CAPABILITY TESTING OF X-RAY SYSTEMS IN THE CARGO EXAMINATION CONTEXT

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BACKGROUND

This paper reports on a project which has operated with the involvement of several Australian Government agencies:

- Prime Minister & Cabinet (PMC)
- Department of Transport and Regional Services (DOTARS)
- Australian Customs Service (ACS)
- Australian Federal Police (AFP)
- Australian Nuclear Scientific and Technology Organization (ANSTO)

The project seeks to evaluate the capability of X-rays to detect explosives in cargo passing through Australia's borders.

PHASE1 of the project studied the capability of equipment currently in use in Australia.

PHASE2 of the project investigated the:

- capability of X-ray systems currently being released onto the market
- the effect of the use of these systems on throughput of cargo through freight-forwarding warehouses

STRUCTURE OF PRESENTATION

X-RAY ABSORPTION SYSTEMS

I shall discuss principally:

- **the different types of X-ray absorption system currently available for purchase and the design principles underlying their construction**
- **the development of standards for the testing of X-ray examination systems with tunnel sizes greater than 1200mm X 1200mm**
- **the performance testing of 24 X-ray systems on three continents using these standards**
- **the characteristics X-ray systems must possess if they are to be used for detecting contraband, including explosives**

SPECTROSCOPIC SYSTEMS

- **(Nuclear) Quadrupole Resonance**

NEUTRON & GAMMA-RAY SYSTEMS

- **Absorption systems**
- **Spectroscopic systems**

SMALL TUNNEL

140 keV
Dual Energy; Single View
Quadrupole Resonance

160/80 keV
Switched Energy; Four Views

160 keV
Dual Energy
Computed Tomography

MEDIUM TUNNEL

300 keV
Dual Energy / Dual View

450 keV
Dual Energy / Dual View

2.5 MeV
Dual View

LARGE TUNNEL

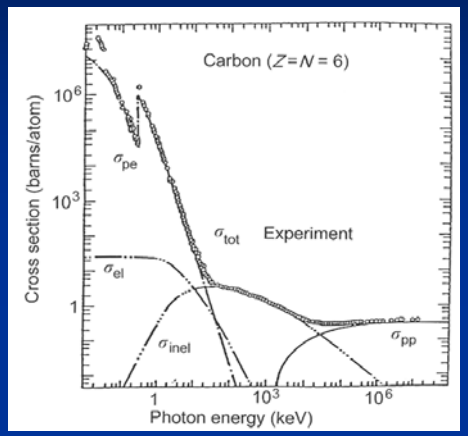
3 MeV
Computed Tomography

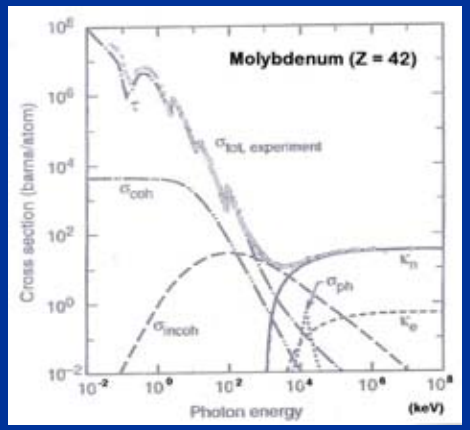
6 / 3 MeV
Dual Energy / Binocular View

6 MeV
Single View
Three 225 keV views
(backscatter)

SOME BACKGROUND INFORMATION

INTERACTION OF X-RAYS WITH ATOMS AS A FUNCTION OF X-RAY ENERGY





For X-ray examination systems: 140 keV<E < 6 MeV

Interactions of significance include:

- photoelectric scatter
- **X-ray fluorescence**
- incoherent (Compton Scatter)
- **coherent scatter (Rayleigh Scatter)**
- pair production

Of these:

- **photoelectric scatter dominates for E < 450 keV and is strongly dependent on atomic number**
- **Compton scatter peaks at ~ 100 keV and is weakly dependent of atomic number**
- **Rayleigh scatter decreases significantly with increasing photon energy and is weakly dependent on atomic number**
- **pair production has a threshold at ~1.1 MeV and is weakly dependent on atomic number**

ABSORPTION TECHNIQUES

- All commercial X-ray examination systems use the absorption of x-rays absorption of x-rays to determine what is present in the objects under scrutiny.
- The Beer Lambert Law is underlying principle of operation.

$$I = I_o \exp - (\mu_l t)$$

where I_o is the incident beam intensity,

μ_l is the linear attenuation coefficient (= $(\sum \sigma_i) / V_c$)

t is the thickness of the medium through which the X-rays travel

- If the medium through which the X-rays travel contains a number of different materials along the path length the linear attenuation coefficient becomes a summation

$$\mu_l = \sum \mu_i t_i$$

- The presence of many different materials (with different values of μ_l) complicates the interpretation of the X-ray image.
- To assist in interpreting the image it is usual to use radiation with two different source energies. This is achieved either by pulsing the source between two different values, or using an energy filter in front of the detector array to change the effective photon energy. Whichever method is used, the procedure is referred to as DUAL ENERGY (DISCRIMINATION). Solving the simultaneous equations allows a degree of MATERIALS DISCRIMINATION to be made.

PERFORMANCE OF SMALL TUNNEL X-RAY SYSTEMS
(TUNNEL < 1000mm X 1000mm)

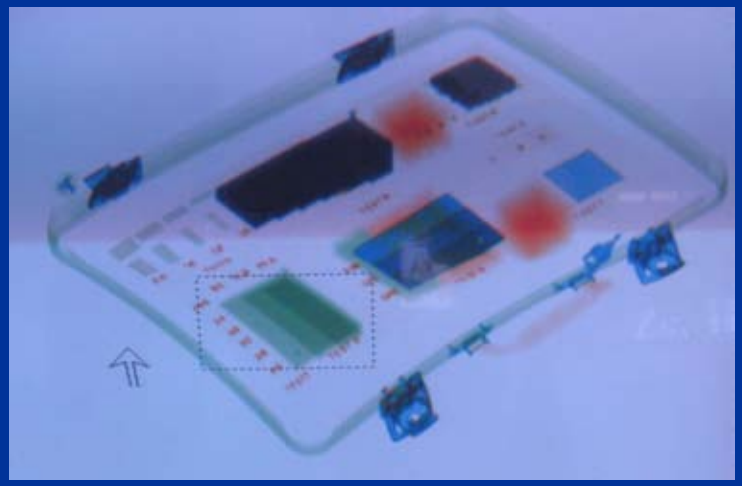
ASTM F792-01 Standard Suitcase

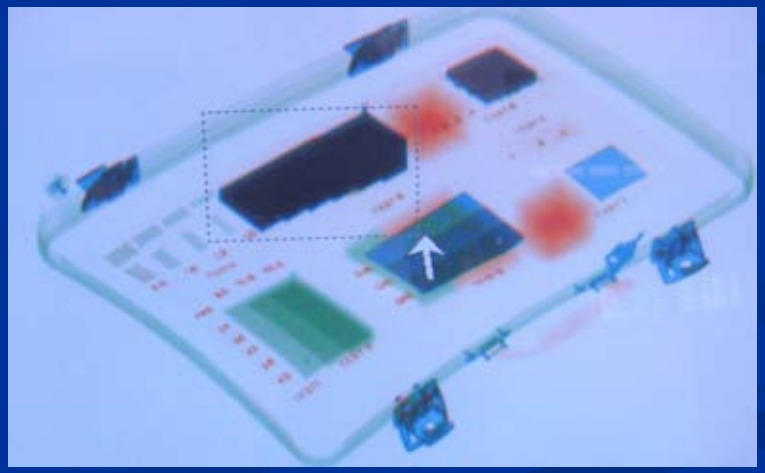
X-ray images below are from:

- **single view, dual energy system.**
- **The manufacturer claims a capability to be able to calculate Z_{eff}.**

THIS IS NOT SO.

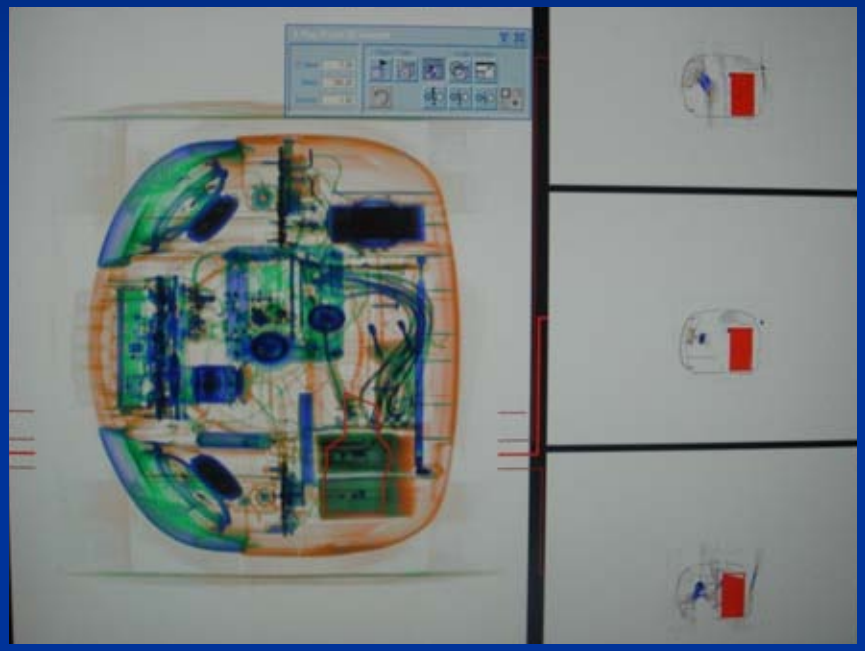
THE BOXES IN THE IMAGES SHOW INCORRECT VALUES OF Z_{eff}.





CALCULATED:	Z_{eff} = 9.4	Z_{eff} = 6
SHOULD BE:	Z_{eff} = 13 (aluminium)	Z_{eff} = 26 (steel)

PERFORMANCE OF SMALL TUNNEL X-RAY SYSTEMS
(TUNNEL < 1000mm X 1000mm)



CALCULATED: Z_{eff} = 7.5

SHOULD BE: Z_{eff} = 7.5 (explosive)

Image of clock radio containing an explosive threat

X-ray images below are from a computed tomography, dual energy system.

The manufacturer claims a capability to be an Explosives Detection System

THIS APPEARS TO BE A VALID CLAIM.

UNFORTUNATLY CT SYSTEMS ARE SLOW COMPARED WITH MORE CONVENTIONAL SYSTEMS

(400 bags/hr compared to 1400 bags/hr)

PERFORMANCE OF MEDIUM & LARGE TUNNEL X-RAY SYSTEMS

(TUNNEL SIZE > 1300mm X 1300mm)

NO STANDARD TESTS EXIST FOR MEDIUM & LARGE TUNNEL SYSTEMS

Existing tests involve the use of rods and steel plates to check image quality in an *ad hoc* fashion to test

- **Image Quality Index (IQI)**
- **Contrast Sensitivity (CS)**
- **Penetration**

THIS IS BOTH INACCURATE & TIME CONSUMING

(typically 4 hours per view)

A NEW STANDARD (ANSI N42.46) IS BEING DEVELOPED AT NIST (USA) BY DR PAUL BERGSTROM

This performs the requisite tests

BUT

requires the removal of rods and plates

to test IQI, CS, and penetration

THIS IS TIME CONSUMING (24 HOURS)

& SINGLE VIEW (HORIZONTAL) ONLY

PERFORMANCE OF MEDIUM & LARGE TUNNEL X-RAY SYSTEMS

WE DESIGNED OUR OWN TEST PIECES

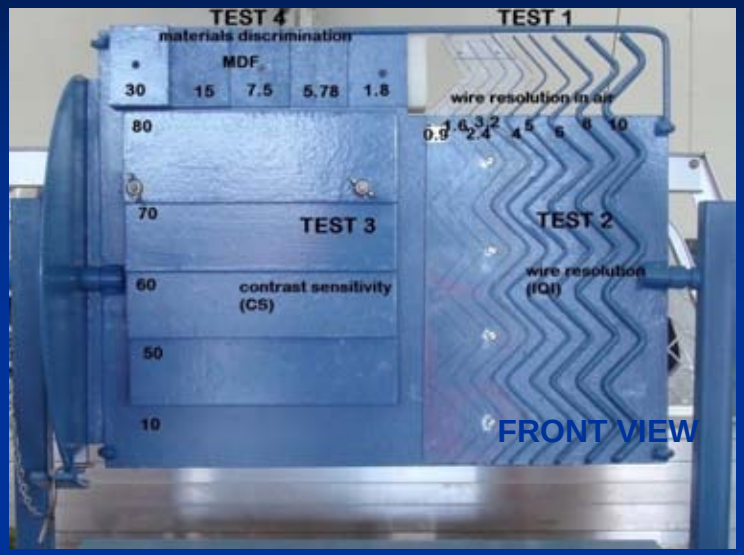
DESIGN CRITERIA

- **Ability to test pallet, air-cargo, and container search systems (tunnel dimensions 1200mm x1200mm) and greater**
- **Test performance effectively for X-ray energies from 160 keV to 6 MeV**
- **Test materials discrimination capabilities of systems where appropriate**
- **Provide the range of tests detailed in the ASTM F792-01 standard and the proposed ANSI 42.46 standard**
- **Be of manageable size (forklift & and 1 ton truck compatible)**
- **Be capable of use in testing both single & dual view systems**
- **The results of all tests should be available after ONE pass per view through the system under evaluation**
- **A standard scorecard should exist to enable easy comparison of system performance with prior tests of the same system or with other X-ray systems**

THESE WERE USED IN TESTING OF 12 OF THE 24 X-RAY SYSTEMS USED IN THE PROJECT

PERFORMANCE TESTING OF MEDIUM & LARGE TUNNEL SYSTEMS

AUS1



TEST1: wire resolution in air

TEST 2: IMAGE QUALITY INDEX (IQI)

- wires to be detected behind step wedge
- plates can be added to change step thicknesses if required

TEST 3: CONTRAST SENSITIVITY (CS)

- plates to be detected behind step wedge
- thickness of step wedge can be altered if desired
- can be used to PENETRATION for systems with X-ray energies less that 450 keV

TEST 4: MATERIALS DISCRIMINATION

- identification of organic material in air (nylon step wedge)
- identification of nylon step wedge in front of a 10mm steel plate, and an MDF step wedge
- this also acts as a **BACKSCATTER TEST**
- identification of the thickness differences for the crossed MDF & nylon step wedges

PERFORMANCE OF MEDIUM & LARGE TUNNEL X-RAY SYSTEMS

PROTOTYPE AUS2

This test piece was not able to be finished in time for testing in China and the USA. It should be mounted on an axle similar to that in AUS1 to ensure that the test piece is normal to the mean direction of the fan beam.

TEST 1: RESOLUTION of wire bundles in air

TEST 2: RESOLUTION of wire bundles behind a steel step wedge with steps of 10, 20, 30 mm.

TEST 3: PENETRATION through steel. 40mm of steel in the shape of a kite behind 160mm of steel.

TEST 4: DISCRIMINATION BETWEEN PLASTIC OBJECTS. Five plastics with different effective electron densities are made in the form of a step wedge with steps of 10, 20, 40 mm.

THIS OBJECT IS PLACED ON THE TEST PLATFORM BESIDE TEST PIECE AUS1.

PERFORMANCE OF MEDIUM & LARGE TUNNEL X-RAY SYSTEMS

AUS1 & AUS2

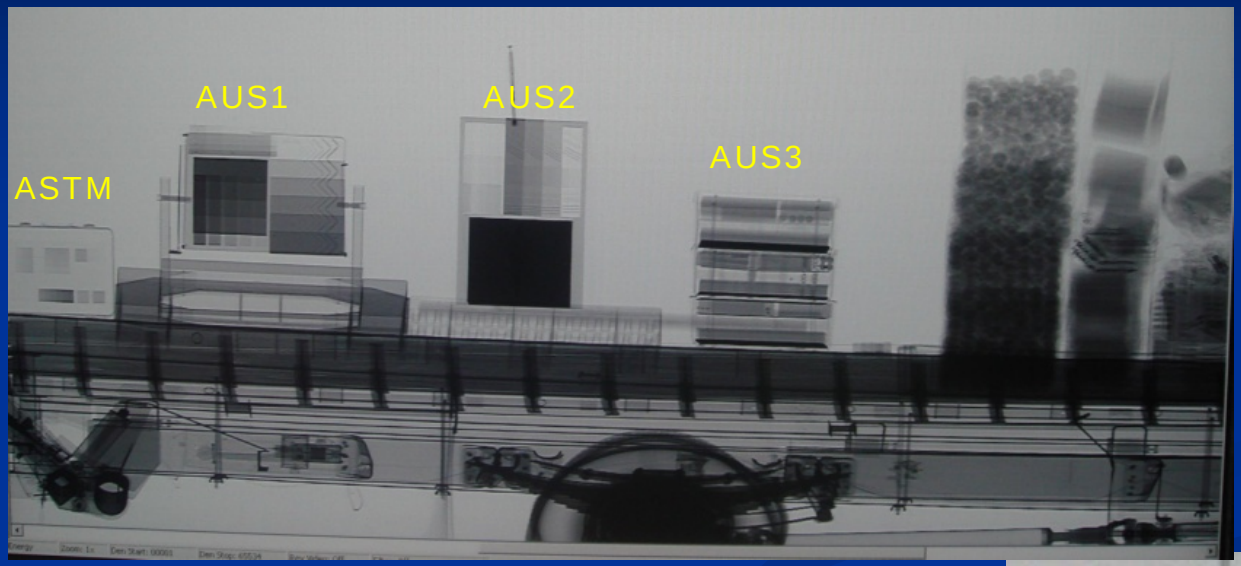
3MeV Single View, Vehicle Speed15kph

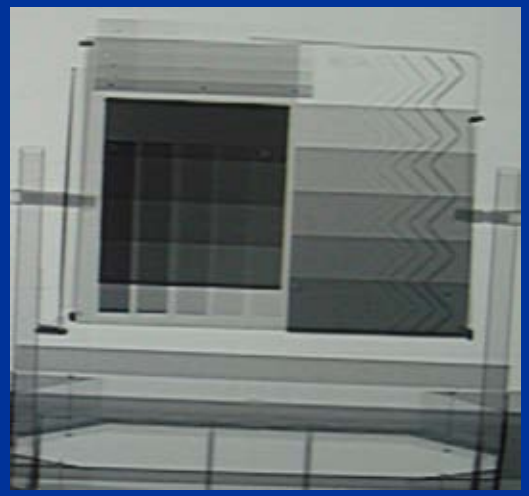
PERFORMANCE

AUS1: 72%
AUS2: 51%

PERFORMANCE OF MEDIUM & LARGE TUNNEL X-RAY SYSTEMS

6MeV Single View Gantry System (200 mm/s)





PERFORMANCE

AUS1: 74%
AUS2: 55%

PERFORMANCE AGAINST STANDARDS

1. SMALL TUNNEL

ASTM

- Manufacturers do NOT meet their own specifications for penetration, wire resolution in air, materials discrimination.
- EDS systems ARE NOT truly automatic; threat boxes are often misplaced with respect to the threat.

2. MEDIUM & LARGE TUNNELS

AUS1

- Most manufacturers meet their specifications for wire resolution in air, IQI, CS, and plastics discrimination.
- A backscatter system does not provide better discrimination between plastics than a transmission system

AUS2

- Most systems struggle to meet the manufacturers' penetration specifications and have poor spatial resolution (wire bundle test)
- Backscatter systems do not provide better discrimination between organic materials than transmission systems.

PERFORMANCE OF X-RAY SYSTEMS WITH IMPROVISED EXPLOSIVE DEVICES & EXPLOSIVES

IEDs & EXPLOSIVES

SOME EXAMPLES

X-ray image of IEDs in their boxes: computers, clock radios, VHS tapes, individual explosive pieces

EXPLOSIVES

cordex
detasheet
booster
C4

SOME TYPICAL CONCEALMENTS IN THE CHARACTERISTIC LOAD

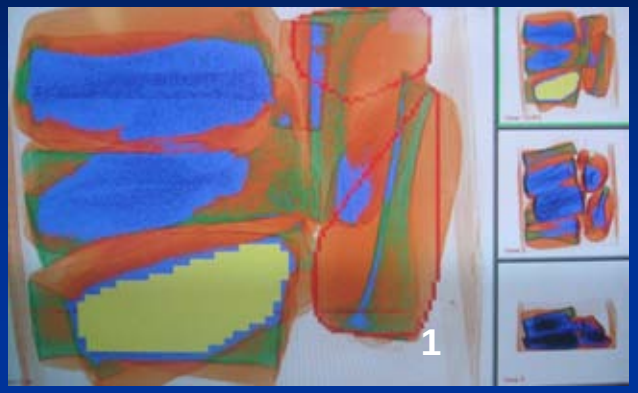
CHARACTERISTIC LOAD
(step wedge)

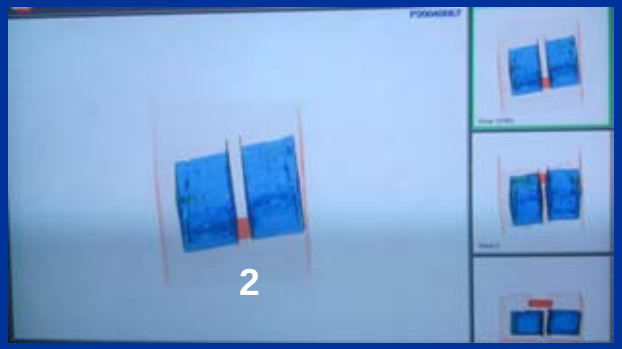
Columns containing:
Oranges
Printed matter
General cargo
Computers
Car parts
Frozen meat

EXAMPLES

SMALL TUNNEL EDS SYSTEMS

EXPLOSIVES





EDS systems should:

- allow items without threat through without producing an image on the screen
- display items with a threat
- place a treat box around the suspicious items

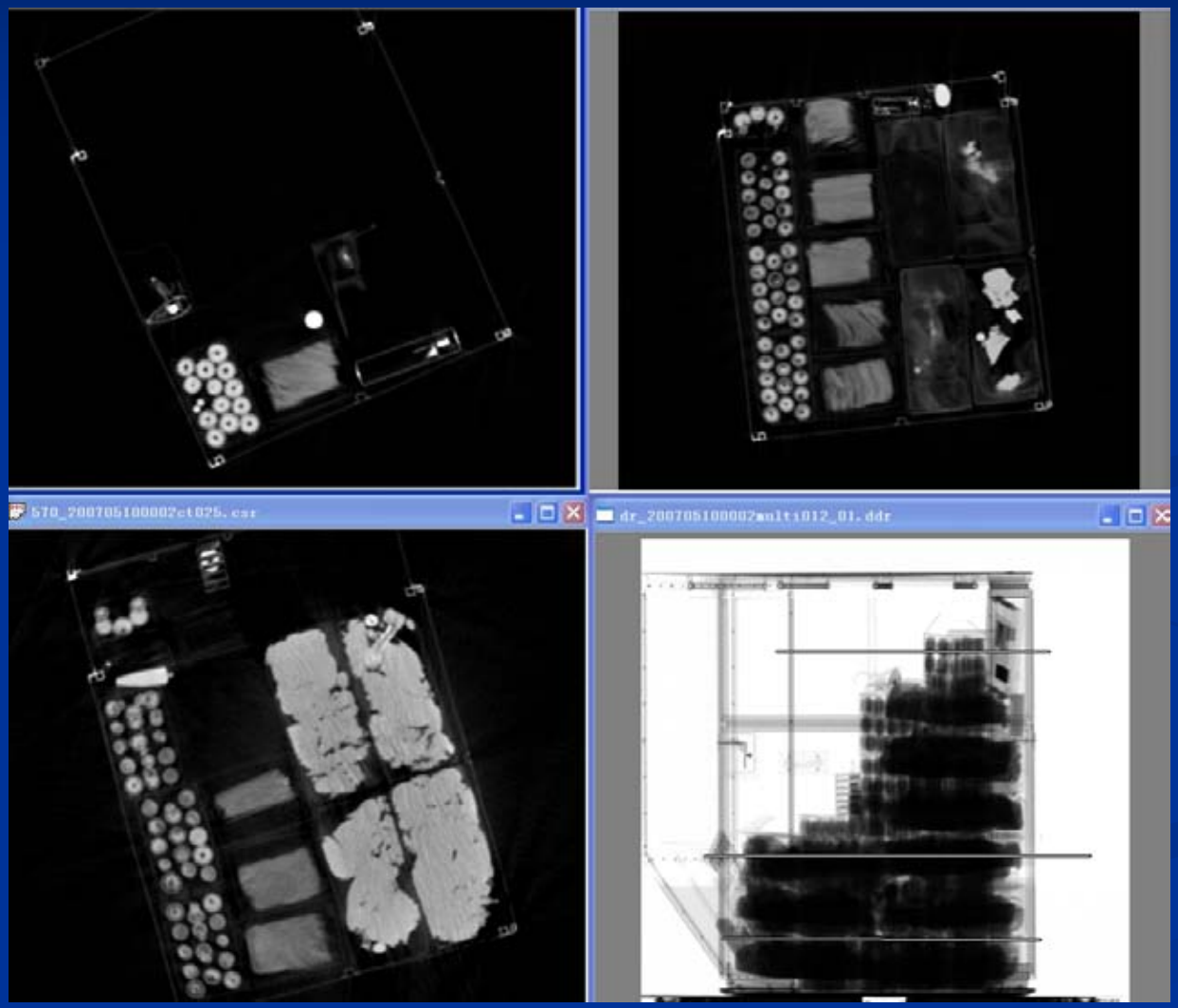
But in the X-ray images

1. The image of booster concealment is seen in the meat but threat box is around the most dense part of the item.
2. The image of booster between the electronic items is seen but is not identified as a threat
3. The concealment can be seen in the carton of oranges, and the threat box is correct.

EXAMPLES

MEDIUM TUNNEL SYSTEMS

EXPLOSIVES



This system is a Computed Tomography system.

The image of the AKE can is shown, bottom right.

The other images are slices through the load at the positions indicated.

In all the images the bright objects are concealments of explosives or bottles of glycerine.

The time taken for a full CT search is ~6 min per AKE 3 ULD.

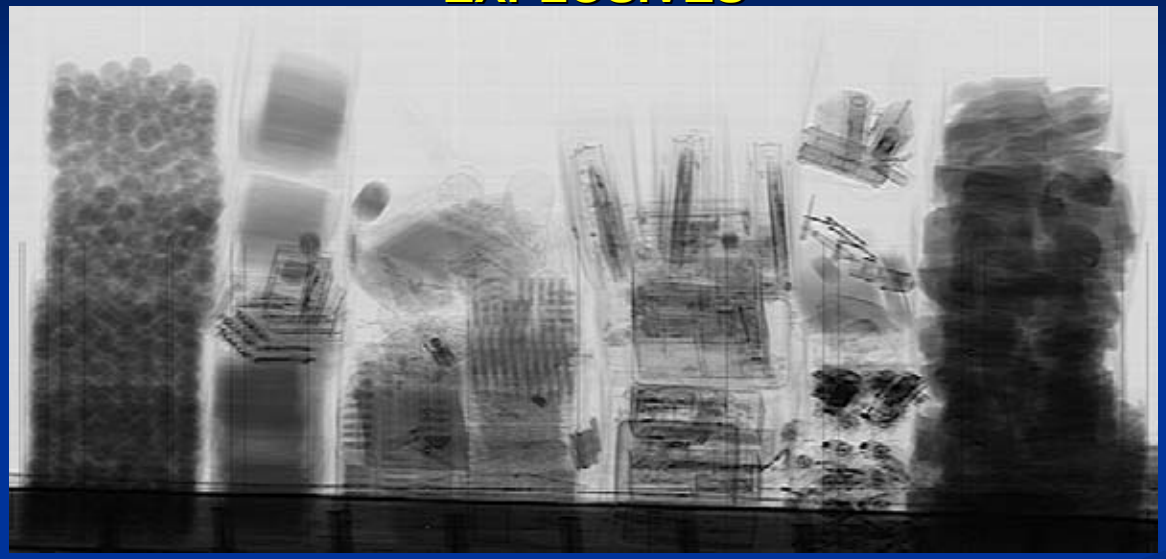
SLOW?

BUT COMPARE THIS TO THE TIME NECESSARY TO SEARCH EACH CARTON INDIVIDUALLY

EXAMPLES

LARGE TUNNEL SYSTEMS

EXPLOSIVES



TRANSMISSION IMAGE (LINAC)

BACKSCATTER IMAGE

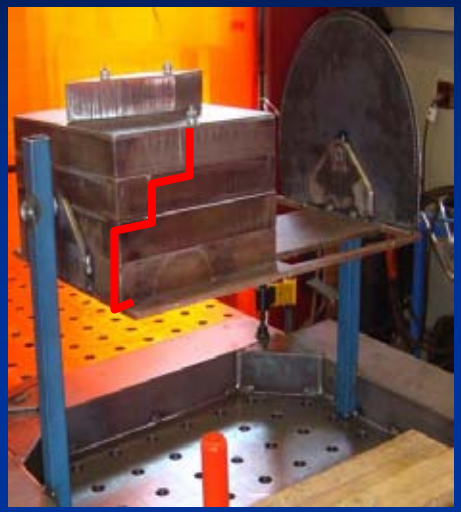
BACKSCATTER HAS NOT ENHANCED THE DETECTION PROBABILITY.

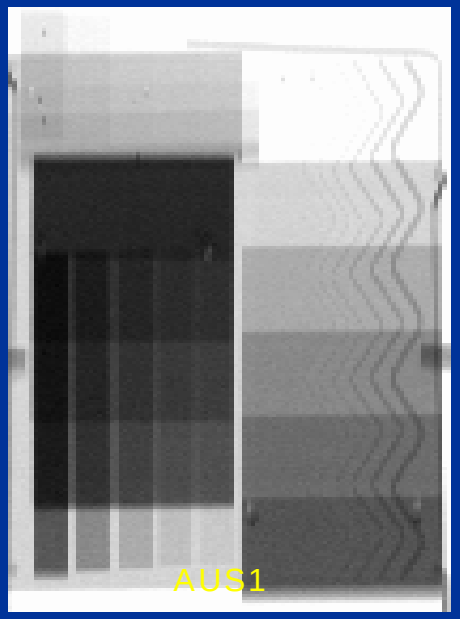
MEDIUM & LARGE TUNNEL SYSTEMS

- All these systems rely on operator identification by shape and contrast to determine what is, or is not, a threat.
- LINAC systems have sufficient source energy to penetrate most loads, but have difficulty in penetrating perishable cargoes.
- ONLY THE TOP ROW OF THE STEP WEDGE OF THE CHARACTERISTIC LOAD CAN BE EXAMINED WITH ANY DEGREE OF CERTAINTY.
- BACKSCATTER DOES NOT ENHANCE THE CAPABILITY TO DETECT CONCEALMENTS.
- COMPUTED TOMOGRAPHY GIVES THE BEST POSSIBILITY FOR RELIABLY DETECTING EXPLOSIVES AND OTHER ANOMALIES IN LOADS.

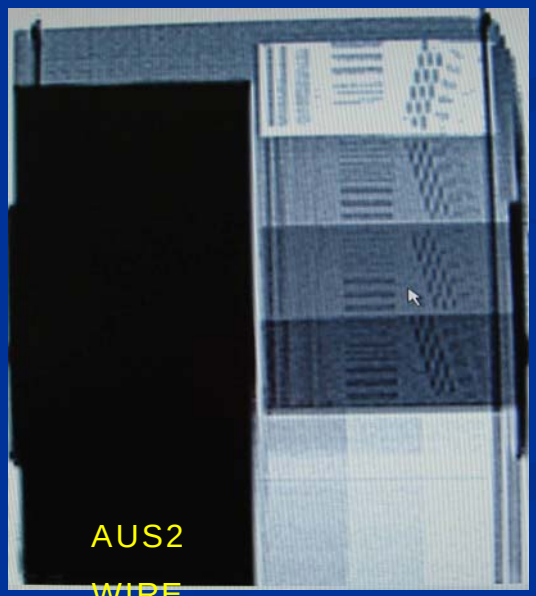
THE FUTURE??

IMPROVE AUS1 & AUS2

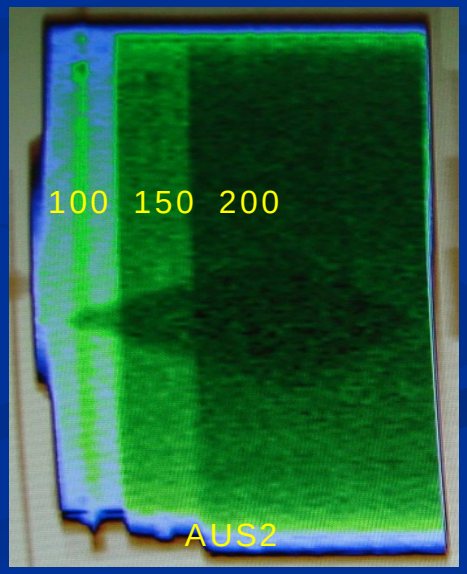




IQI & CS



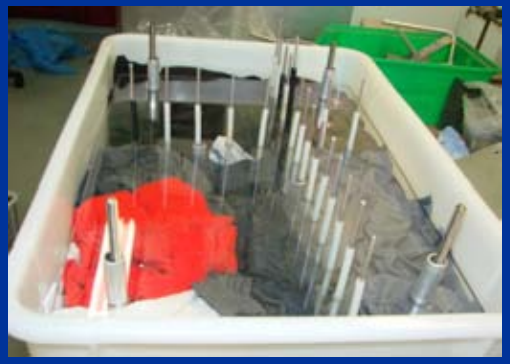
WIRE BUNDLES



PENETRATION

COMPUTED TOMOGRAPHY?

NO STANDARD OBJECT EXISTS FOR COMPARISON OF CT SYSTEMS



AUS3 WAS PUT HASTILY TOGETHER TO TEST CT SYSTEMS

THREE POLYPROPYLENE STACKABLE TUBS

Each contains layers of:
- **steel (10mm)**
- **MDF (10mm)**
- **clothing**
- **paper**
- **aluminium lid (2mm)**

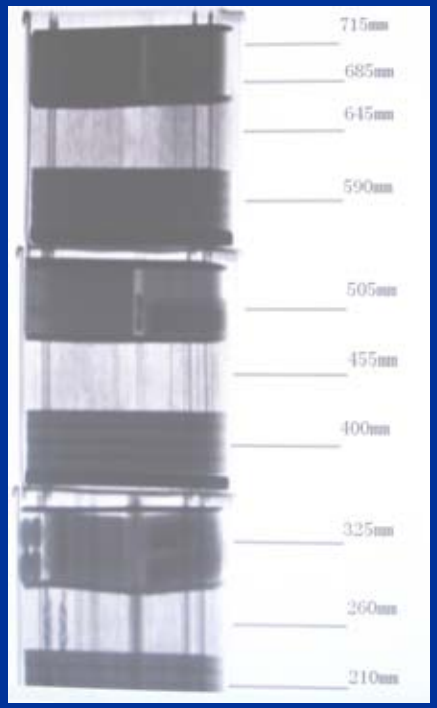
In these holes are made as shown.

Objects are inserted into some of the holes, as well as into the layers of material in each tub.

COMPUTED TOMOGRAPHY

AUS3 IN A CT SYSTEM

CT test piece assembled

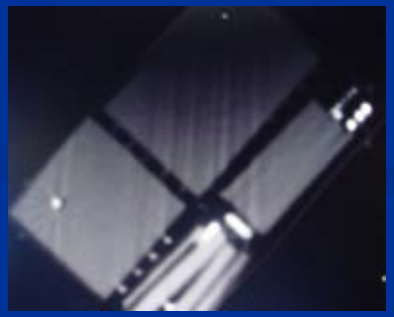


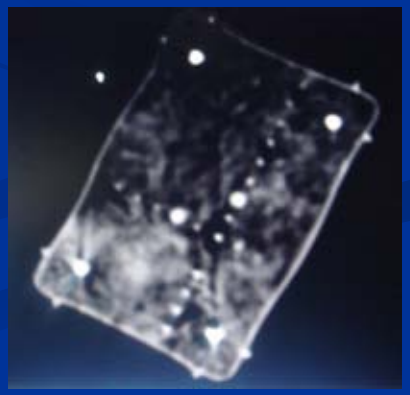
CT slices at selected heights

above the table top.

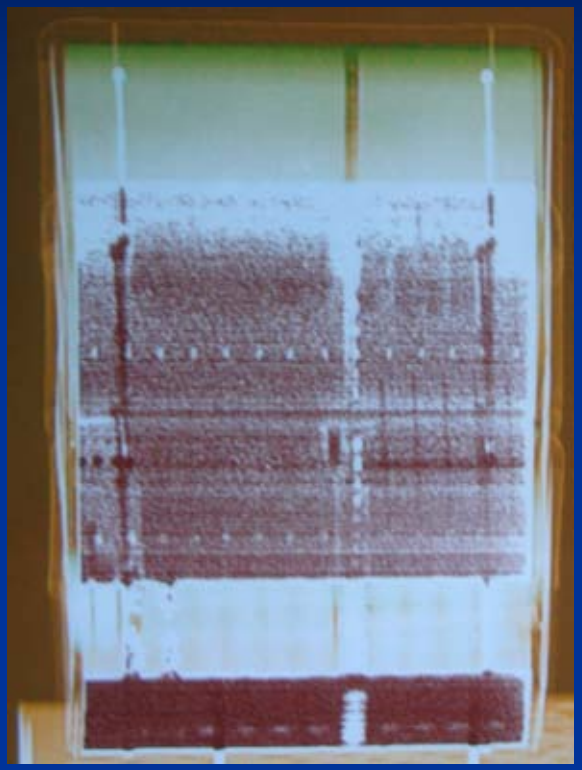
From top left, moving clockwise:

- 210mm through steel
- 260mm through cloth layer
- 325mm through paper layer
- 645mm through cloth layer





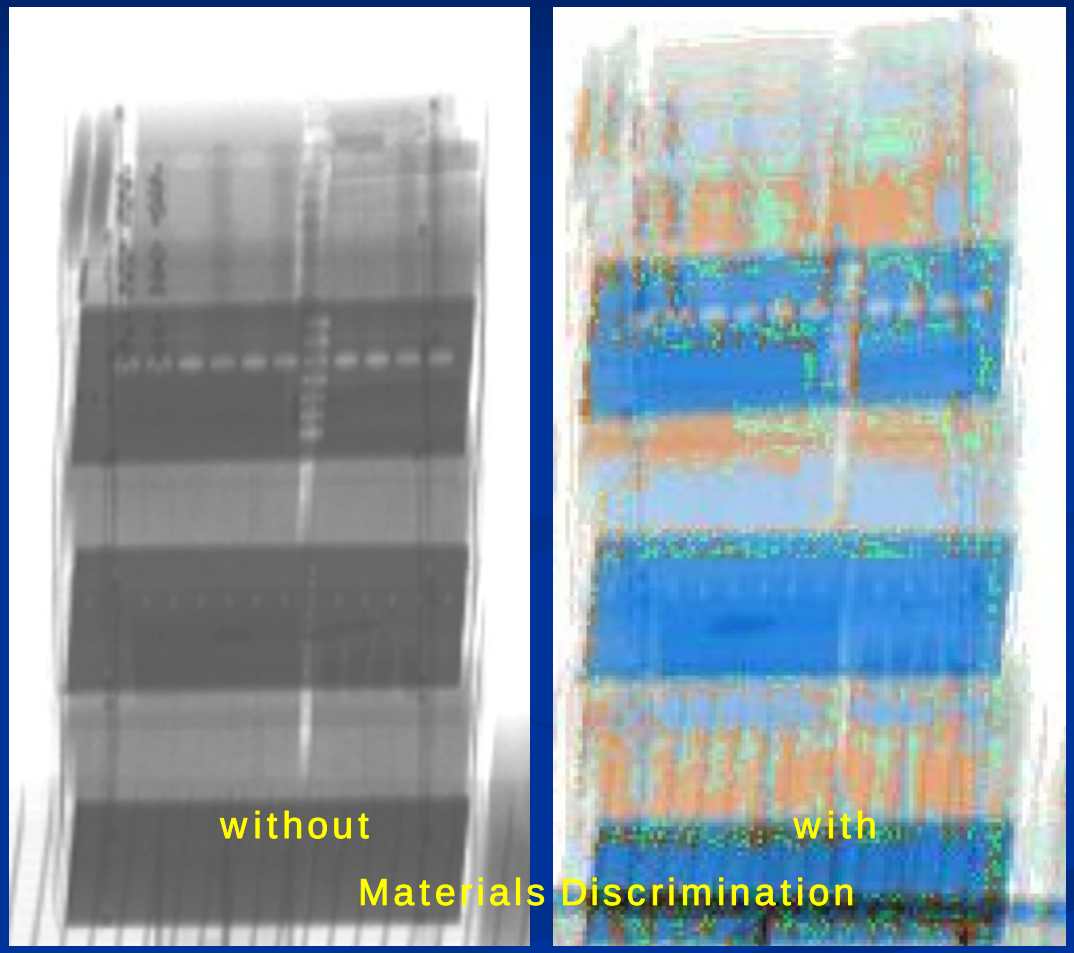
AUS3 USED IN OTHER SYSTEMS



MEDIUM TUNNEL

ONE TUB

200keV



LARGE TUNNEL

6/3MeV

THREE TUBS

PRINCIPAL PARTICIPANTS

- Winton Brocklebank (DOTARS) Team Leader
- Mike McCartney (DOTARS) Project Manager
- Professor Dudley Creagh (University of Canberra) Commonwealth Scientific Advisor
- Dr Ned Blagojevic (ANSTO) Scientific Support
- Maj Geoff Robinson (ABDC) Explosives Expert

A WORK IN PROGRESS