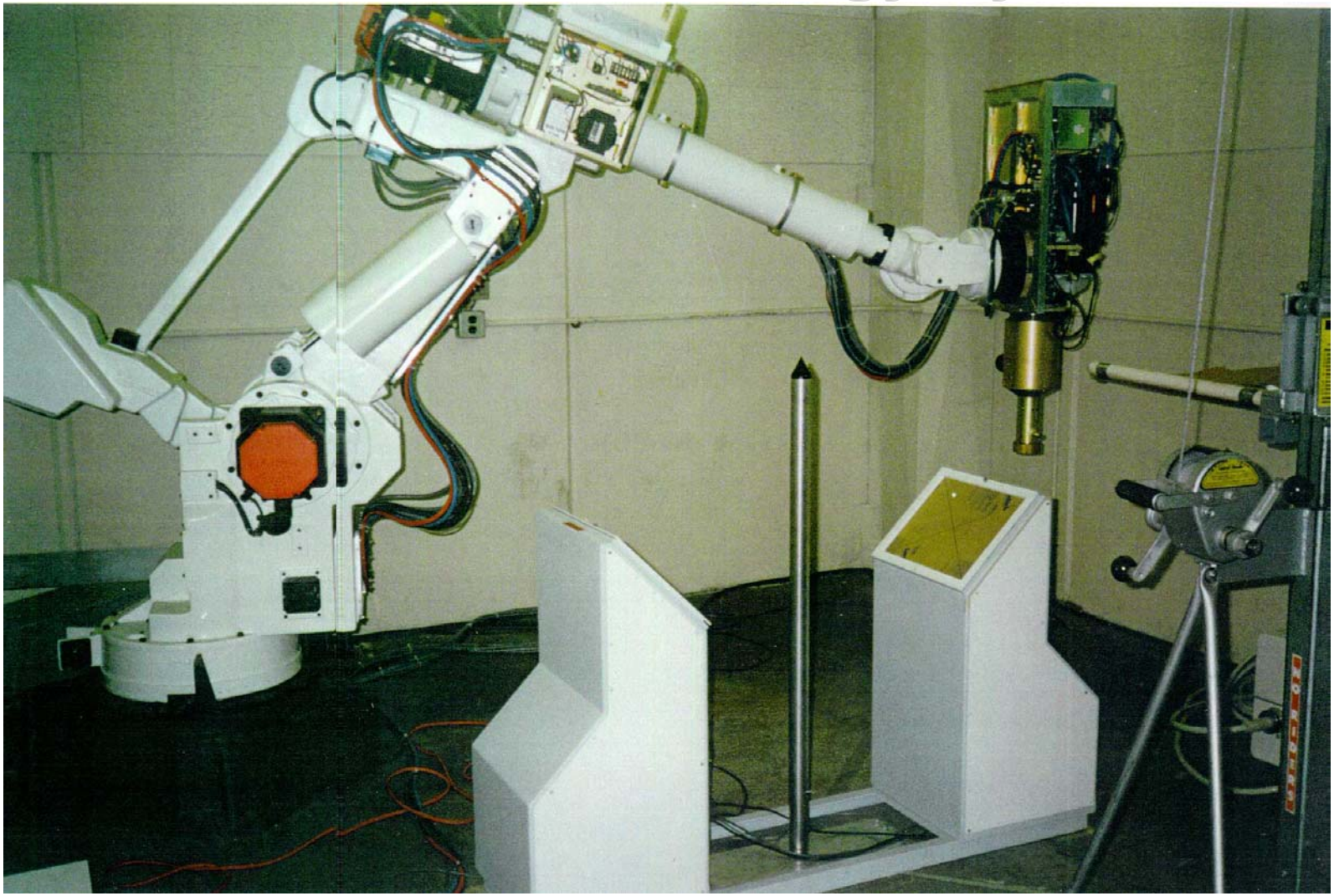
- Generally used where higher energies are needed for greater penetration
- X-ray energies above 1 MeV
- Tumor therapy applications typically at several MeV
- Inspection of densely loaded cargo
  - Typically from 2.5 up to 9 MV, 100 to 300 watts

Medical LINAC (6 MeV)



Medical LINAC Subsystem

LINAC Based Oncology System



Gamma Ray Sources

- Discrete energy: Differ from tubes and LINACs
- Advantages:
  - Consume no power
  - Low maintenance
- Disadvantages:
  - Low flux
  - Limited contrast sensitivity
  - Potential for contamination
  - Performance degradation over time (half-life)
  - Disposal issues

Most common sources are ^{60}Co and ^{137}Cs

X-ray Tubes vs Radioactive Sources vs LINACs

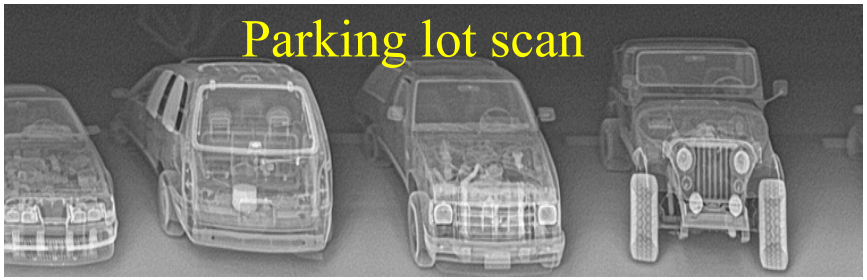
- A 450 kV, 3 kW X-ray tube produces 1.4 x 10^{14} photons/sec/steradian with an average energy of approximately 150 keV
- A 37 GBq (1 Ci) ^{137}Cs source (30 year half-life) produces 2.6 x 10^{9} photons/sec/steradian, each with an energy of 662 keV
- Flux advantage of a tube generally overwhelms energy advantage of gamma source for light to medium density cargoes
- For penetration of very dense cargo, nothing beats a LINAC at several MV energy

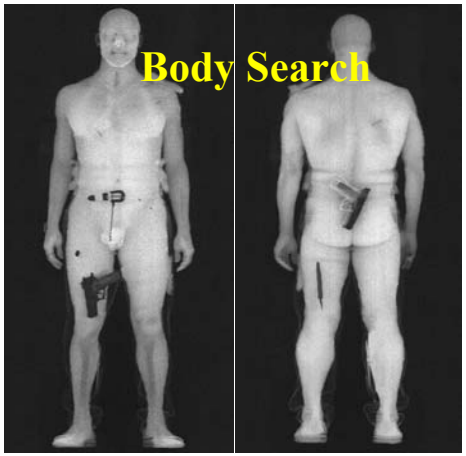
X-ray Inspection Systems

- Penetration is key, but, as always, the issue is <u>detection</u>
- Transmission-only systems most common
  - But, complex cargo images difficult to interpret
- Another option: combination of conventional high energy transmission x-ray images with Compton scatter (Z® Backscatter)
  - Backscatter provides immediate feedback on the presence of unobstructed organics (explosives, people)
  - Backscatter provides critical contextual understanding for transmission image interpretation

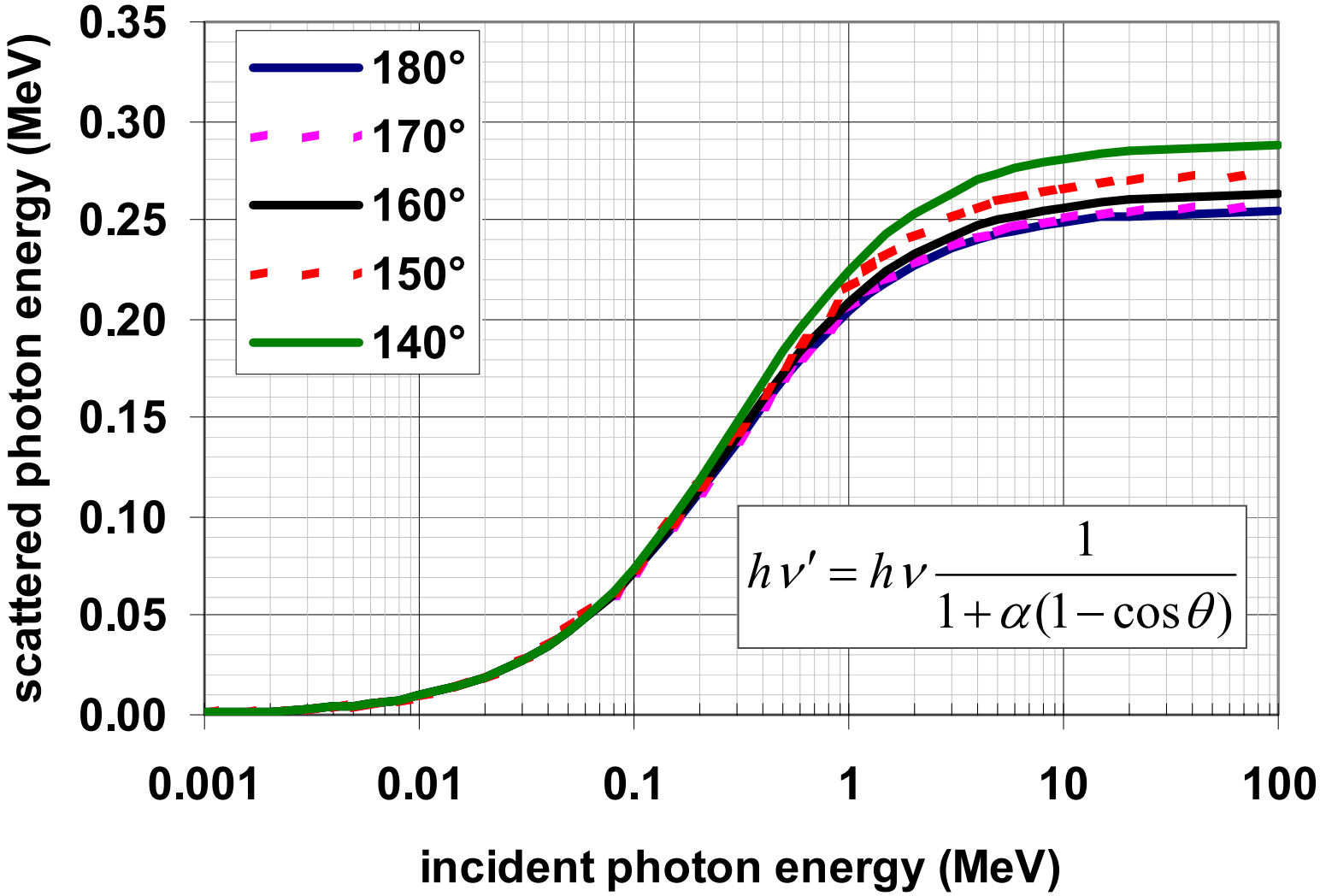
Backscatter X-ray Imaging Systems

X-ray Backscatter: A Powerful Detection Tool



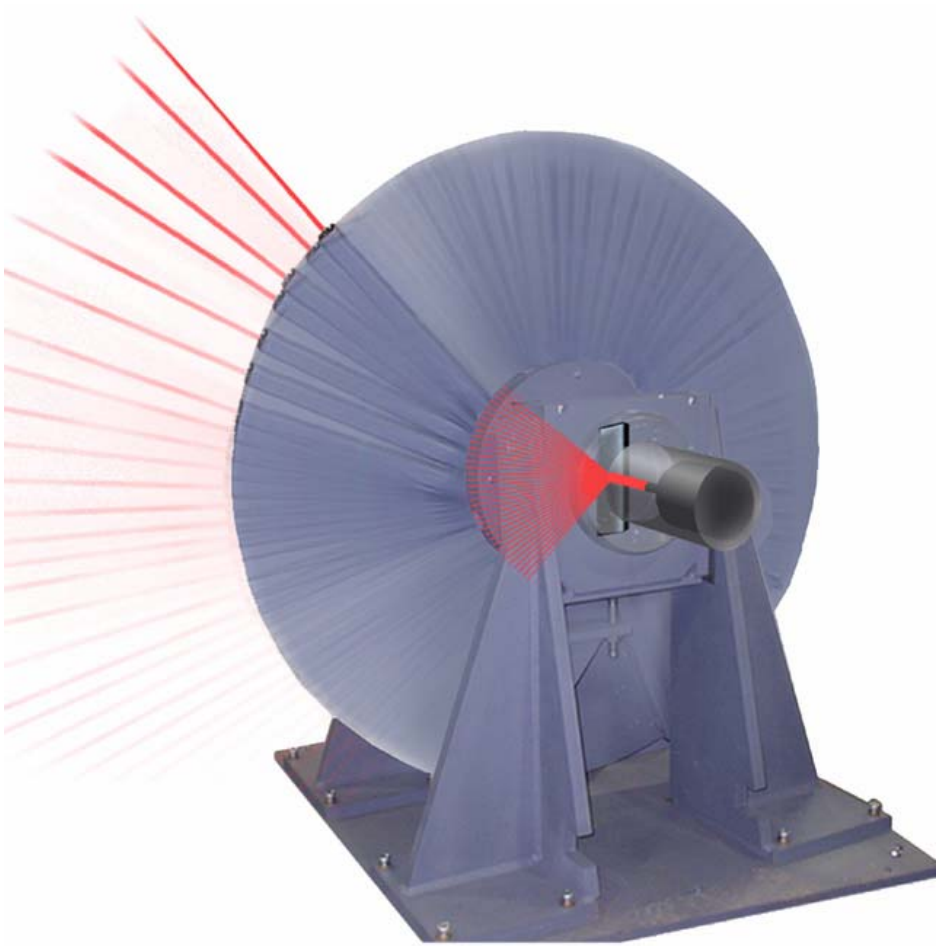


Compton Scattering: Dependence on Scattering Angle and Incident X-ray Energy



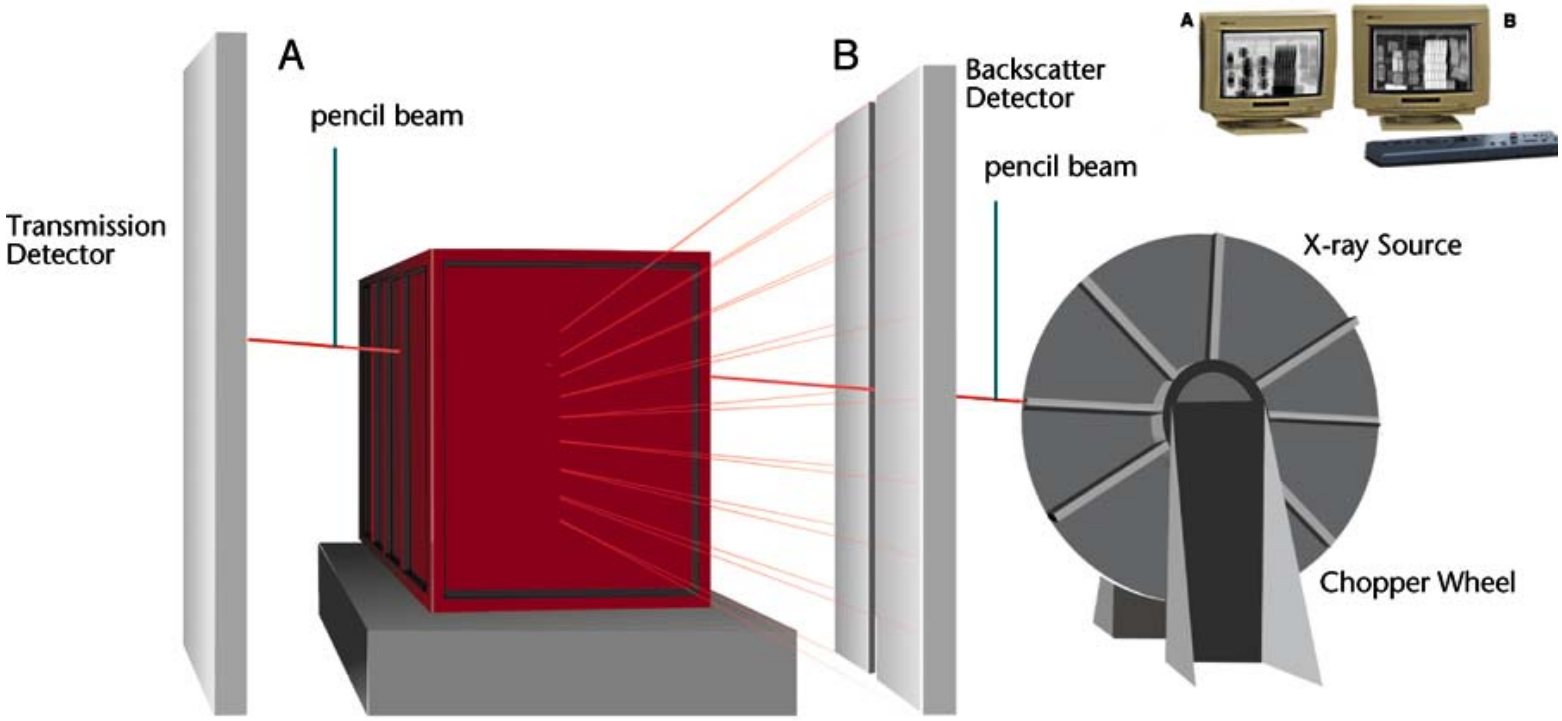
AS&E 's Patented Flying Spot Technology

- makes Z Backscatter scanning possible
- allows the position of the X-ray beam to be defined at every instant of time
- any Z Backscatter signal received is easily correlated with the particular region of the cargo undergoing inspection



Flying Spot X-ray

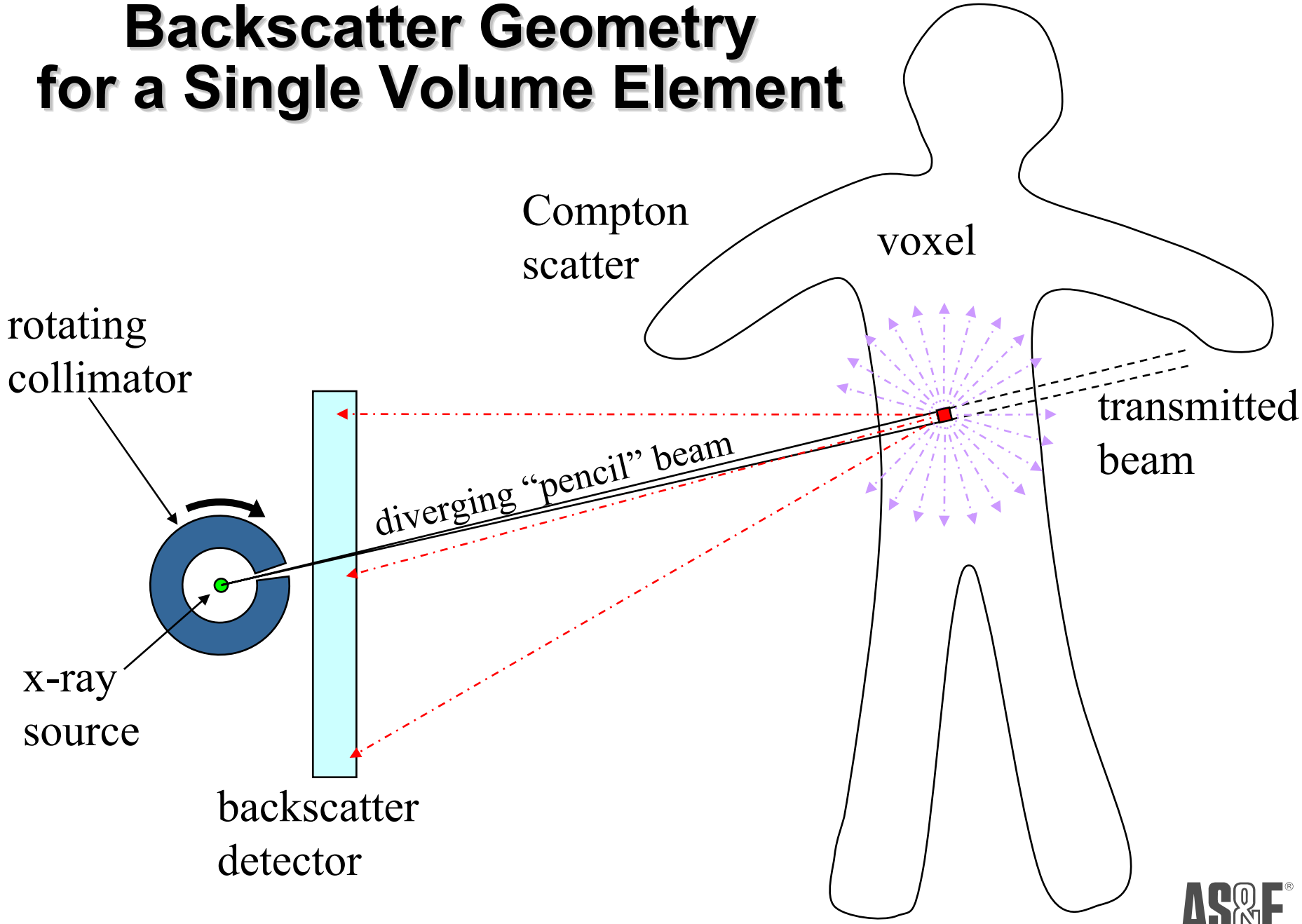
AS&E's Flying Spot X-ray Produces Both Transmission and Backscatter Images



A. Transmission X-ray Image

B. Z®Backscatter X-ray Image

Backscatter Geometry for a Single Volume Element



MobileSearch™ Pencil Beam

Backscatter Animation

Backscatter Signal in the Absence of Absorption

In addition to different Compton scattering by different elements, signal from a volume element (voxel) in material being scanned is affected by

- Geometry
- Source-object distance, r_{SO}
- Object-detector distance, r_{OD}
- Source intensity: number rate, $\dot{N}$, photons/s
- Detector area, A_{D}
- Detector efficiency, E_{D}
- Result: the “radar equation”

$$Signal \propto \frac{\dot{N}}{r_{\mathrm{SO}}^2} \frac{A_{\mathrm{D}} E_{\mathrm{D}}}{r_{\mathrm{OD}}^2} \sim \frac{1}{r^4}$$

Backscatter Signal from a Voxel Affected by Absorption and Scan Speed

- Absorption of incident beam on the way in
- Absorption of backscattered beam on the way back out
- Absorption greater in
  - High-Z materials
  - Dense materials
  - Thick materials

$$Signal \propto \frac{1}{v_{\mathrm{SCAN}}} \frac{\dot{N}}{r_{\mathrm{SO}}^2} e^{-\sum_i \mu_i x_i} \frac{A_{\mathrm{D}} E_{\mathrm{D}}}{r_{\mathrm{OD}}^2} e^{-\sum_j \mu_j x_j}$$

- Signal inversely proportional to scan speed, v_{SCAN}

Total Signal at Backscatter Detector

- Sum of scatter from all voxels in pencil beam

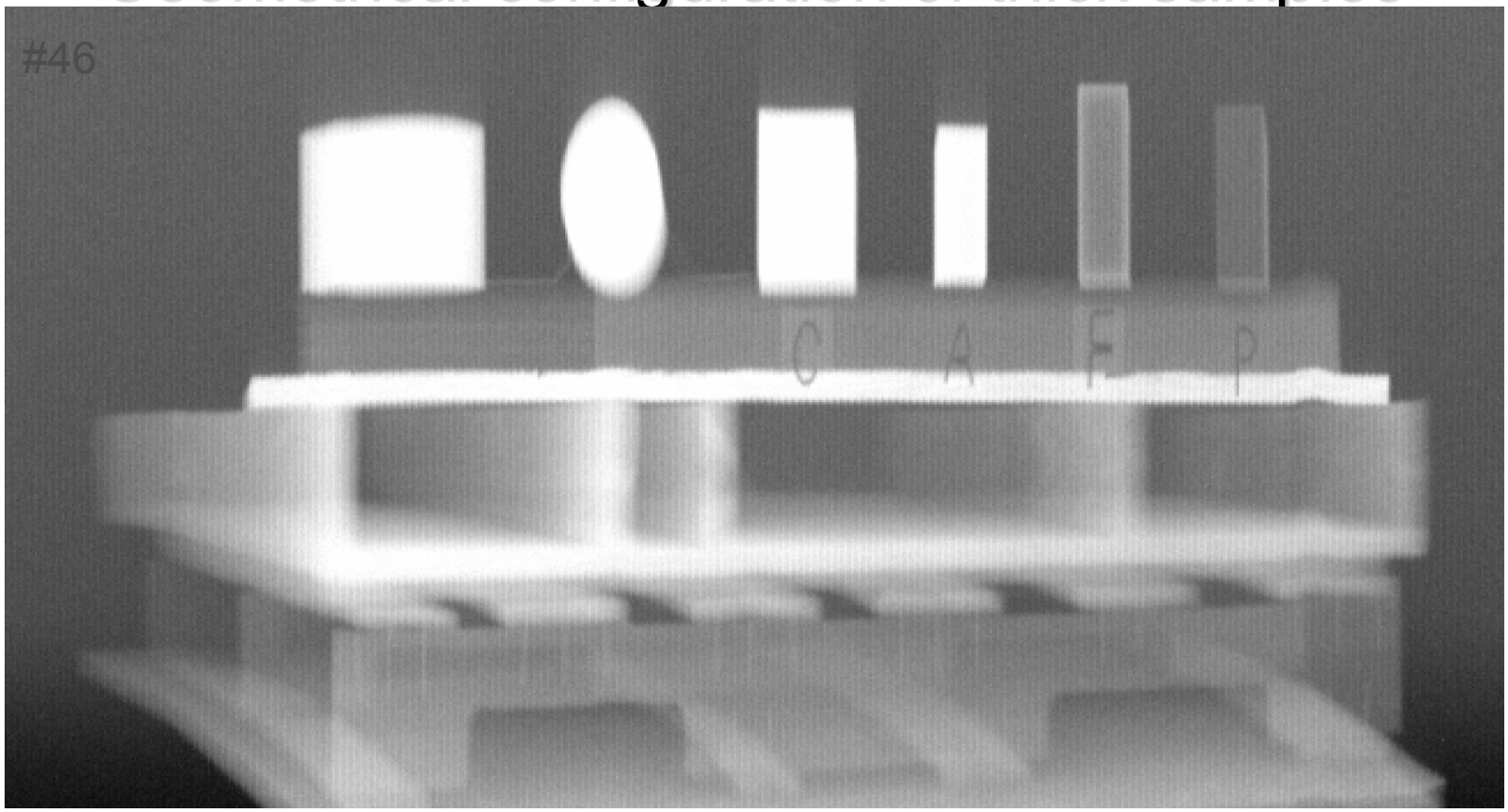
$$Signal \propto \frac{1}{v_{\mathrm{SCAN}}} \sum_{\substack{\text{all voxels in} \\ \text{pencil beam}}} \frac{\dot{N}}{r_{\mathrm{SO}}^2} e^{-\sum_i \mu_i x_i} \frac{A_{\mathrm{D}} E_{\mathrm{D}}}{r_{\mathrm{OD}}^2} e^{-\sum_j \mu_j x_j}$$

- Radii differ for different voxels
- Voxels farther from source (deeper in object) produce less signal because
  - the pencil beam has been partly absorbed
  - the pencil beam has diverged (inverse square)
  - the return (scatter) beam has diverged (a second inverse square attenuation)
- Consequence: images near surface are brighter

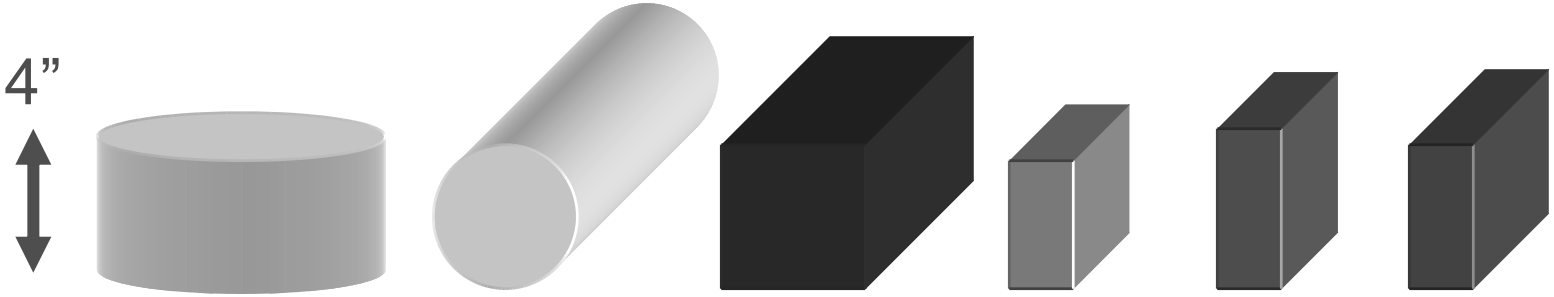
More Geometry

- Thickness of objects being imaged may be a significant fraction of source-object distance r_{SO}
- Leads to foreshortening, distortion
- Some experiments to look at *Z*-dependence

Geometrical configuration of thick samples



160 kV

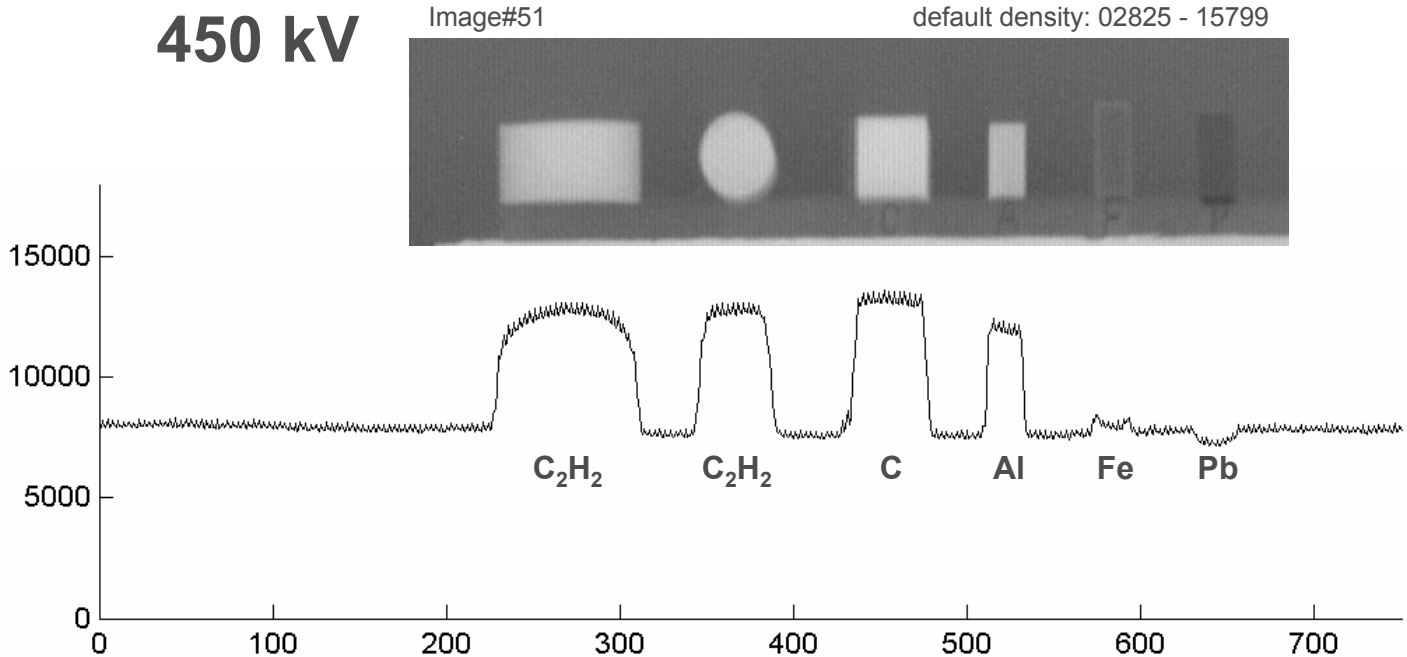


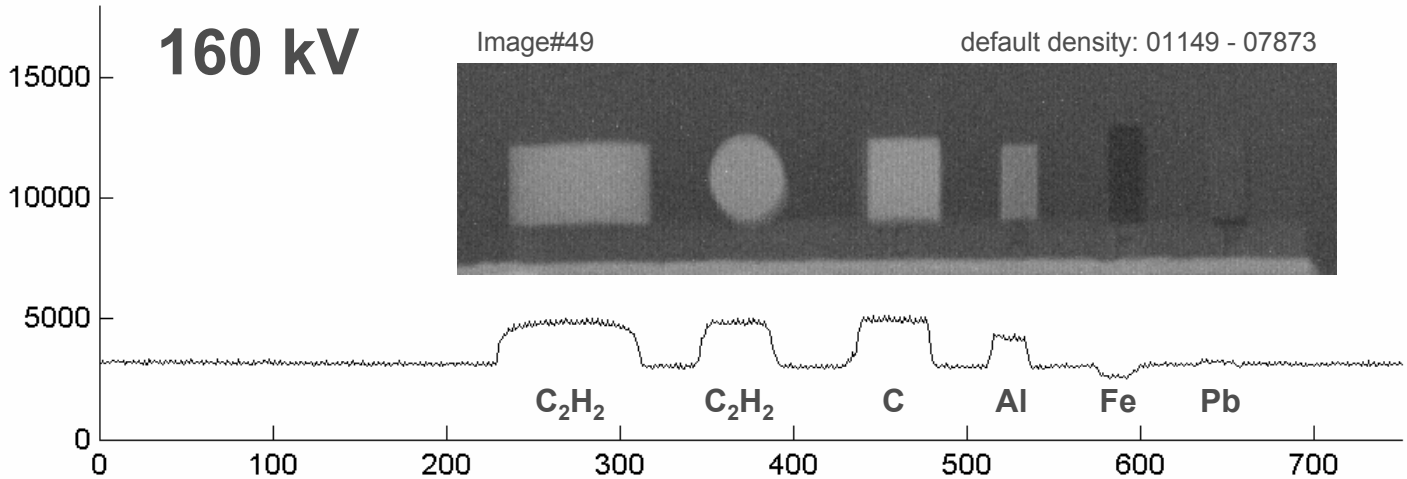
HDPE (C_2H_2)	HDPE(C_2H_2)	Graphite	Aluminum	Steel	Lead
Ø8 x 4”	Ø4 x 15”	3.9 x 3.9 x 11.6”	2 x 3.5 x 6”	2 x 4.5 x 6”	2 x 4 x 8”

Battelle

AS&E®

SUMMARY: Targets ~ infinitely thick

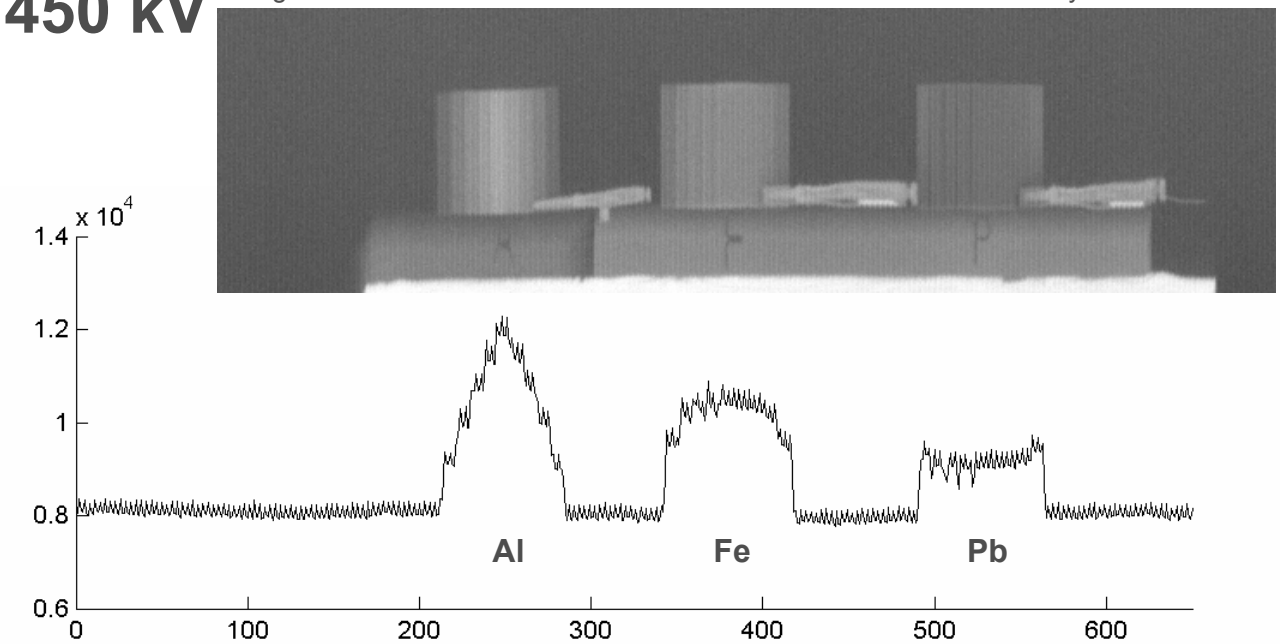




SUMMARY: Al, Fe, Pb Shims

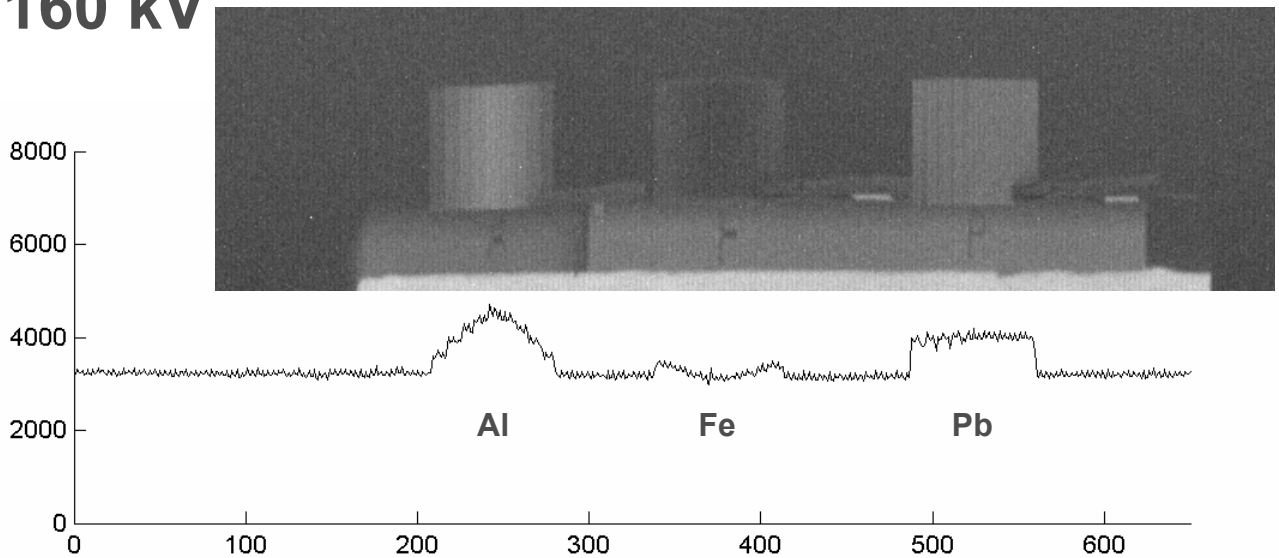
450 kV

Image#66 default density: 03141 - 16384



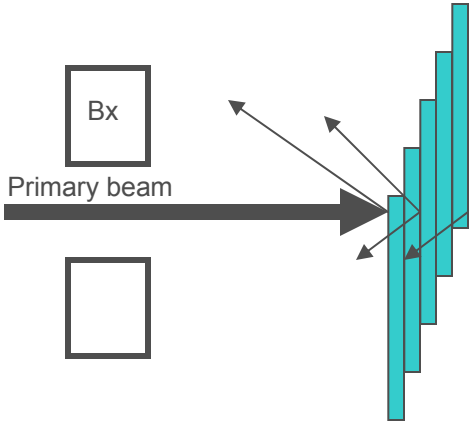
160 kV

Image#69 default density: 01233 - 07253



GEOMETRY

- Step wedges are constructed from sets of five shims: steps are 0.75” wide
  - Aluminum: 0.087” x 4” x 4”
  - Steel: 0.087” x 4” x 4”
  - Lead: 0.060” x 4” x 4”
- 14.5” from Bx detectors.



TOP VIEW

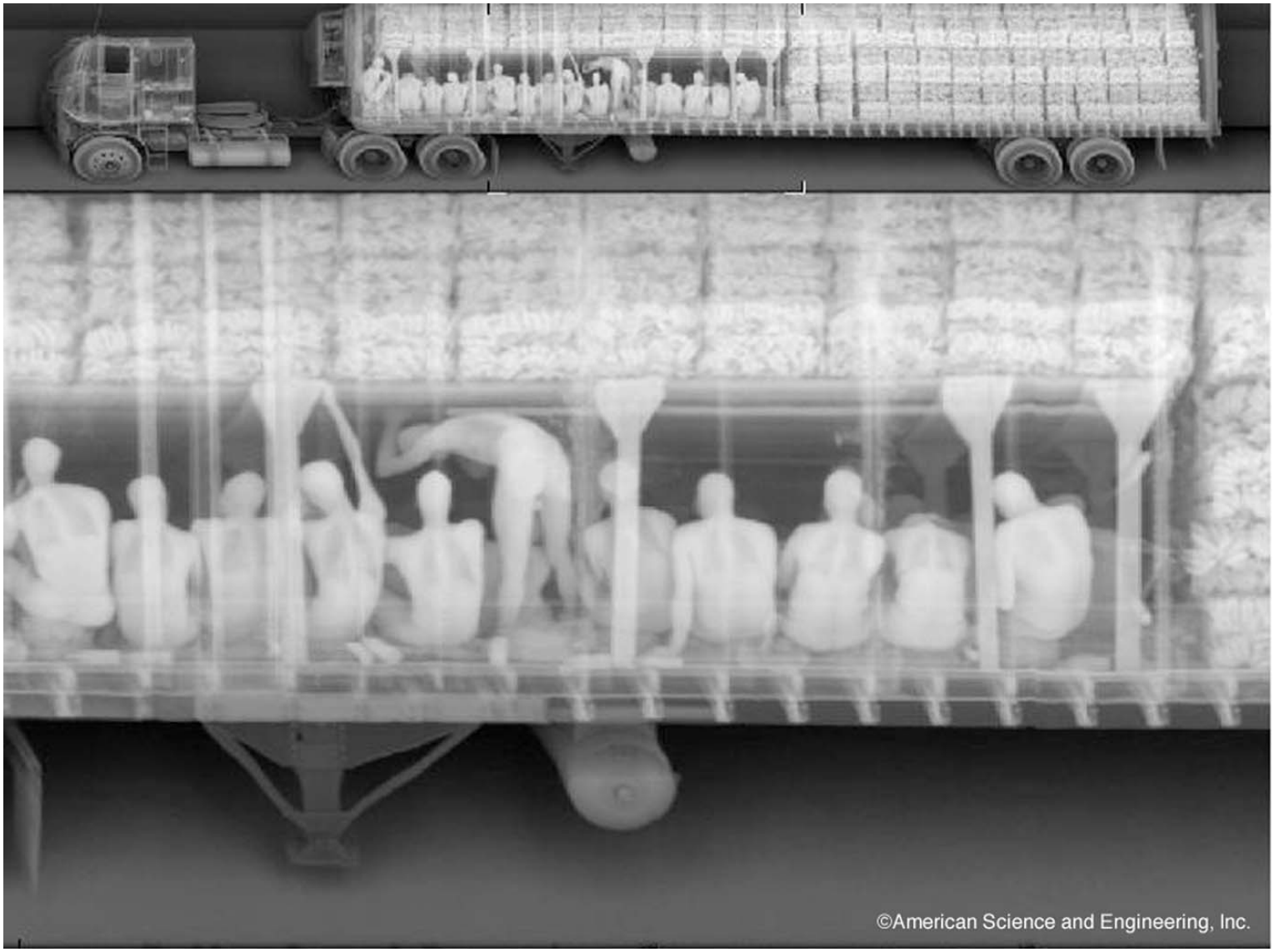
AS&E®

Z® Backscatter Van

Backscatter: Camera-Like Images

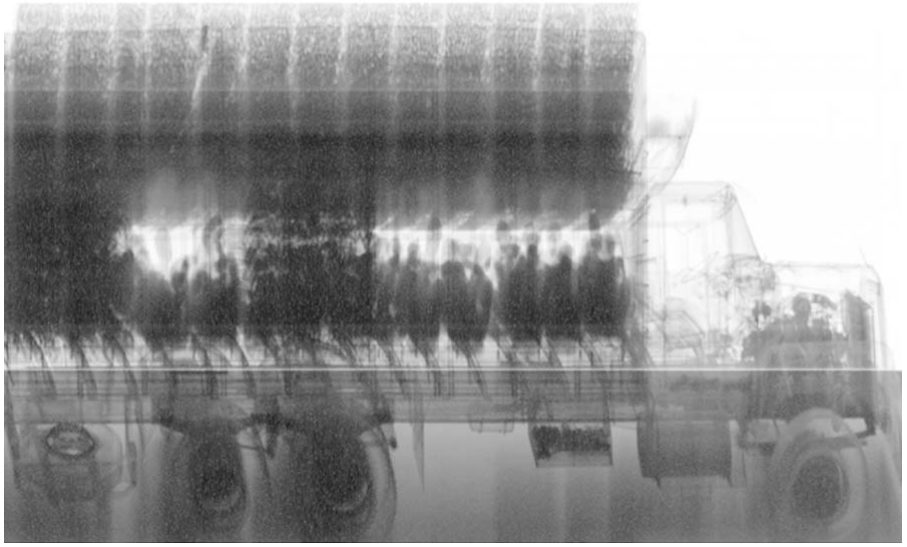
- *"Drive-by" Scan 2 to 5 metres from the vehicles, 0.5 km/hr*
- *Detect personnel or organic material hidden in vehicles*

Backscatter Image of Illegal Immigrants



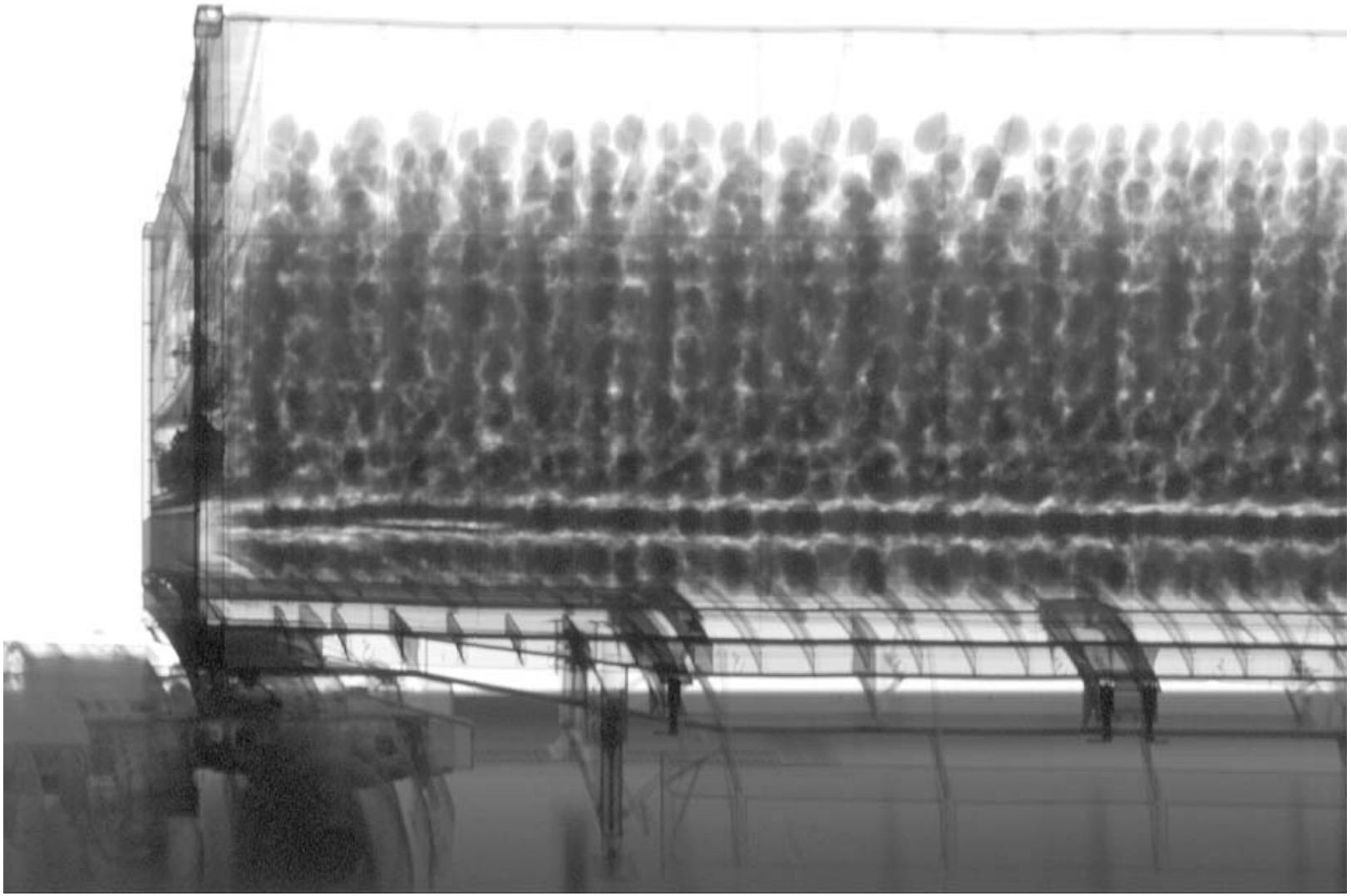
X-ray Images: Illegal Immigrants

Z® Backscatter X-ray Image



Transmission X-ray Image

Transmission Image: MobileSearch™

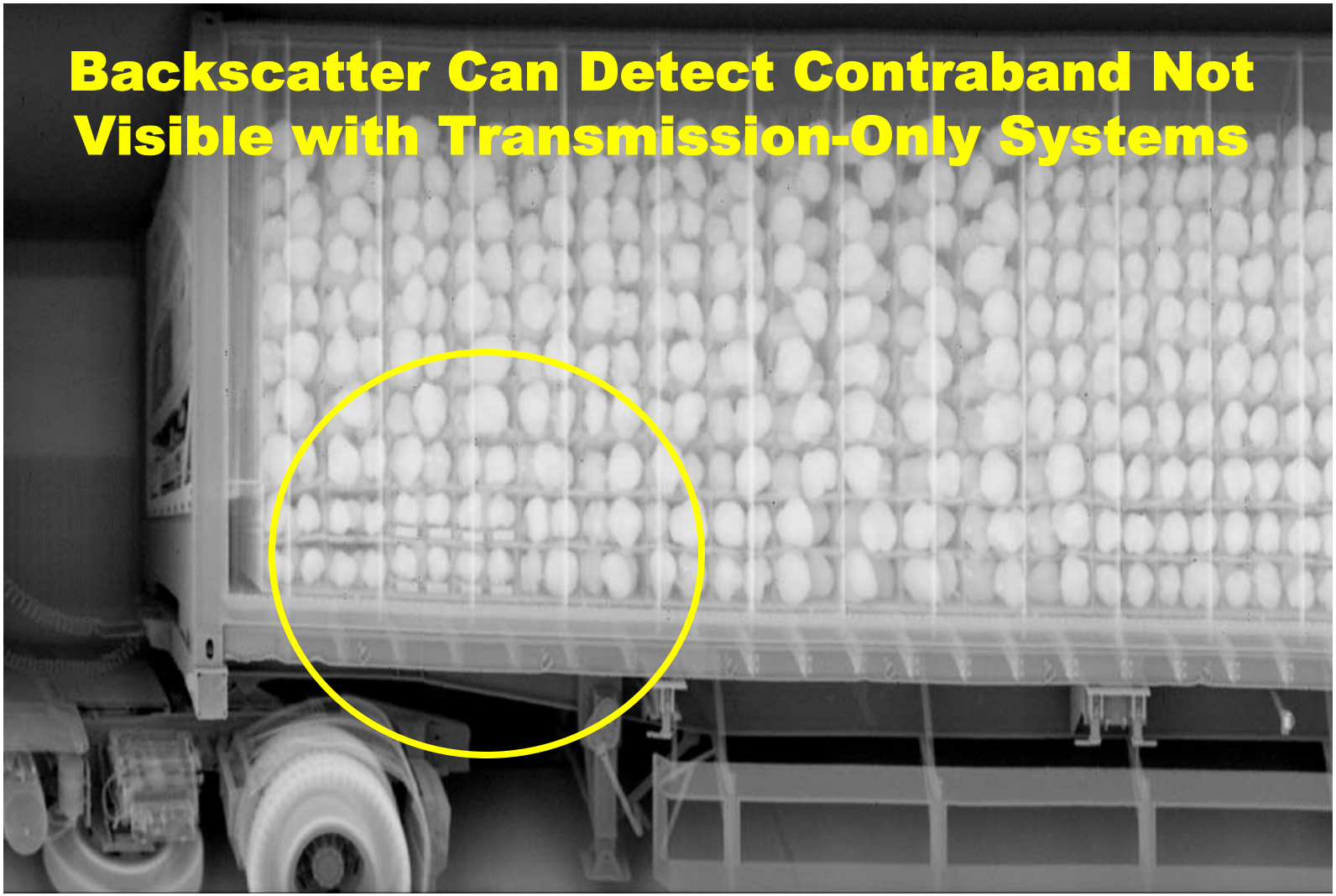


Transmission X-ray image of a truckload of durians

Battelle

AS&E®

Backscatter Image: MobileSearch™

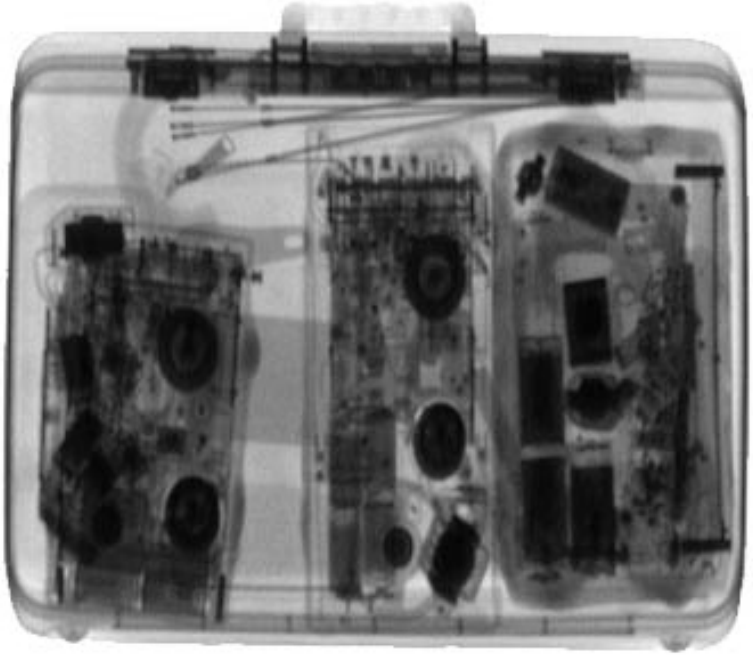


Z® Backscatter X-ray image reveals an anomaly

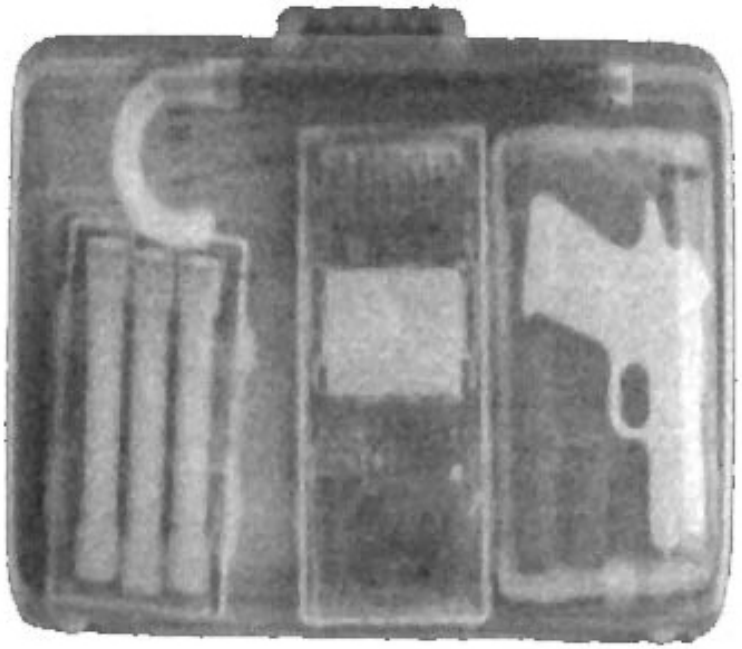
Backscatter Critical to Detection

The raw heroin was confiscated

Pipe Bombs, Cocaine, & Plastic Gun Hidden in a Briefcase



Transmission Image

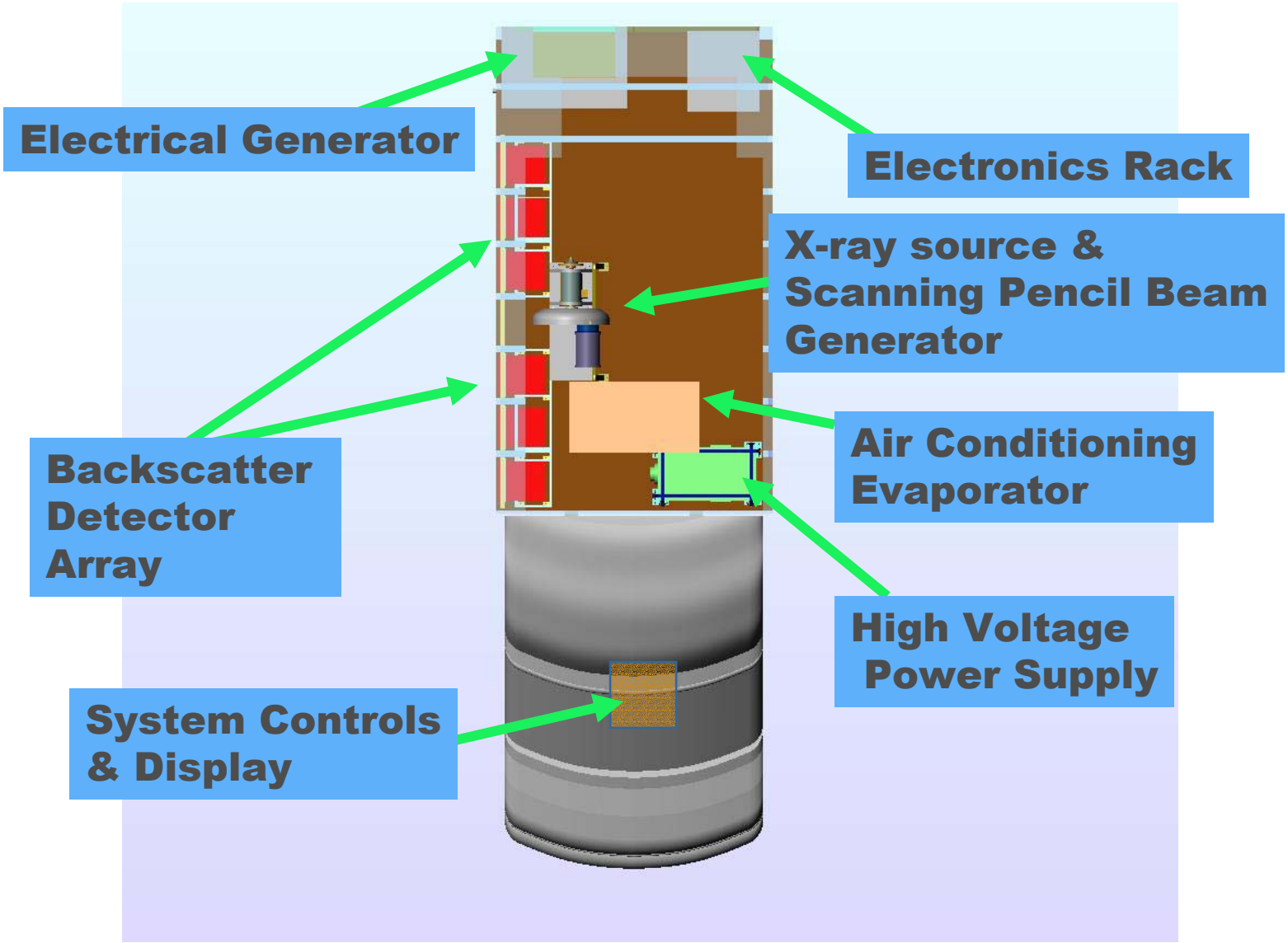


Backscatter Image

ZBV's Geometry Well-Suited for Large Trucks

Quick and Easy One-Sided Inspections

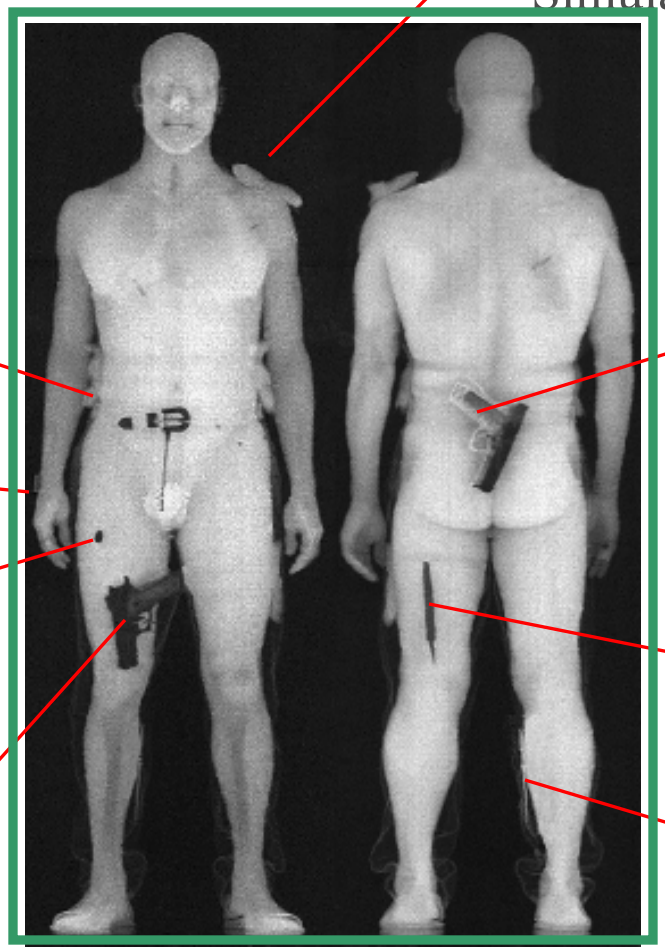
ZBV Layout


Electrical Generator
Electronics Rack
X-ray source & Scanning Pencil Beam Generator
Backscatter Detector Array
Air Conditioning Evaporator
High Voltage Power Supply
System Controls & Display

BodySearch Apparatus

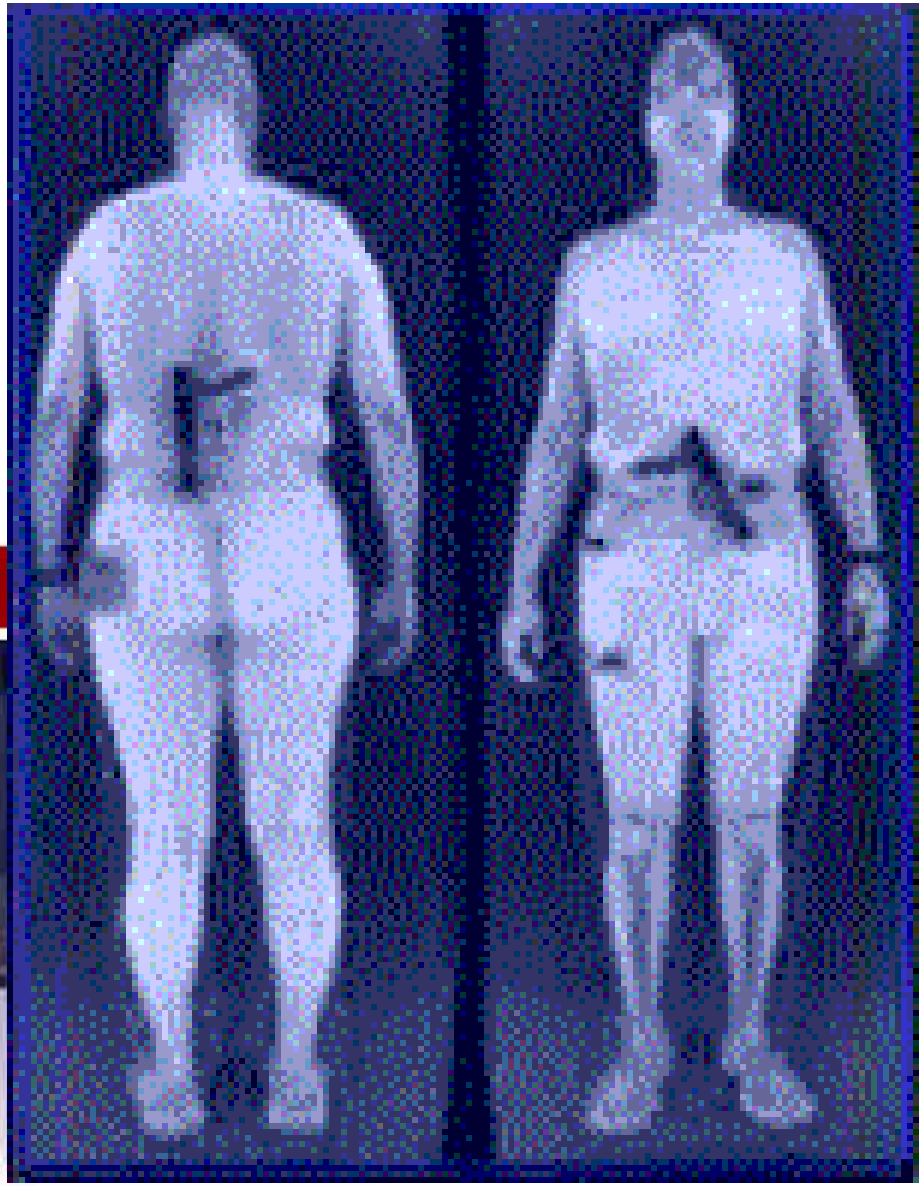
BodySearch Reveals Both Metallic and Non-Metallic Objects

- One BodySearch Scan (One-Sided) ~ 12 seconds



Rapiscan Secure 1000 People Imager

http://www.rapiscan.com/



Rapiscan Secure 1000

- Scan Rate <8 s per view
- < 0.1 μSv (10 μrem) /scan
- 1.1kW
- 123 x 92 x 202cm
- 1.1 m^2 floor space
- 295 kg

BodySearch Issues

- Privacy is the primary issue
  - Who sees the image? Same sex operator?
  - Medical devices
  - Is image stored?
  - Is image information available to others?
  - USA Today 6/26/2003: TSA still interested
    - “It does basically make you look fat and naked, but you see all this stuff” –TSA official
- Radiation dose secondary
  - Equivalent to 2 minutes at altitude in a commercial jet

Dual-Energy Transmission Systems

Dual Energy Transmission Systems

- Expose package to
  - 2 distinctly different energies of x-rays, or
  - a range of energies

  and image transmitted radiation at different energies
- Distinguish low-Z from high-Z materials
- Low-Z materials
  - organic materials such as drugs and explosives
  - composed mainly of light elements such as H, C, N, O, Cl
  - produce relatively large amounts of backscattered radiation
  - less efficient at absorbing radiation
- High-Z materials
  - nearly all metals
  - composed of heavier elements
  - produce little backscattering
  - more efficient at absorbing radiation

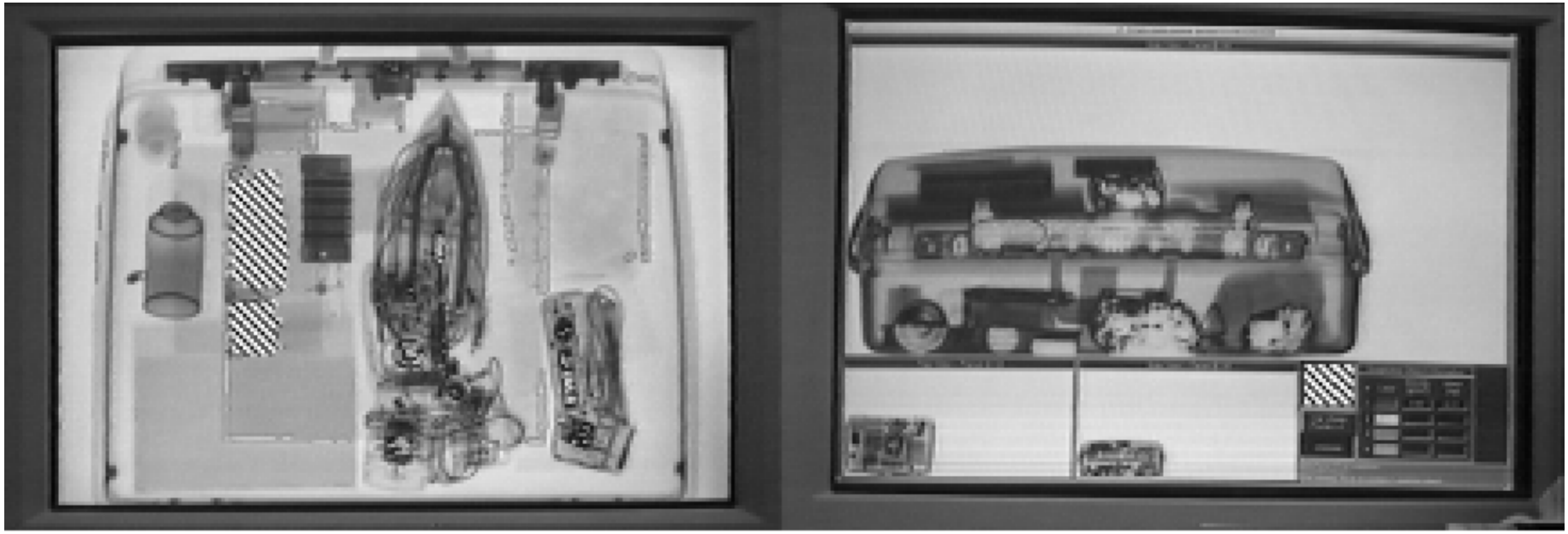
Dual Energy Transmission Systems

- Simple black-and-white transmission systems cannot easily distinguish between thick sections of organic low-Z materials and thin sections of high-Z materials
- Dual energy systems can distinguish between these materials and highlight the difference using color
- Beware pseudocolor
- Some dual energy systems have enough specificity not only to distinguish between low-Z and high-Z materials, but also to distinguish among various low-Z materials

Dual Energy Transmission Systems

- X-ray generator
  - Vertical, upward projecting, X-ray fan beam
  - 75 kVp/150 kVp
  - pulsed, dual energy
- Radiation levels
  - <1μSv per inspection
  - Scatter < 1μSv/h at cabinet surface

Dual Energy Images



Vivid VDSI (stripes indicate the presence of contraband)

EG&G/Astrophysics Z-Scan (striped alarm square in the lower right hand corner indicates presence of contraband)

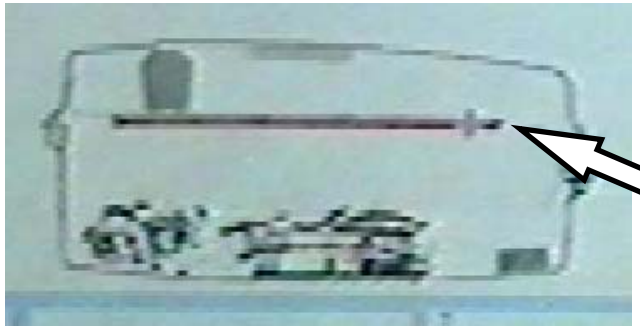
Computed Tomography Systems

Computed Tomography (CT) Baggage Scanner

- Many manufacturers
- e.g., Invision Technologies www.invision-tech.com
- X-ray System
  - Pre-scanner: 145 kV, 2.2 mA, 768 Detectors
  - CT: 180 kV, 15 mA, 576 Detectors
  - Continuous Duty Cycle
  - Complies with FDA's cabinet x-ray standards, 21 CFR 1020.40
  - "high dose X-ray system"
  - Do not put unprocessed film in checked baggage
  - Place film and cameras containing film in carry-on luggage

Computed Tomography (CT) Baggage Scanner

- e.g., L-3 Communications eXaminer 3DX®6000 www.L-3Com.com
- X-ray System
  - 165 kV
  - Duty Cycle: continuous
  - Cooling: oil filled
  - 6048 detectors
  - Helical-cone-beam, multi-slice computed tomography



Thin layer of contraband

Multi-View Tomography (MVT) Baggage Scanner

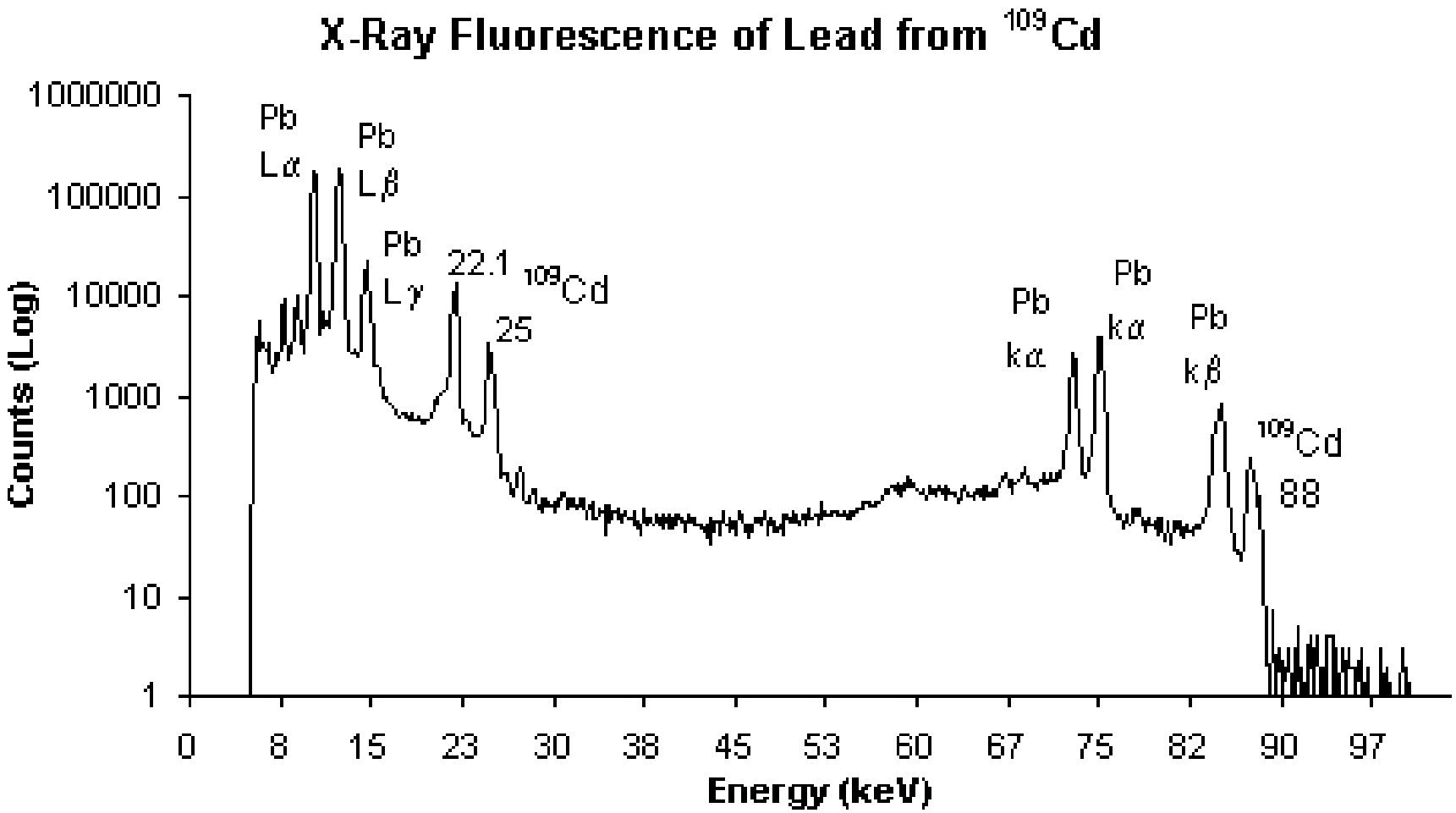
- e.g., L-3 Communications MVT www.L-3Com.com
- Three pulsed, true dual energy X-ray fan beams, 75 kVp/150 kVp. Two sources projecting upward from below the conveyor belt and one projecting across the belt
- Radiation Safety
  - <2.5μSv per inspection
  - Scattered radiation <1μSv/h at cabinet surfaces

X-ray Fluorescence

X-ray Fluorescence (XRF)

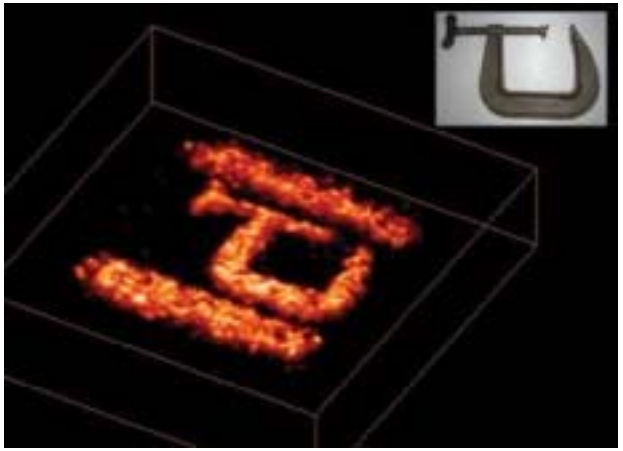
- Portable XRF instruments have been in use for decades
- perform on-the-spot analyses of metals and minerals
- common design
  - 1.5 GBq (40 mCi) ^{109}Cd source
  - excites characteristic x-rays from materials
  - detectors commonly are room-temperature
    - silicon surface-barrier detectors or
    - CdZnS detectors
  - with computer analysis of spectra
  - Readouts can be given in seconds

X-ray Fluorescence (XRF)



Muon Scattering for Imaging High-Z Materials

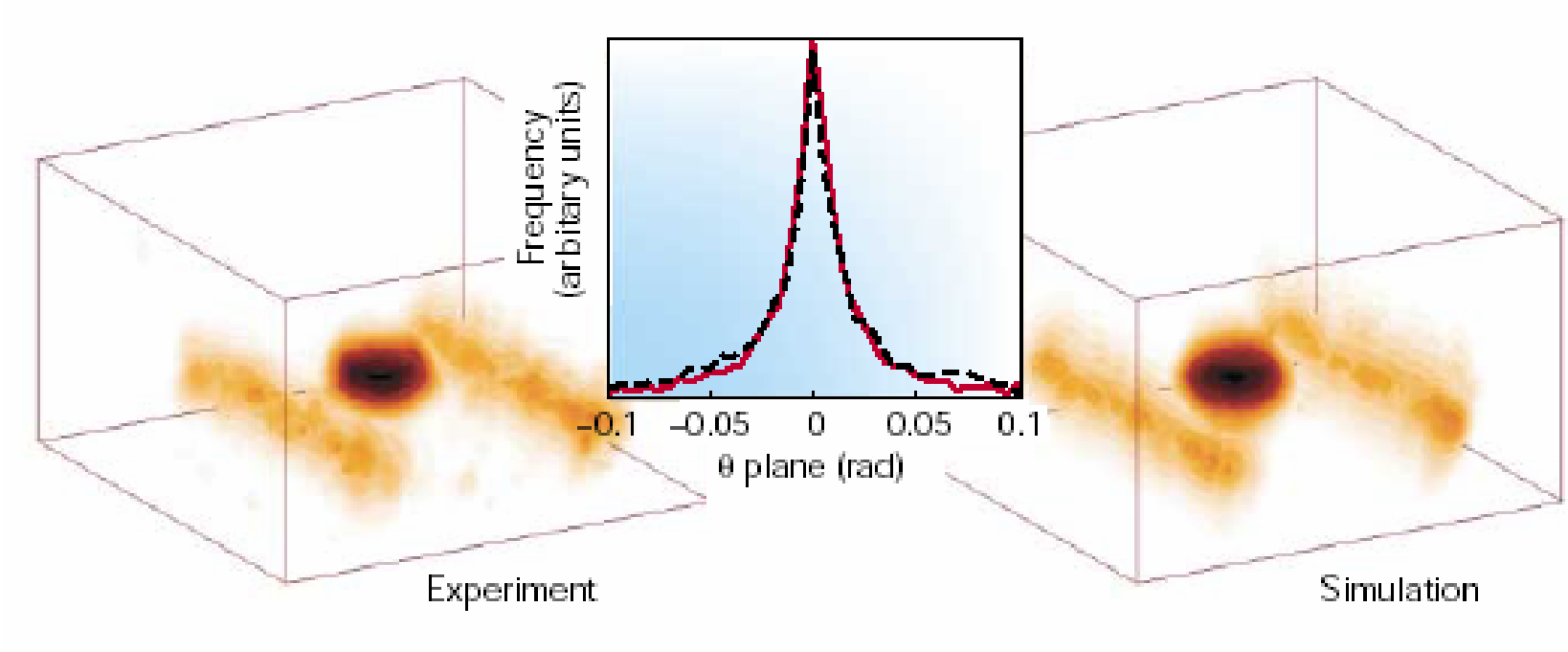
Muon Scattering for Imaging High-Z Materials



- Borozdin et al. (2003), Los Alamos National Laboratory
- radiographic imaging with cosmic-ray muons
- "Natural background muons, which are generated by cosmic rays and are highly penetrating, can be used for radiographic imaging of medium-to-large, dense objects, without these limitations and with a reasonably short exposure time. This inexpensive and harmless technique may offer a useful alternative for detecting dense materials."
- most sensitive for the highest-Z materials
- can reliably detect a 10×10×10 cm block of uranium concealed inside a metal container full of sheep in 1 min.

Muon Scattering for Imaging High-Z Materials

- Borozdin, K.N., *et al*. 2003. Radiographic imaging with cosmic-ray muons. *Nature* 422(March 20):277



- http://www.mu-vision.com

Thermal Neutron Activation (TNA)

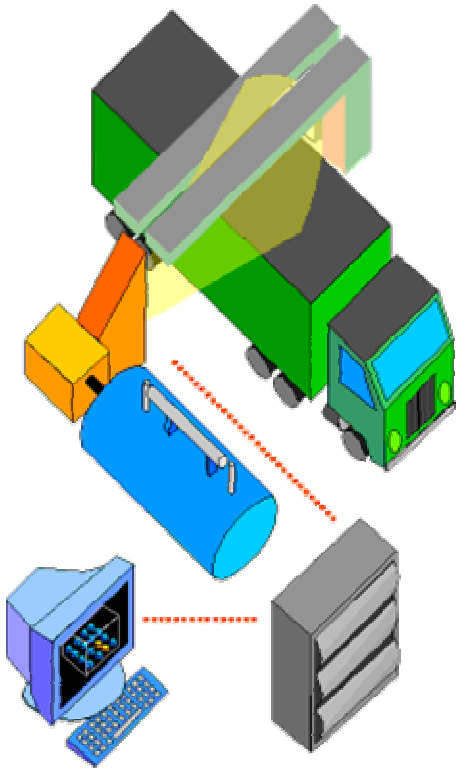
Thermal Neutron Activation (TNA)

- standard technique
- activates cargo
- look for gamma spectra or resultant radionuclides
- not for imaging

Pulsed Fast Neutron Analysis (PFNA)

Pulsed Fast Neutron Analysis (PFNA)

- measures the elemental contents within small volume segments (voxels) of a scanned object
- measurements generate three-dimensional maps of the cargo's elemental composition
- amounts and relative concentrations of key elements are used to identify specific substances
- inspected objects (cargo containers or goods-carrying trucks) move through the system
- objects are exposed to short (10^{-9} s) pulses of fast (4×10^{7} m s^{-1}) neutrons
- beam is collimated and scanned in a vertical plane



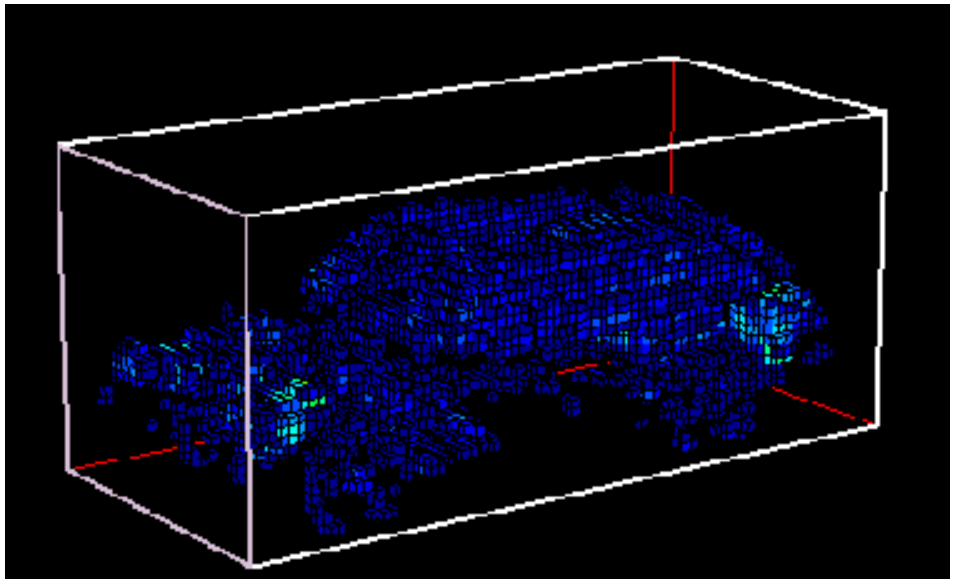
Pulsed Fast Neutron Analysis (PFNA)

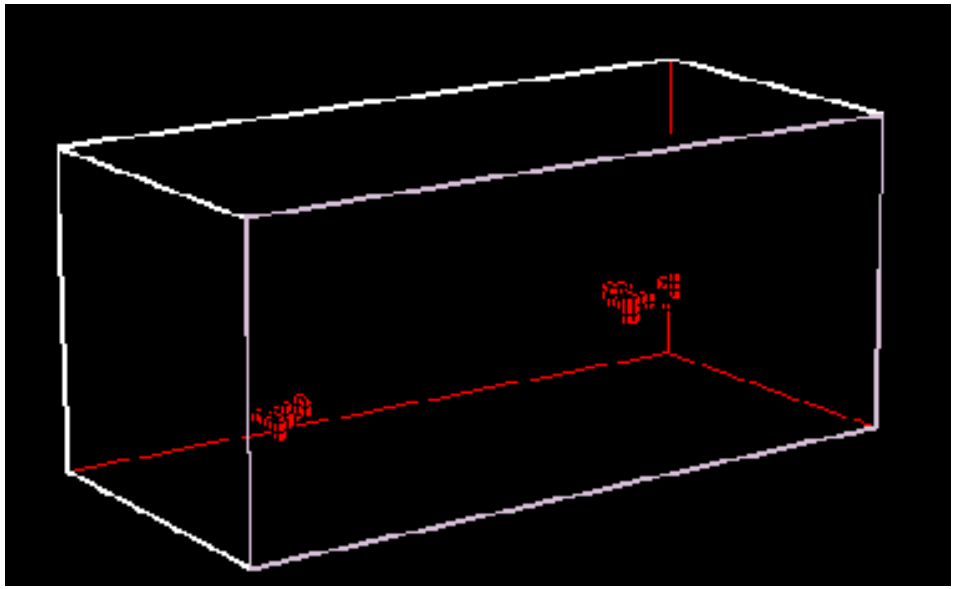
- produce "nearly instantaneous" (n,γ) reactions
- γ-detectors located around the inspected containers collect neutron-capture gammas emitted by the container contents
- data acquisition system processes the signals and routes
- time-of-flight gives 3rd dimension
  - narrow energy range of neutrons required for high resolution
  - spectrum should not change much as neutrons traverse container
  - need lots of shielding
  - large (20 m × 70 m) building
- result: elemental images of what is present in the cargo container
- elemental signatures are compared to material signatures which have been programmed into the computer

Pulsed Fast Neutron Analysis (PFNA)

- comparison enables the system to automatically identify a variety of contraband types
- high resolution images display the position and extent of contraband in the cargo container or truck
- entire process fully automated
- does not require human operator interpretation
- detection does not rely on shape
- detection immune to diligent packaging

Pulsed Fast Neutron Analysis (PFNA)





PFNA Radiation Protection Issues

- Tritium production
  - $d(d,n)^3He$ reaction is used
  - $d(d,p)^3H$ competes, resulting in about 1:1 ^3H:n
  - tritium production in
    - target: 1.3×10^8 Bq (3.5 mCi) from 10^{10} n s^{-1} for 2000 h
    - beam line: <10% of target
- Stowaways: 300 μSv per pass
- Activation products in food, pharmaceuticals, medical devices and other cargo
  - e.g., 1 nGy from eating 10 g of NaCl

(NCRP Commentary 17, 2003)

Summary

- A variety of imaging and identification techniques are needed
- Traditional
  - Intelligence reports
  - Cargo tracking technology
  - Manual search techniques
  - Canine detection
  - Trace detection technologies
    - passive radiation detectors
- Bulk detection technologies: interrogate with
  - non-ionizing radiation
  - ionizing radiation

Summary

- Combination of high energy transmission X-rays with backscatter is a powerful inspection tool
  - Transmission penetrated 30 cm steel equivalent
  - Backscatter for organic detection
    - Explosives
    - Drugs
    - Weapons
    - Other Contraband
  - Backscatter aids in image understanding; helps to deconvolve complex transmission imagery
  - Low doses to stowaways and to cargo
  - Radioactive threat detection <u>while scanning</u>
- New technologies being developed

Acknowledgements

- Pacific Northwest National Laboratory (http://www.pnl.gov) is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RLO 1830

  strom@pnl.gov

- American Science and Engineering, Inc. manufactures X-ray inspection systems for security applications (http://www.as-e.com).

  JCallerame@as-e.com

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