
Development of Backscatter X-Ray Imaging Techniques for Space Vehicle Applications

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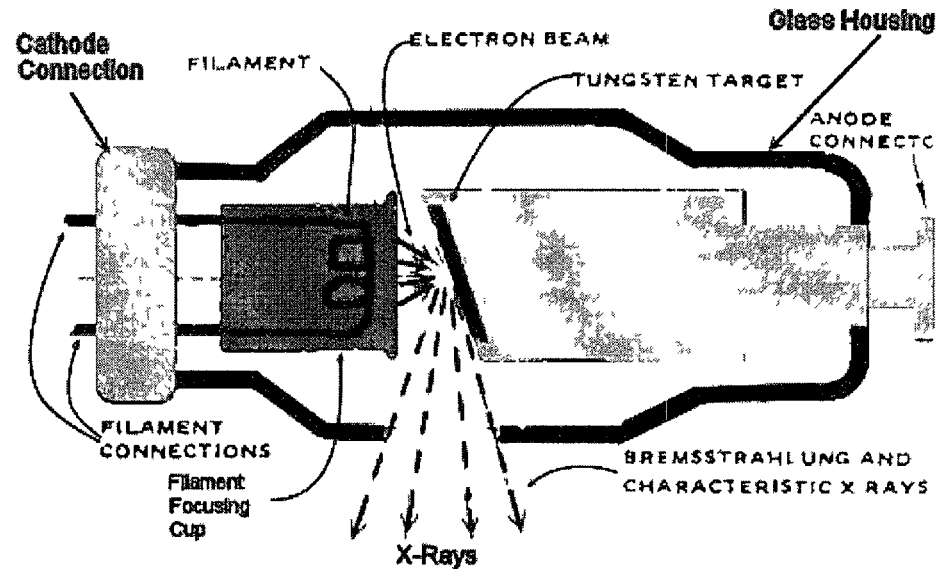
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Background and Outline

- **Overview of X-Ray Techniques**
- **A backscatter x-ray (BSX) imaging system was received from University of Florida for development and testing purposes, current systems from NucSafe**
- **Current BSX shuttle applications**
- **Development with NASA for Constellation applications**
- **Development of system toward foam applications**
- **Conclusions and future work**

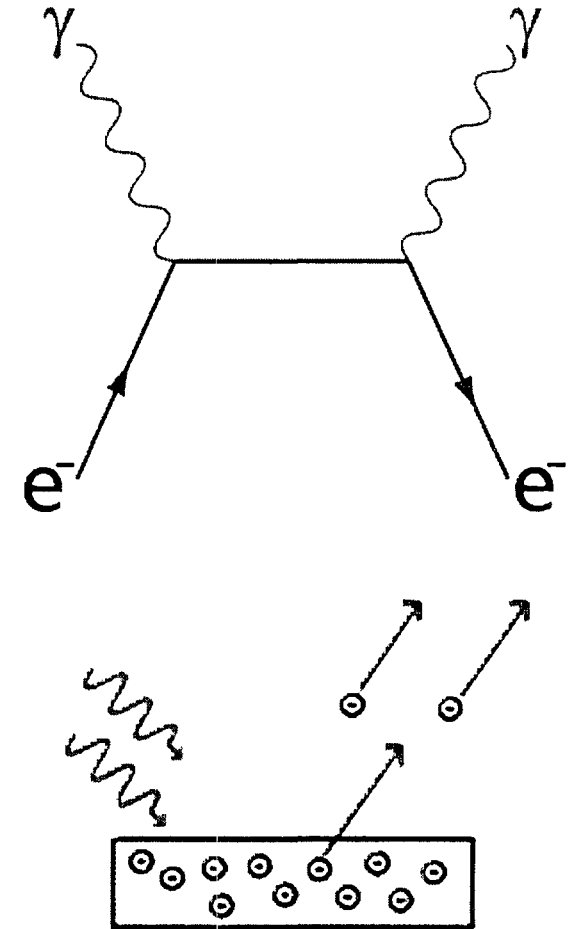
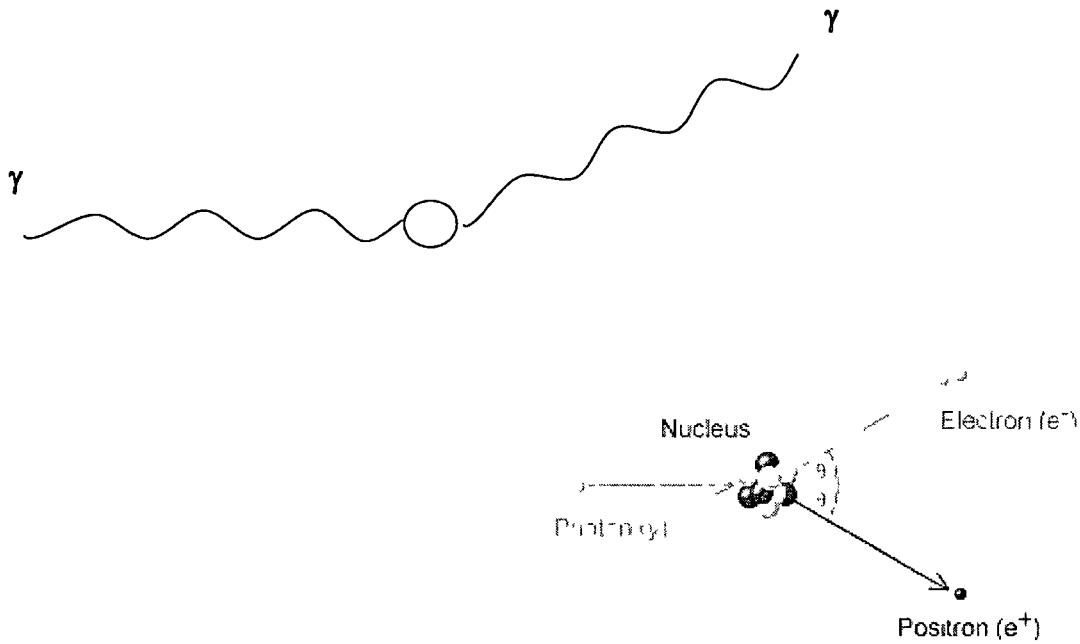
X-Ray Background

- X-Rays produced from tungsten anode target
- Energy of electrons produced from cathode determines energy of x-rays
- Number of electrons determines number of x-ray photons



Types of Photon Scatter

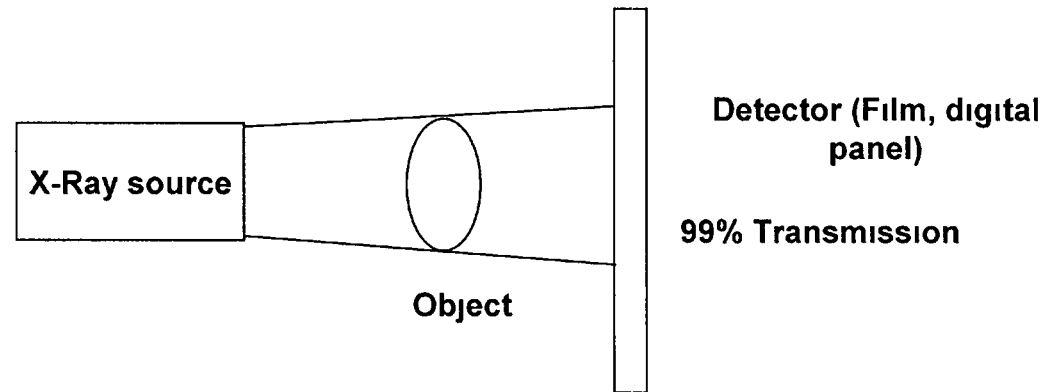
- Rayleigh
- Pair production
- Photoelectric Effect
- Compton Scatter



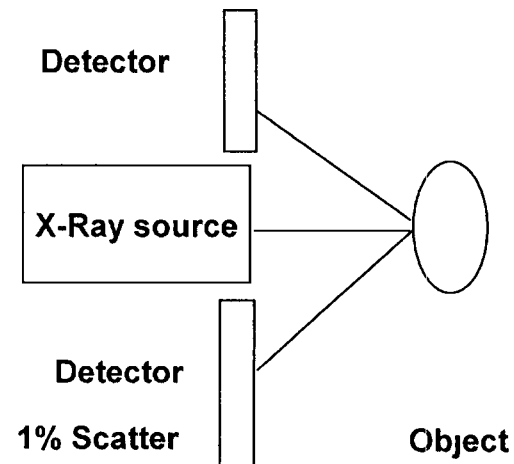
X-Ray Imaging Techniques

- **Through Transmission**
- **Scatter Imaging (BSX)**
- **Backscatter uses detectors on same side as source**
- **Beams usually highly collimated**
- **Detectors more sensitive than through transmission technique**
- **Beam rastered across part with backscatter technique**

Through Transmission X-Ray Imaging

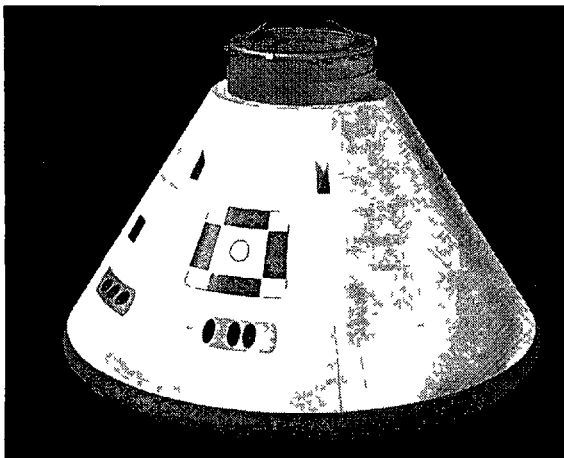


Backscatter X-Ray Imaging



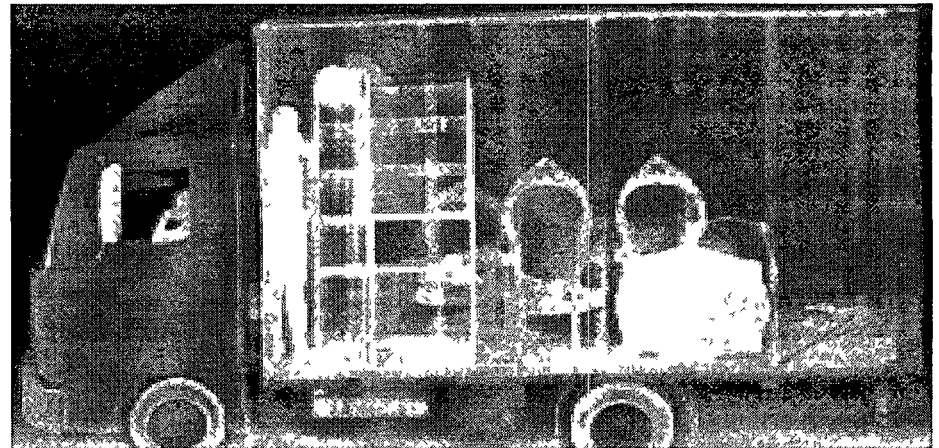
Current Backscatter X-Ray Applications

- X-Ray techniques used to look for flaws in materials such as castings, forgings, welds, insulation, tiles
- BSX X-Ray techniques are currently used for inspecting cargo, at borders and airports
- Can also look for voids, lack of fusion, inclusion, corrosion, disbonds, composition, thickness, water intrusion
- Used to inspect External Tank
- Initial development for Constellation program applications

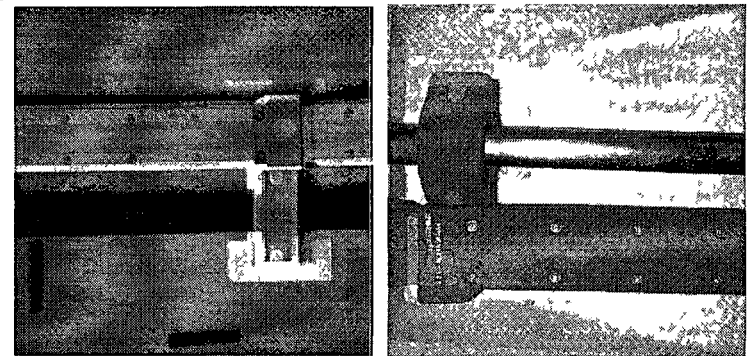
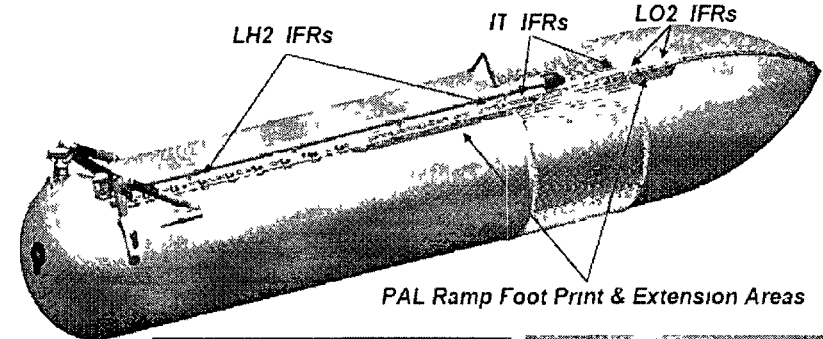


Orion CEV

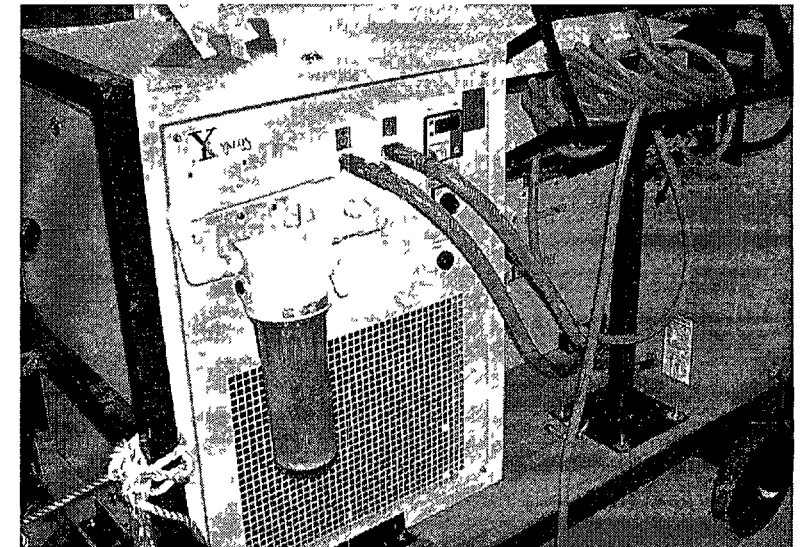
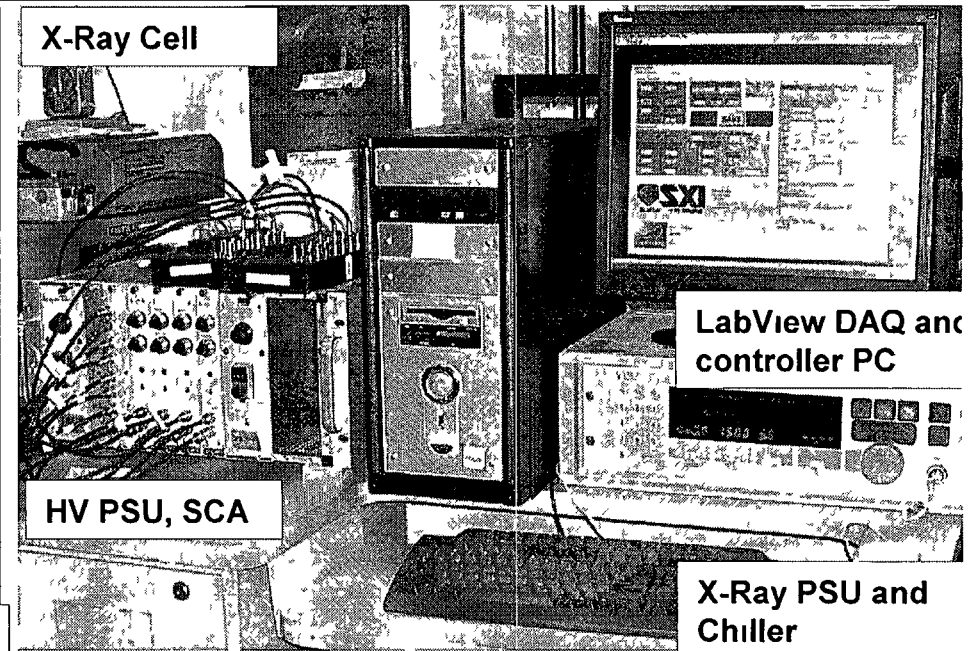
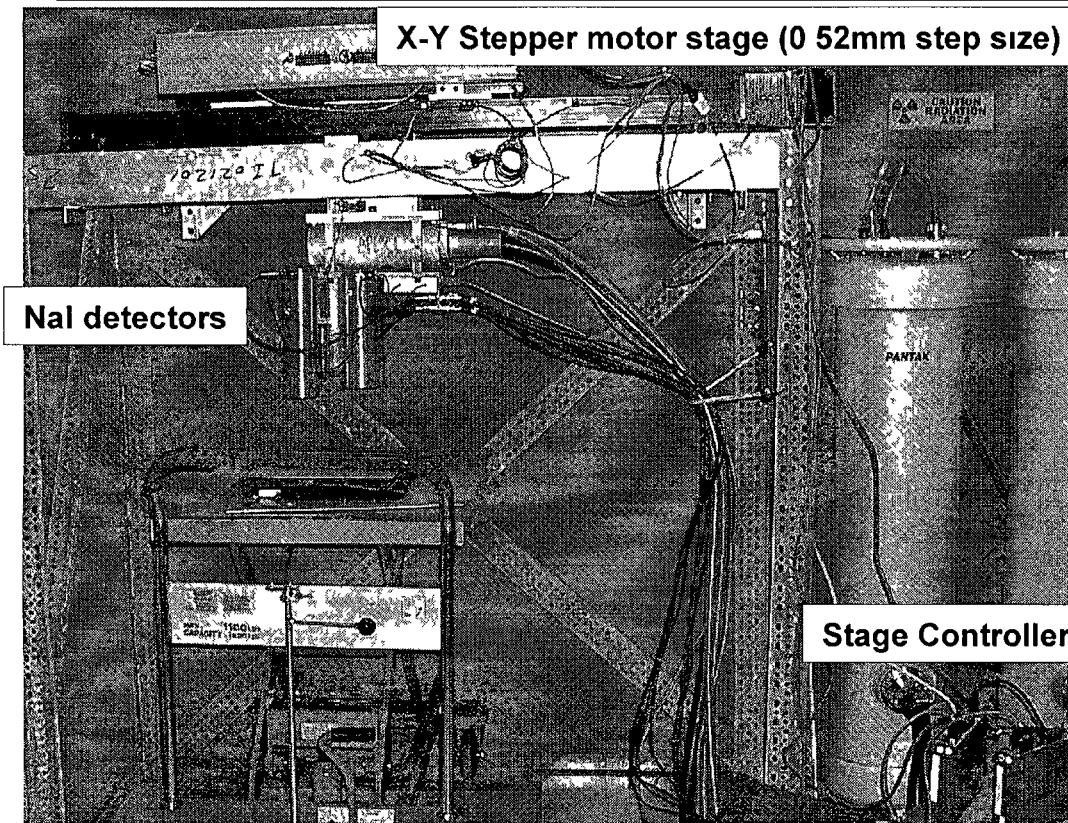
American Science and Engineering



Shuttle External Tank

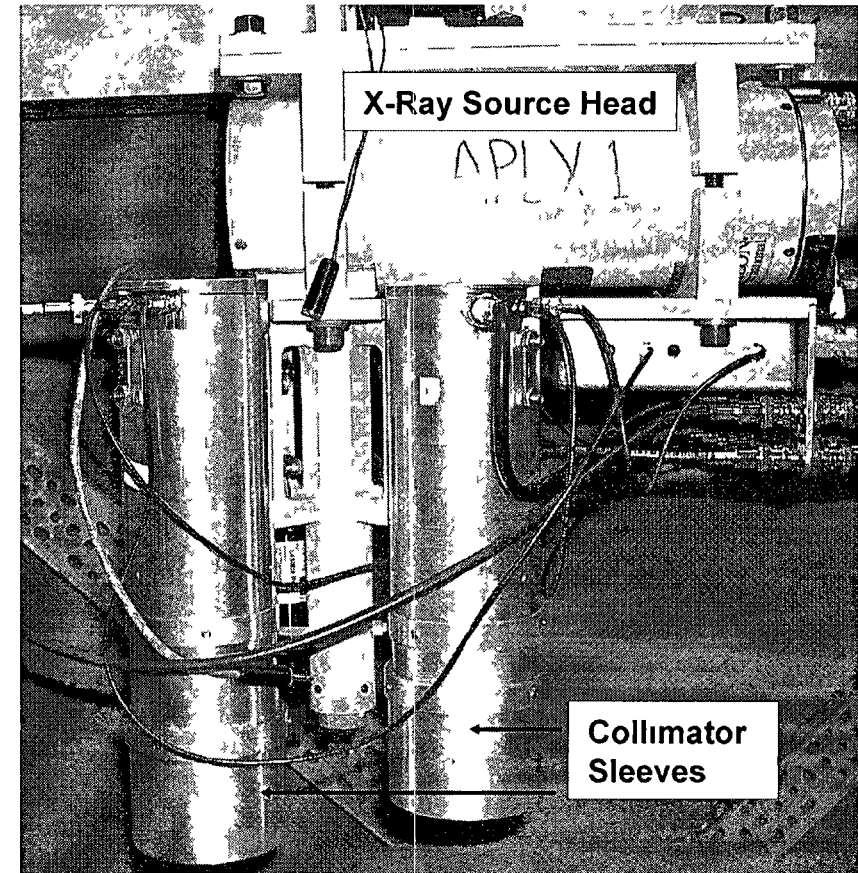
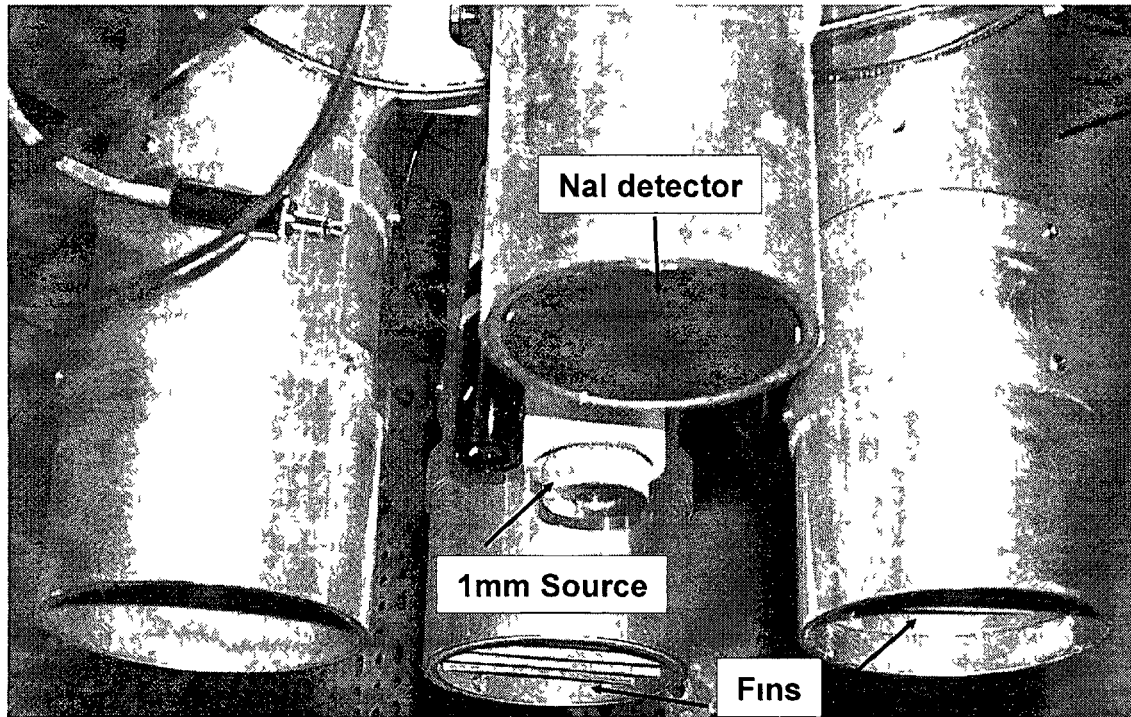


Backscatter X-Ray Experimental Setup



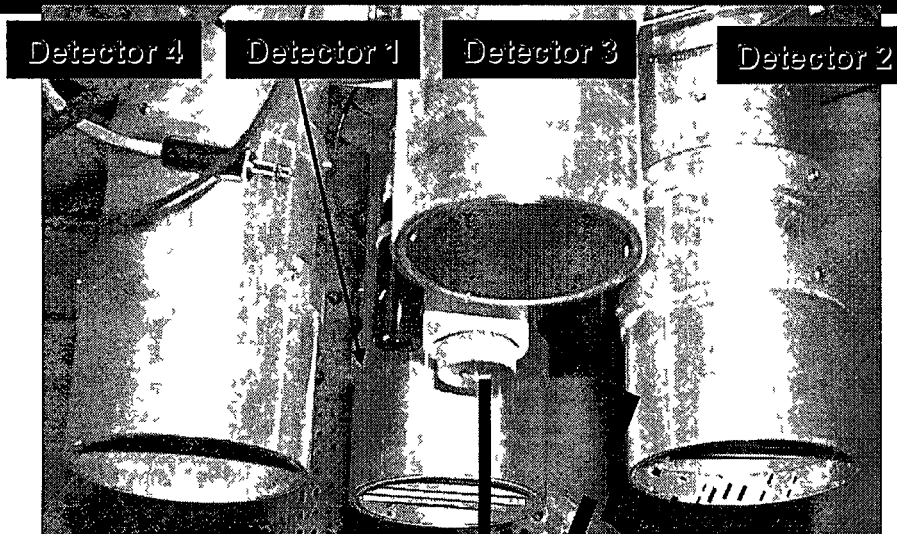
- Yxlon x-ray source
- Maximum settings 110kV 20mA
- Four NaI detectors
- 5 5mm spot size
- LabView stage control and DAQ

Backscatter X-Ray Experimental Setup

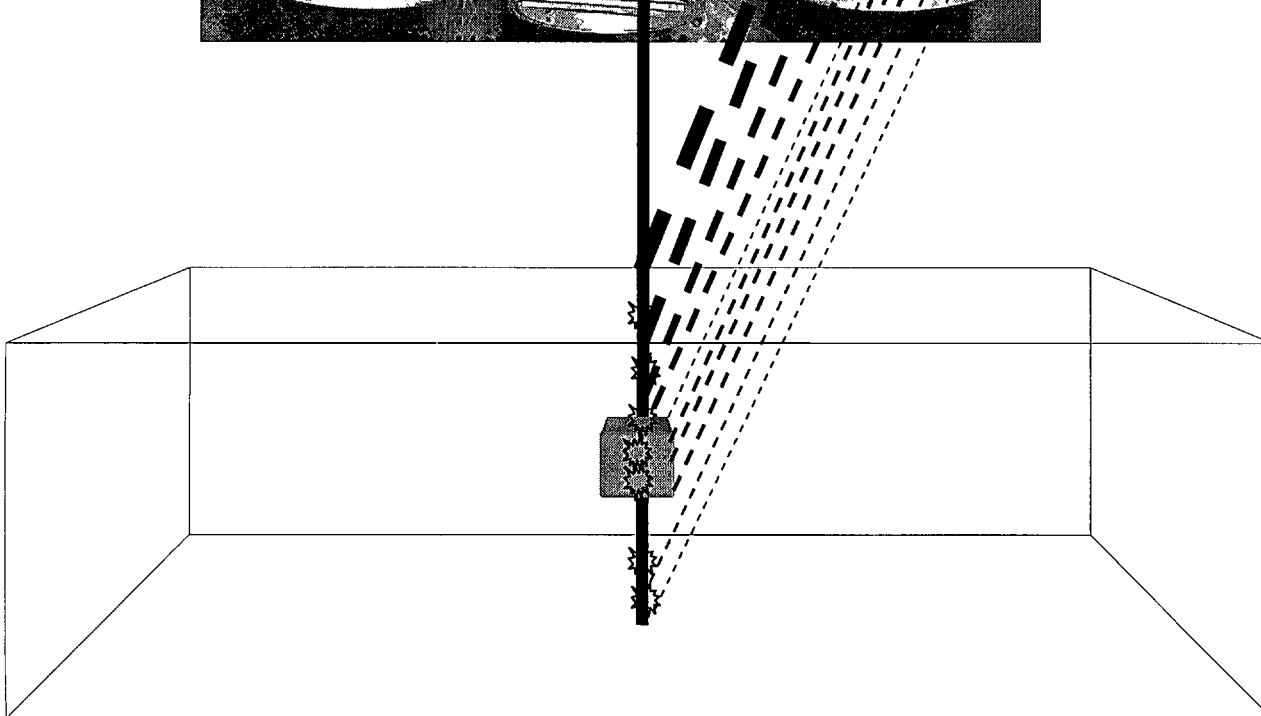


- Spot size focused to 1mm with lead apertures
- Collimator sleeves have 60mm travel length
- Lead fins are inside collimator sleeves and can be rotated to block out primary backscatter x-ray signals
- The Source and the detectors raster across the imaging area of interest

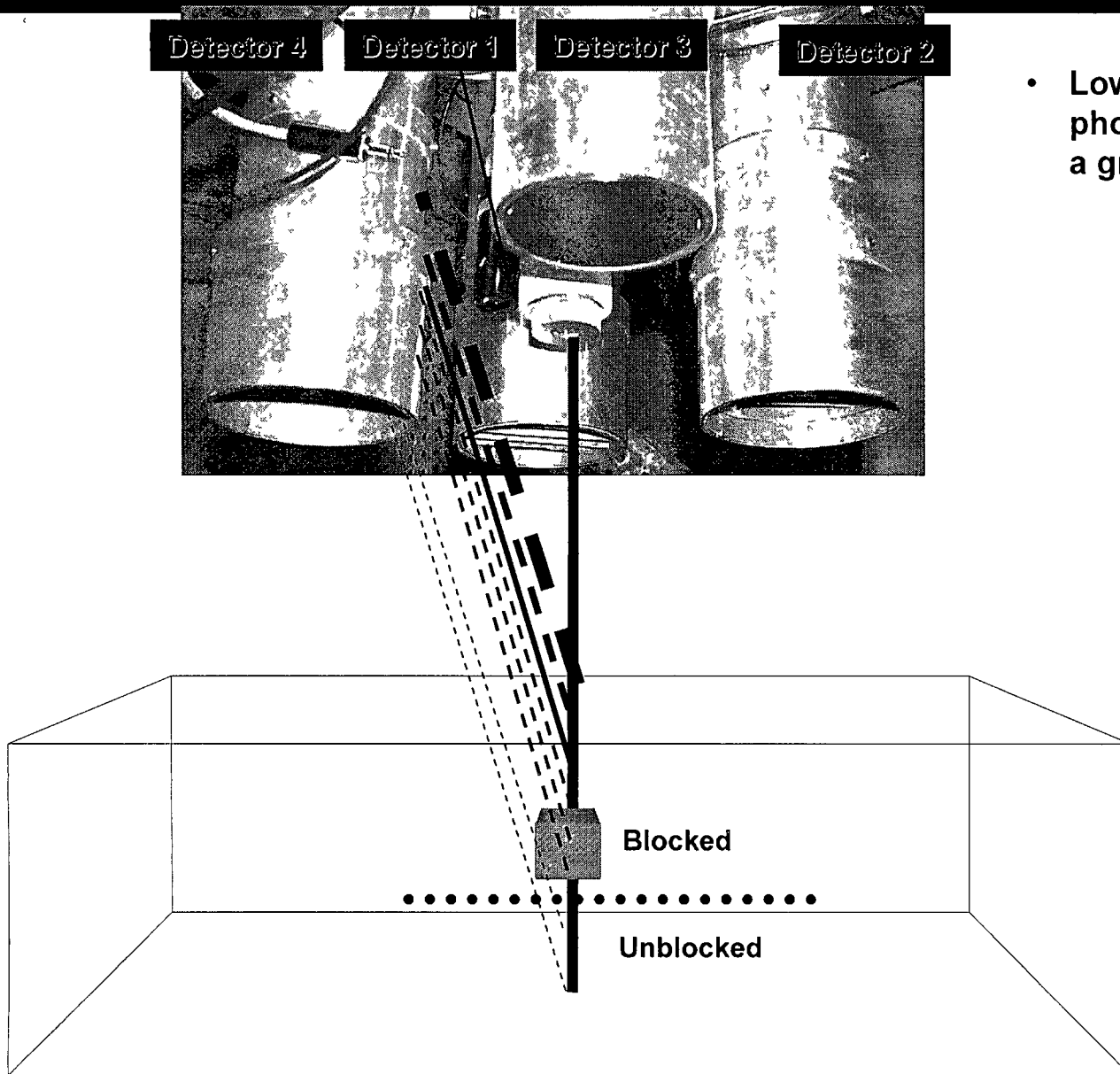
Collimator Setting BSX Imaging Basics



- High collimator settings allow photons from all depths to enter the detector

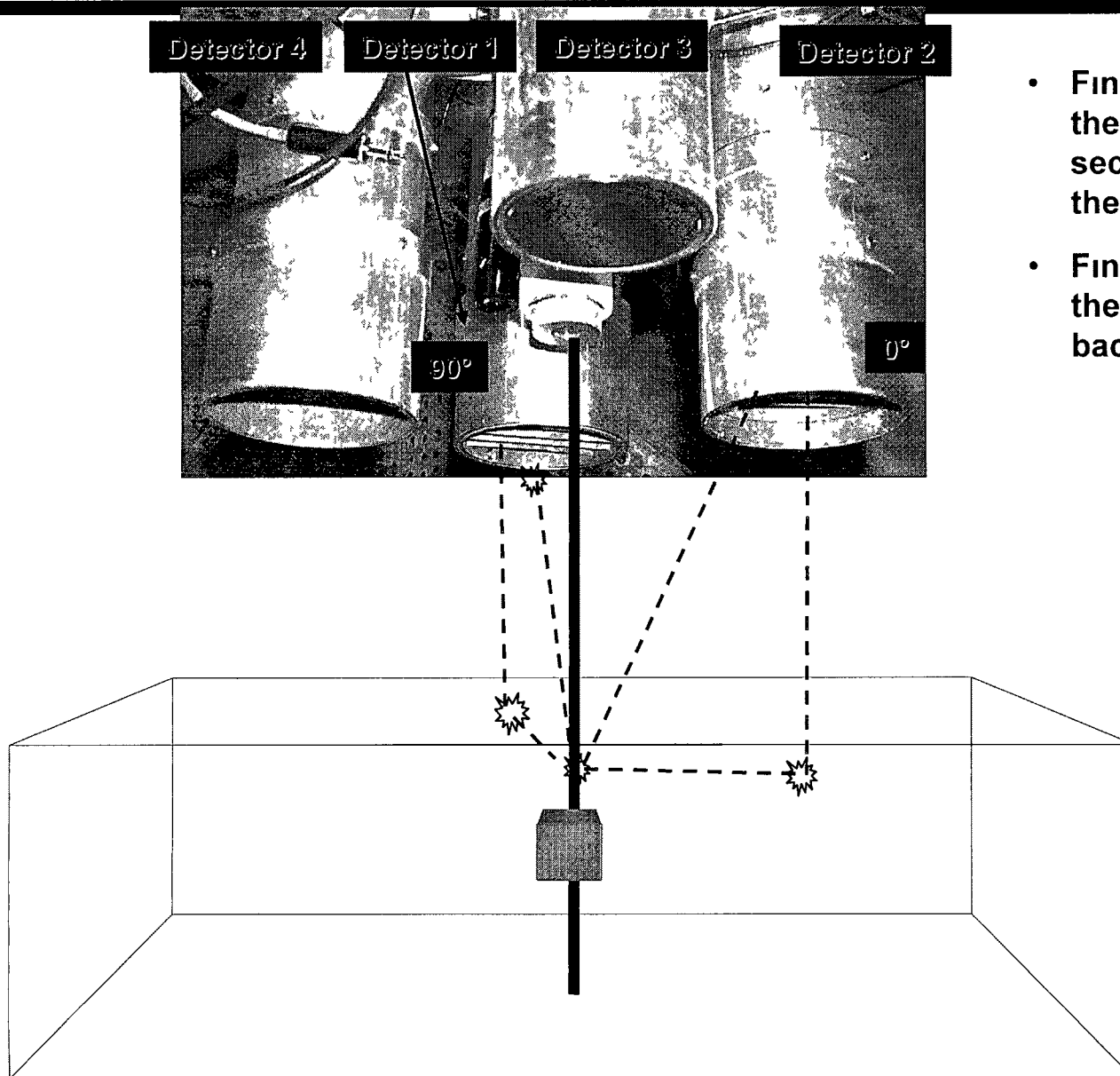


Collimator Setting BSX Imaging Basics



- Low collimator settings block out photons scattered from the surface and a given depth into the subsurface

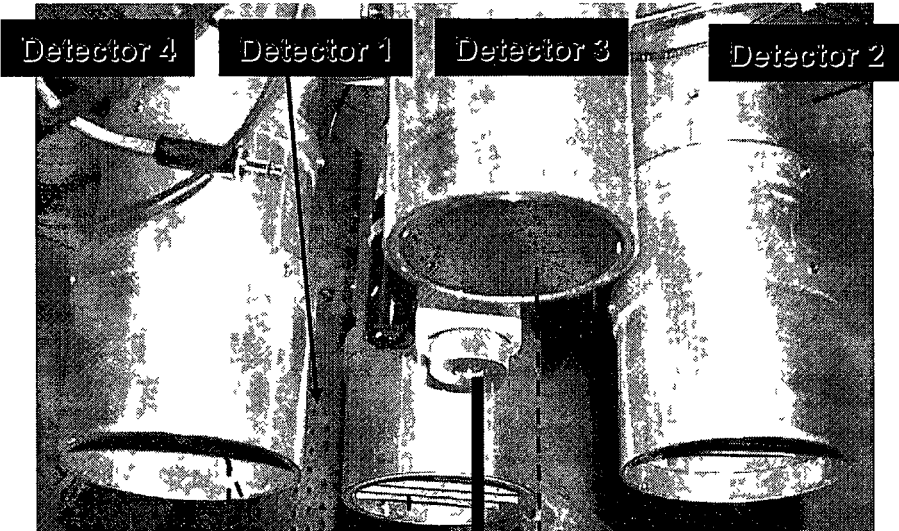
Fin Rotation BSX Imaging Basics



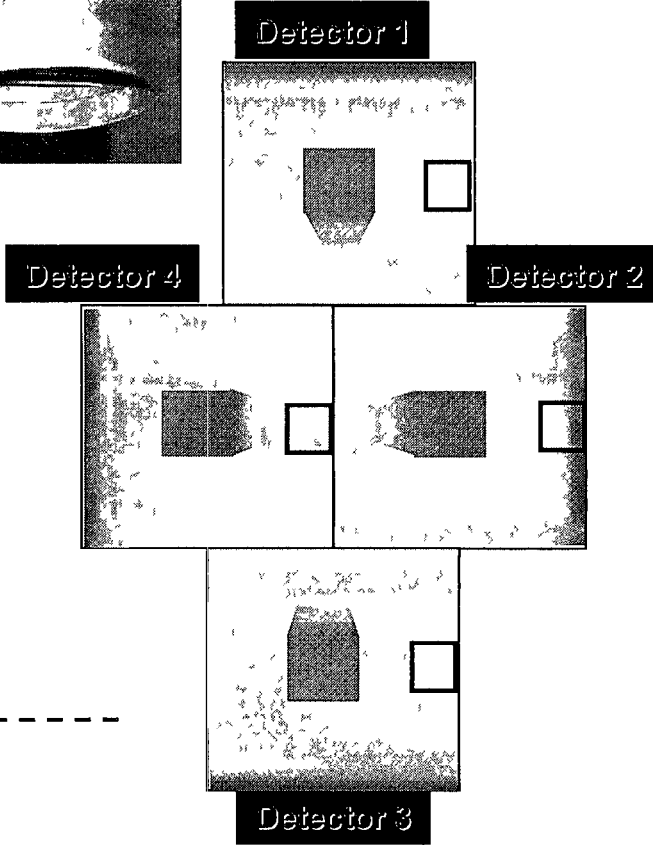
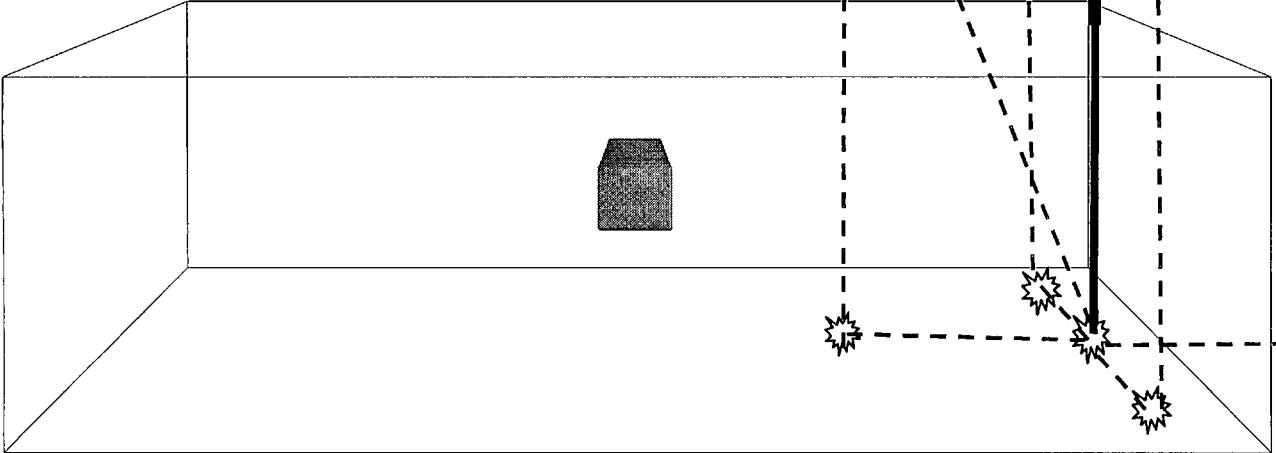
- Fin setting of 0 degrees with respect to the source allows both primary and secondary backscatter photons to enter the detector
- Fin setting of 90 degrees with respect to the source block out primary backscatter signal

Edge Effect BSX Imaging Basics

- X-ray beam
- - - Primary backscatter
- - - Secondary Backscatter

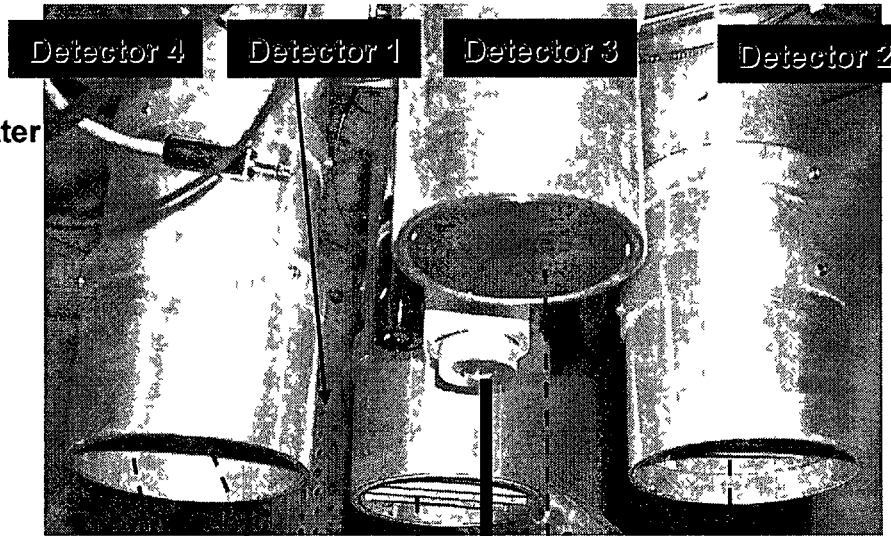


- Near specimen edges a lower signal is collected due to the inability of the photons to backscatter to the detector

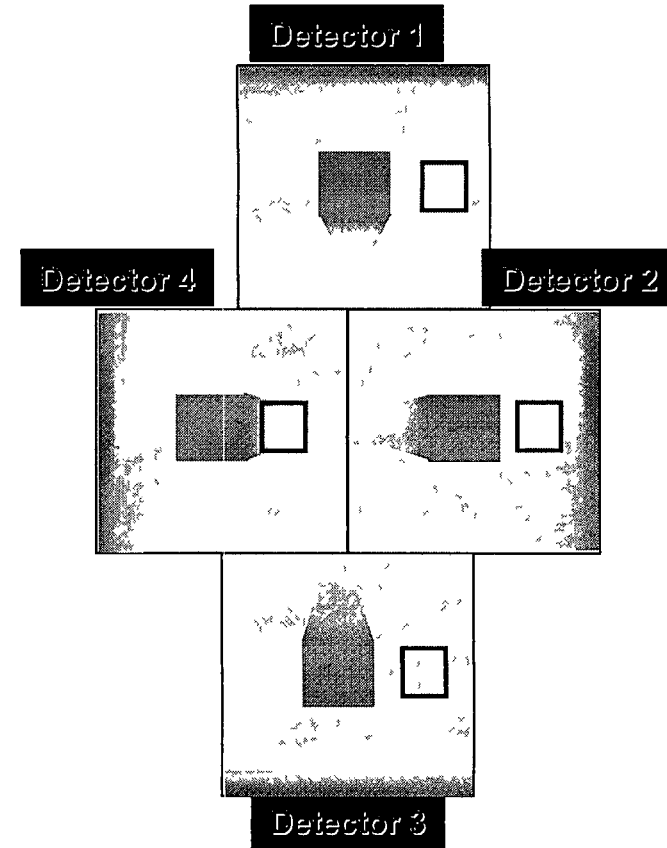
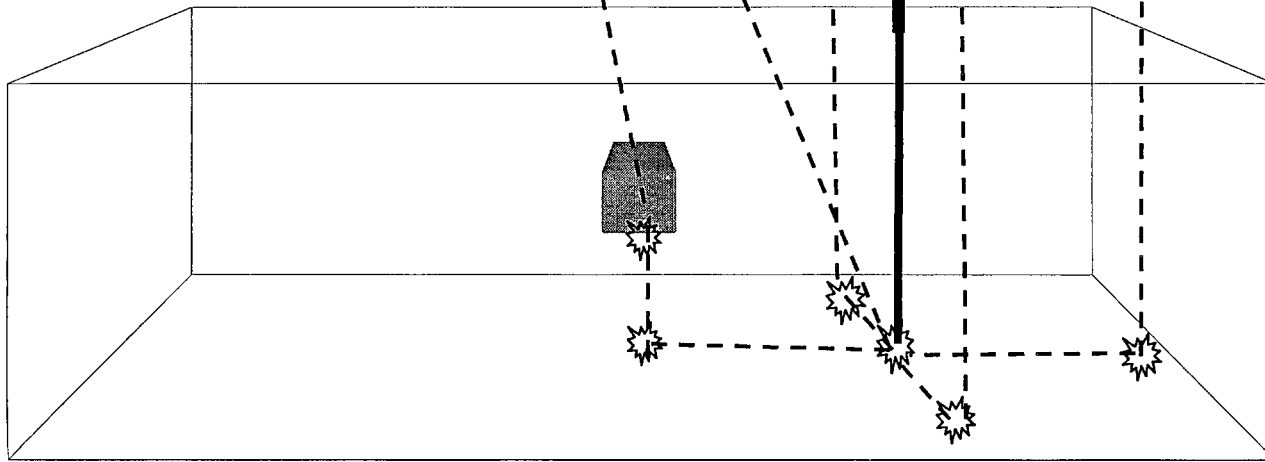


Shadowing Effect BSX Imaging Basics

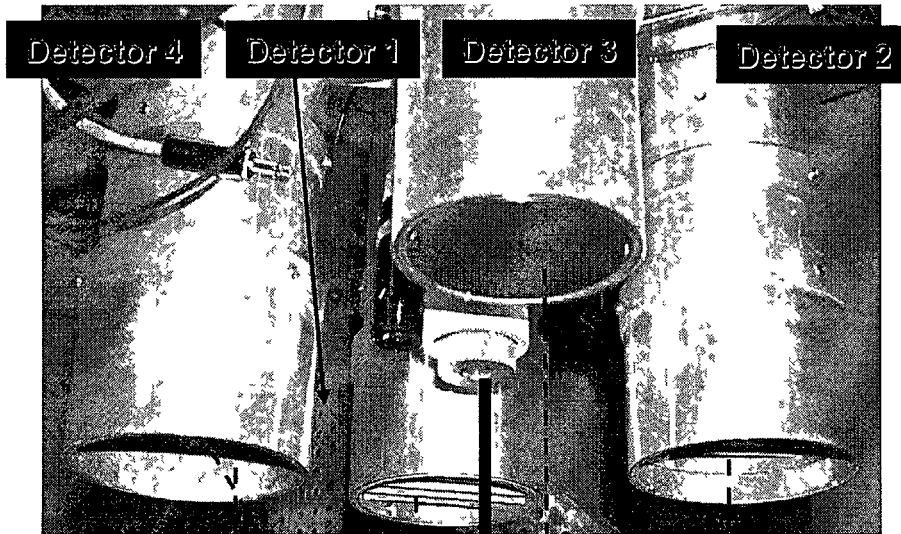
- X-ray beam
- - - Primary backscatter
- = = = Secondary Backscatter



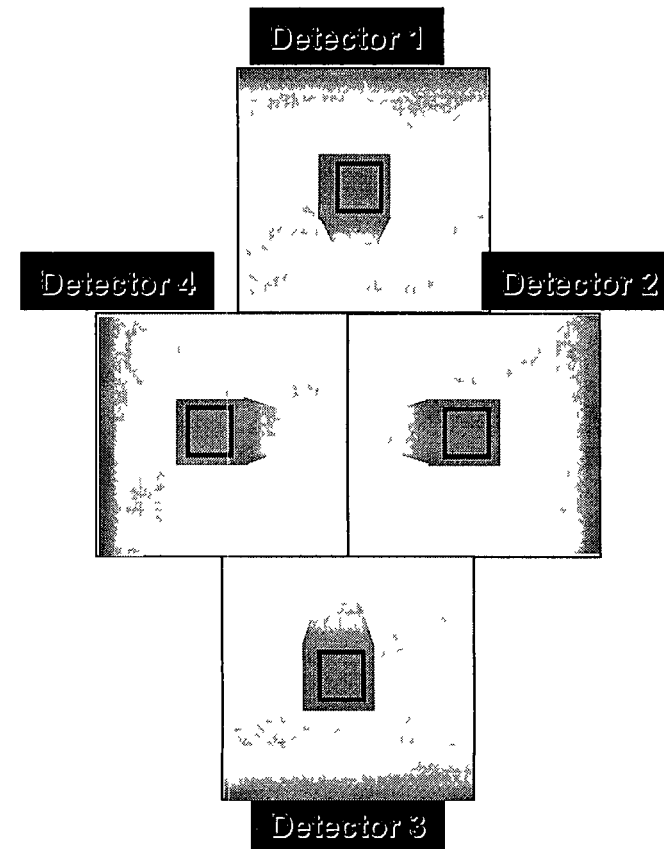
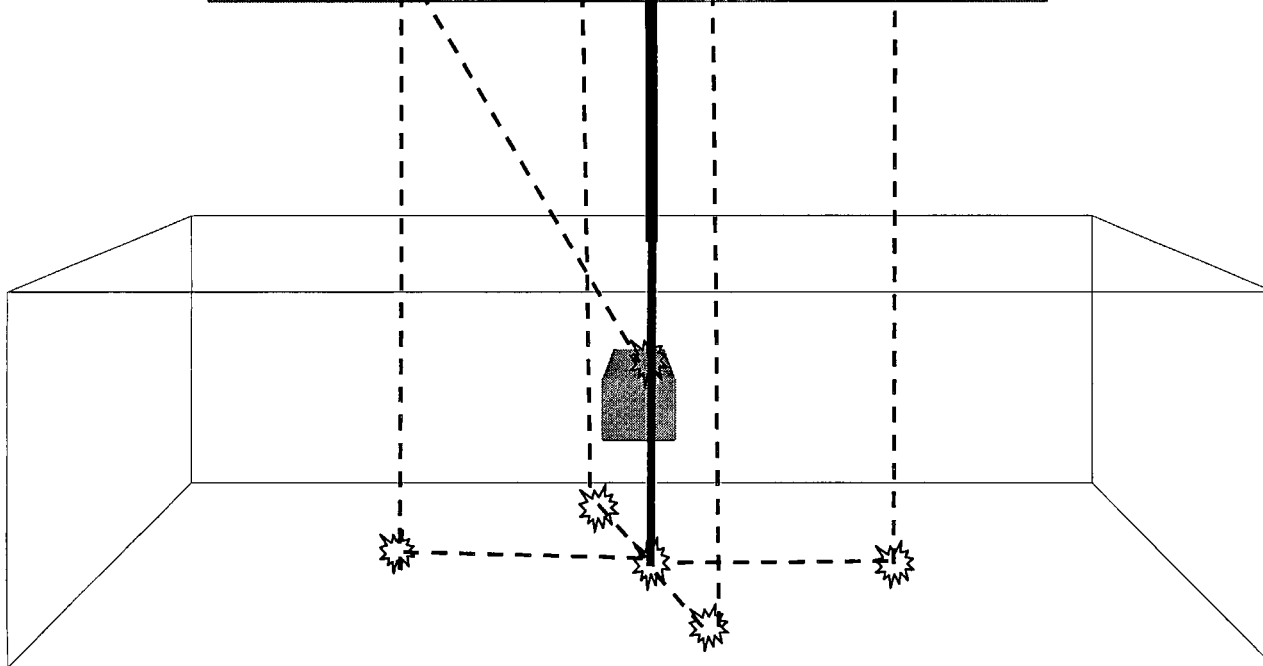
- A shadowing effect near objects is produced due to tertiary backscatter
- Edge effects disappear near the center of the sample
- There would be no shadowing effect if the detector is exactly at the location of the source



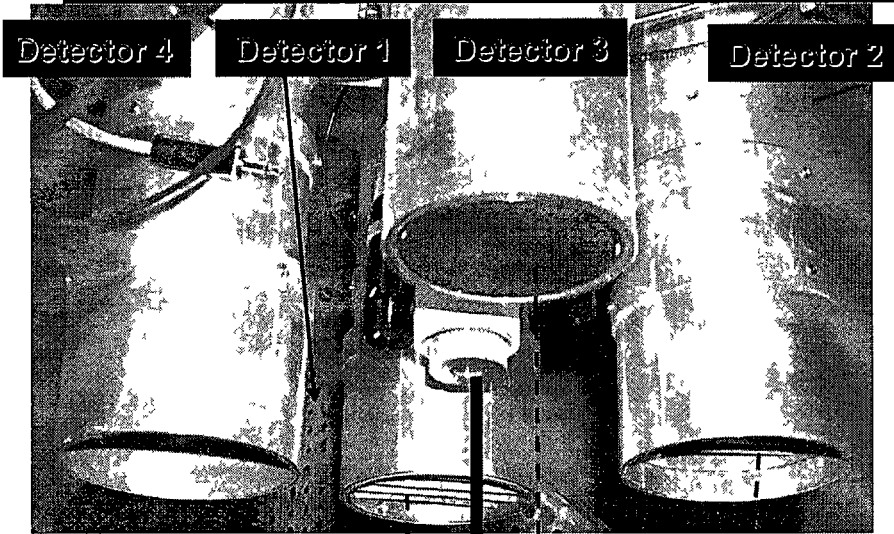
BSX Imaging Basics



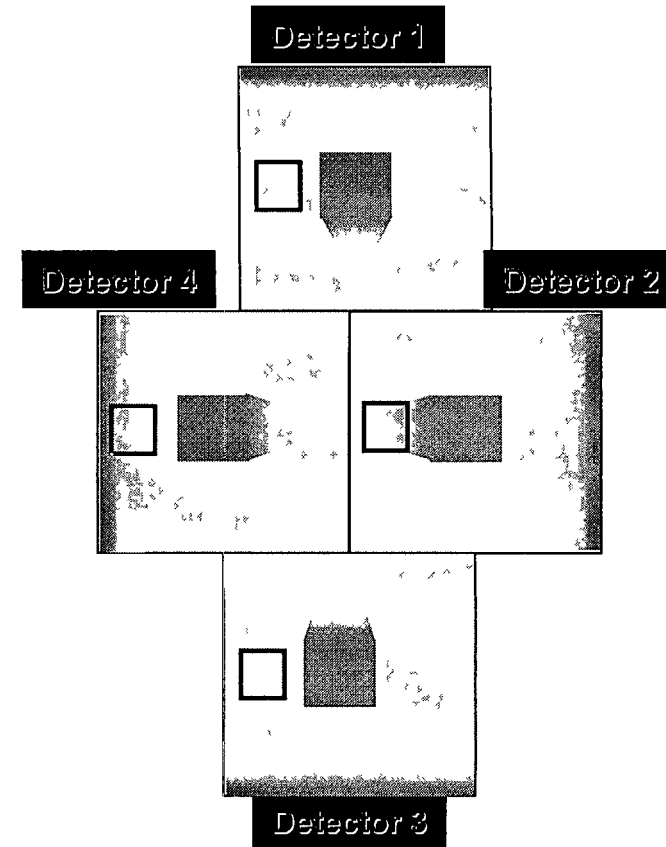
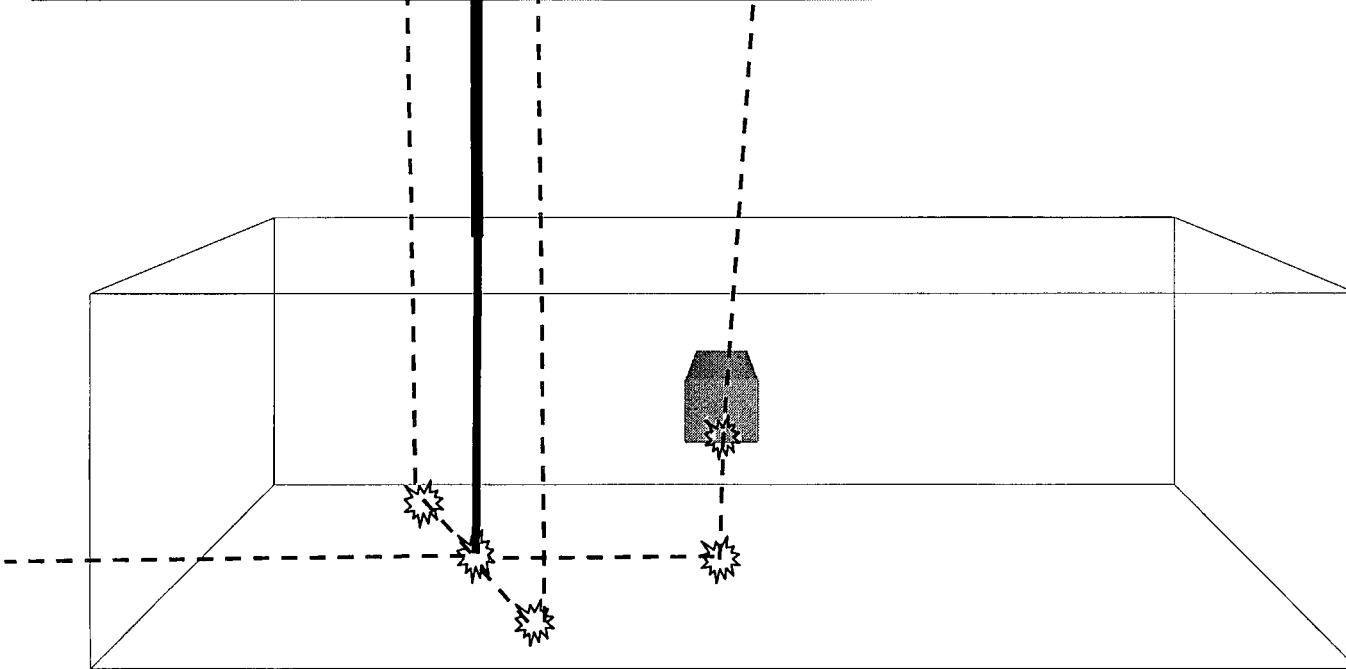
- The best signal is produced when the source is over the object



Edge and Shadowing Effect BSX Imaging Basics

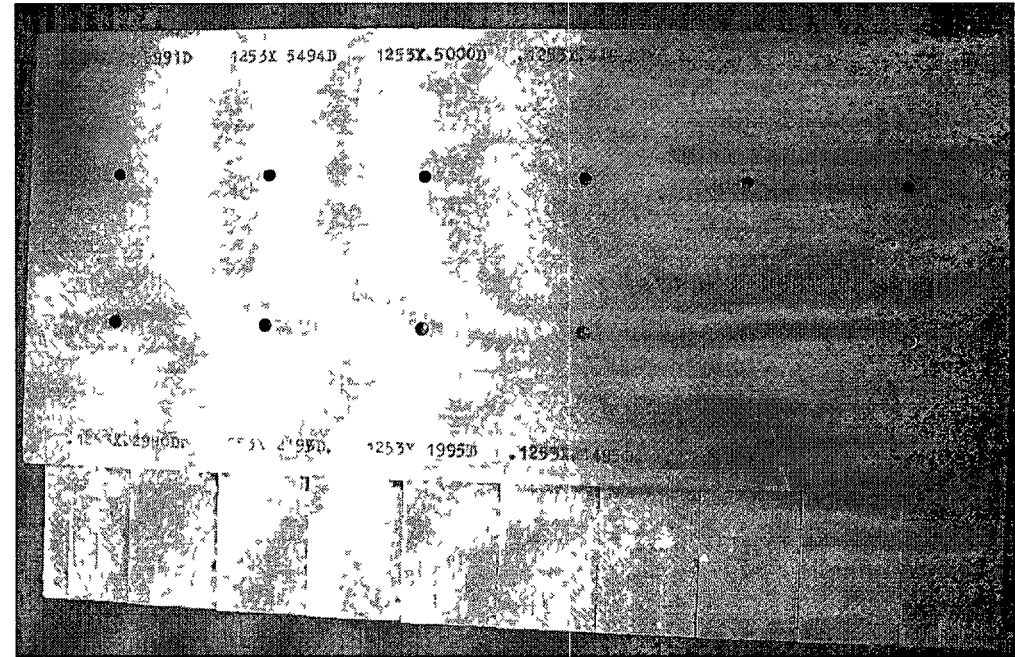


- Shadowing effect is produced again in the detector directly above the object
- Edge effect is produced in the detector off of the edge of the object



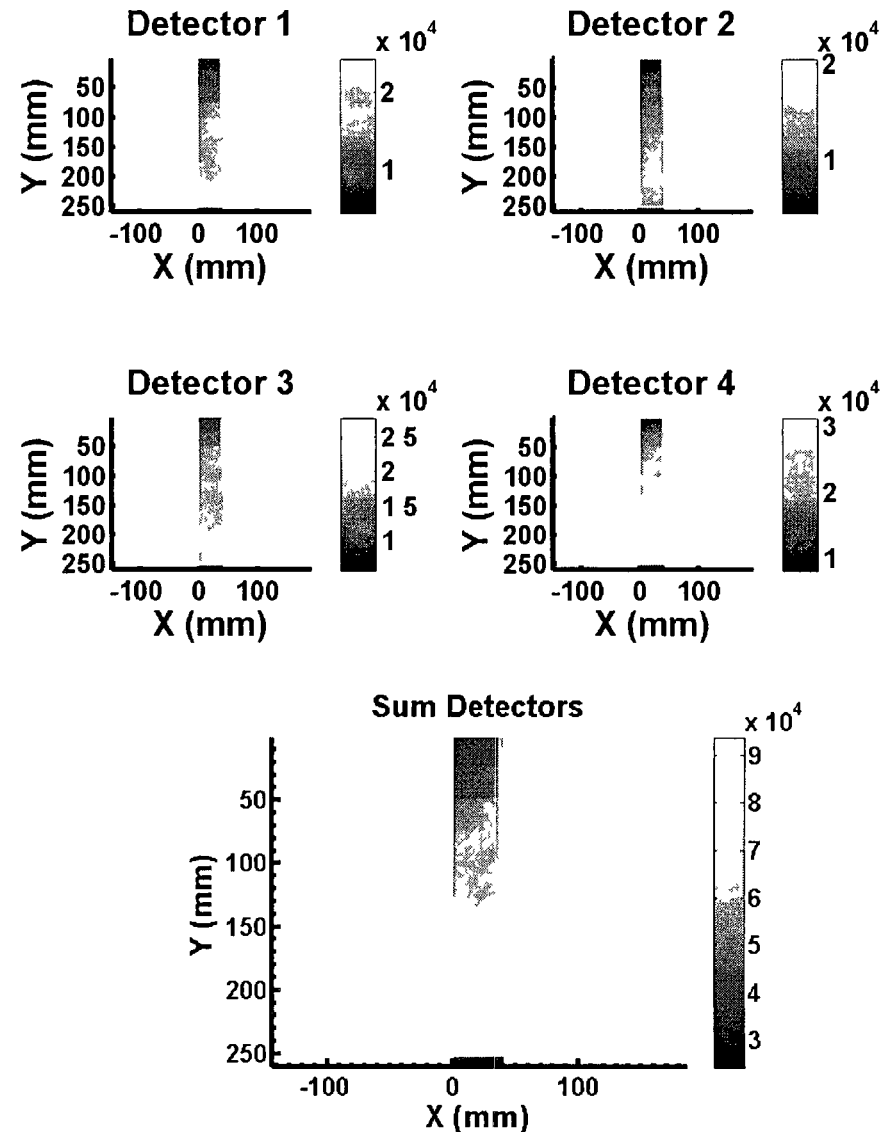
Aluminum Wedge Block Setup

- Aluminum standard wedge block with thickness from 1.59mm (1/16in) to 15.9mm (5/8in) thickness in 1.59mm (1/16in) increments
- Flat bottom holes (FBH) of 3.18mm (1/8in) diameter with depths from 1.27mm (0.050in) to 15.24mm (0.60in)
- Each area was imaged using the BSX detector with 100kV, 20 mA, 5mm/s scan speed 1mm pixel size, 0 degree fins, and a source to object distance of 127mm (5in)



Wedge Thickness Results

- Detectors showed significant variations in photon counts for the for thinner wedges
- As expected it was difficult to resolve the thickness differences for the thicker wedges
- The results from the four detectors were summed up to attempt to enhance the contrast between the different thickness wedges in one image



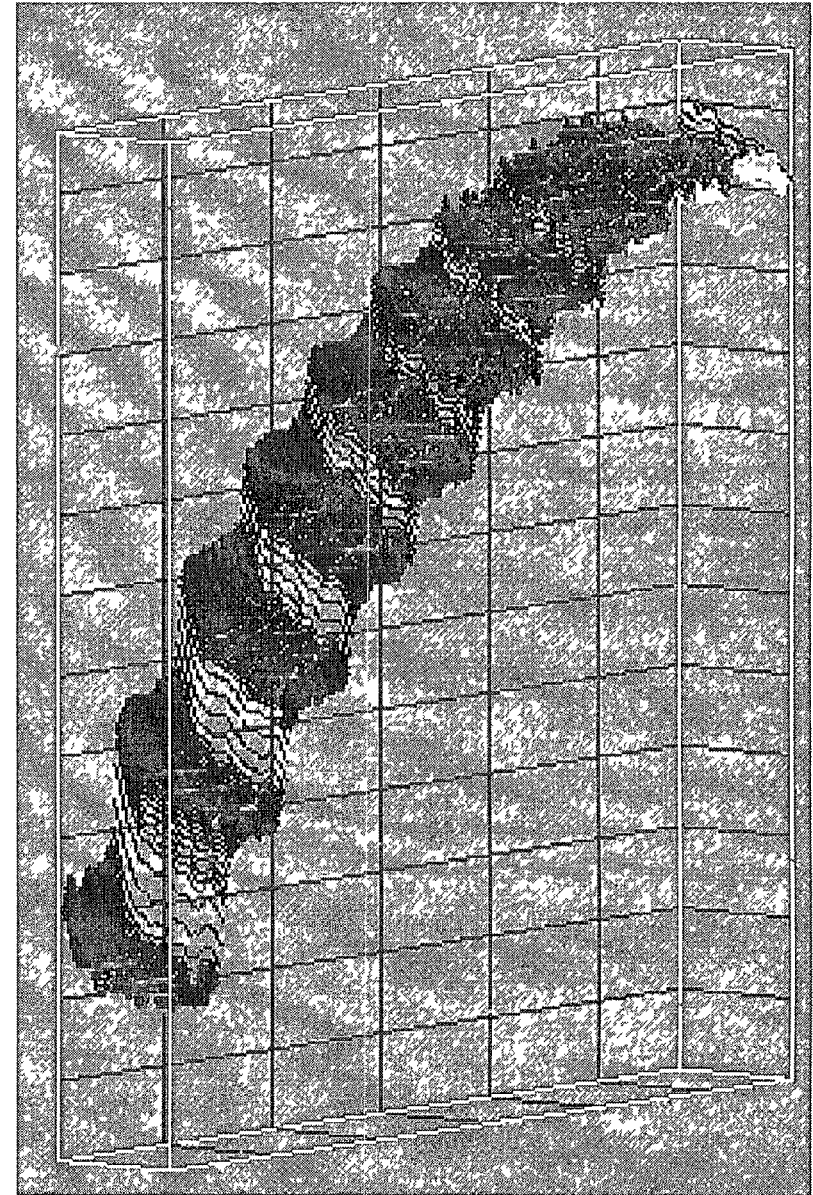
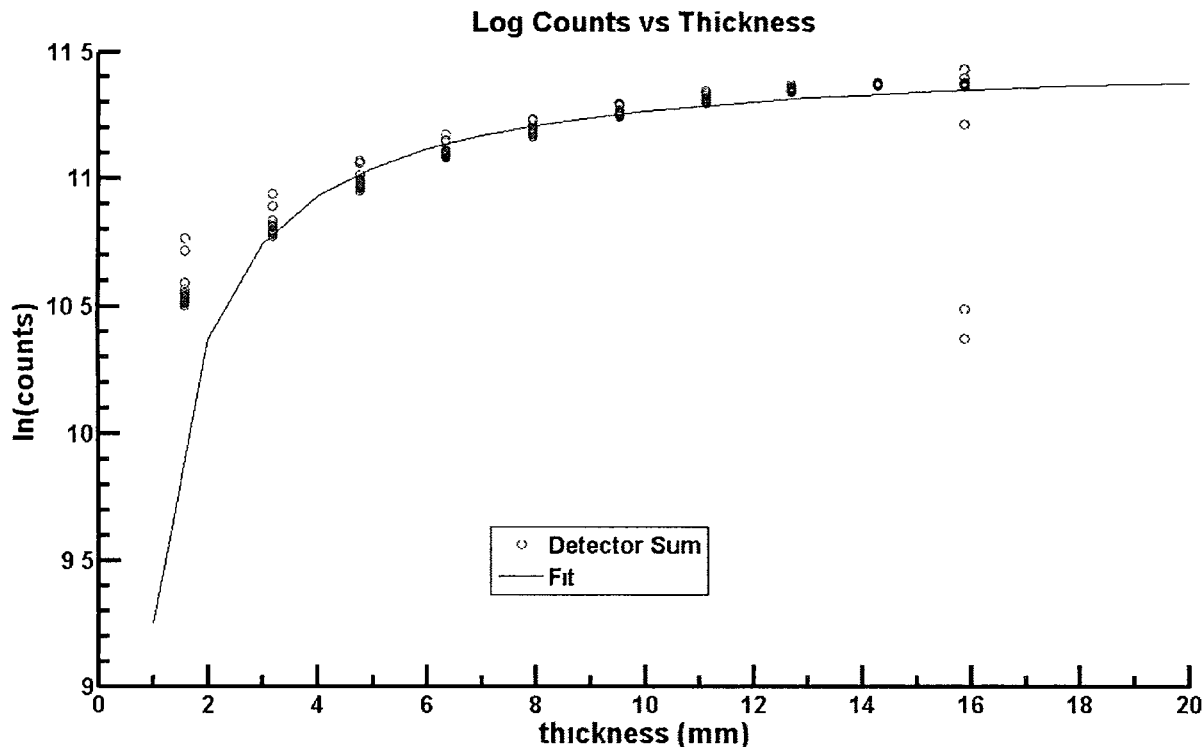
Wedge Thickness vs Photon Counts

The data was fit assuming that the photon counts decay exponentially to 0 with decreasing thickness

$\text{counts} = \exp(-A/\text{Thickness})$ where (A is a constant)

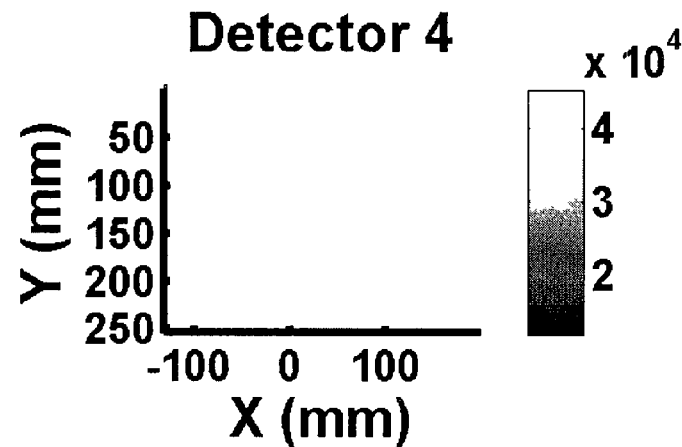
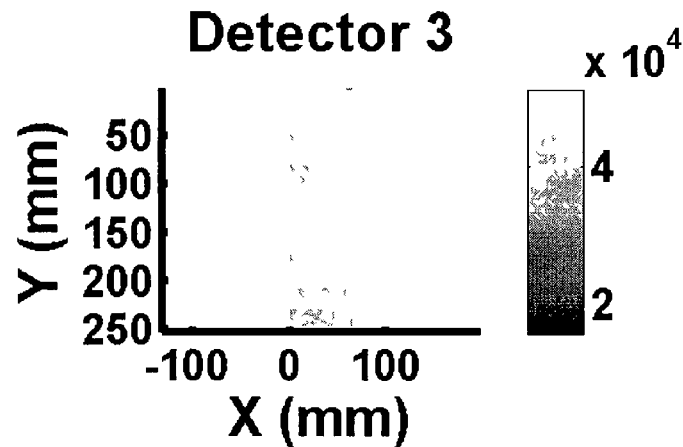
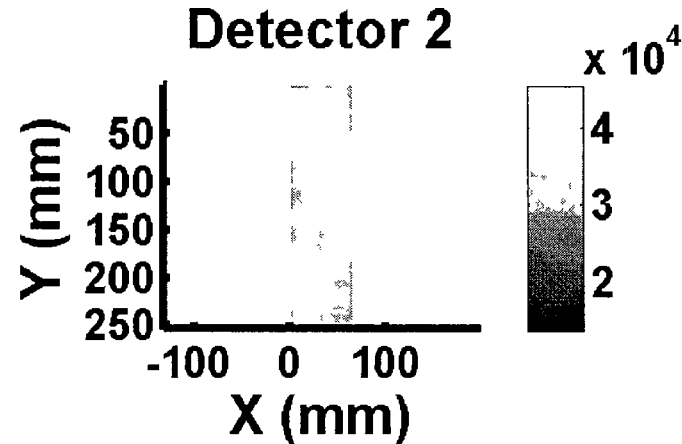
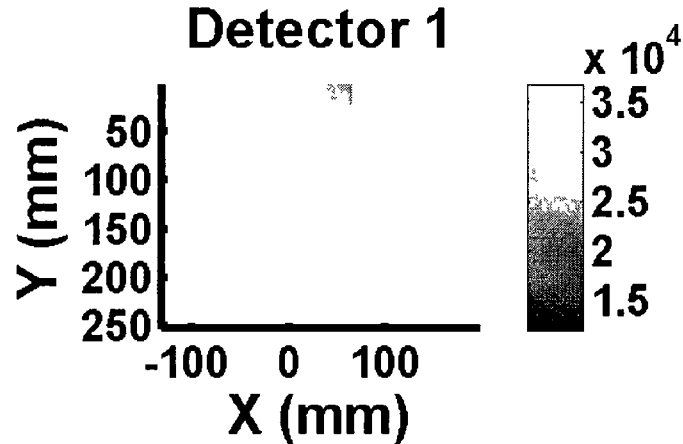
The change in each wedge thickness was detectable up to 15.9mm aluminum thickness

It is difficult to use the entire data set for the fit since the photon counts change near all the edges of the wedges



Flat Bottom hole Results

The FBH results for each detector shows that tit is difficult to detect each FBH without significant image processing due to the 1mm spot size of the source being close to the diameter of the flat bottom holes



FBH Image Enhancement

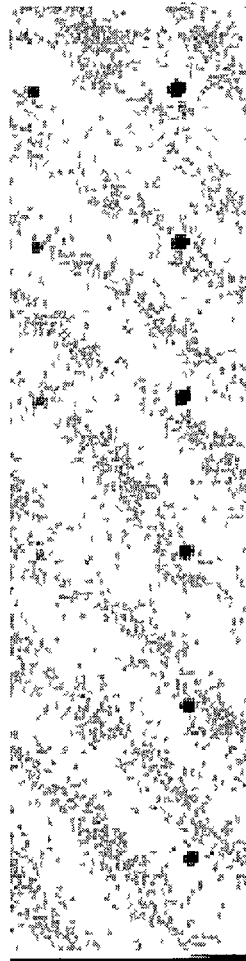
The background value was first subtracted from each image and the contrast was stretched to bring out each FBH in more detail

The 1 27mm and the 2 54mm deep FBH were the most difficult to detect, and can only be slightly seen with detector 1

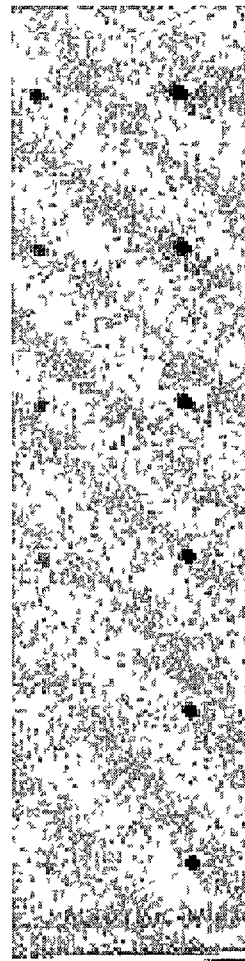
Various filters were used to enhance the images to detect all of the flat bottom holes

A Kalman filter was used on the stack of images obtained from the four detectors which brought out the the 1 27mm deep FBH

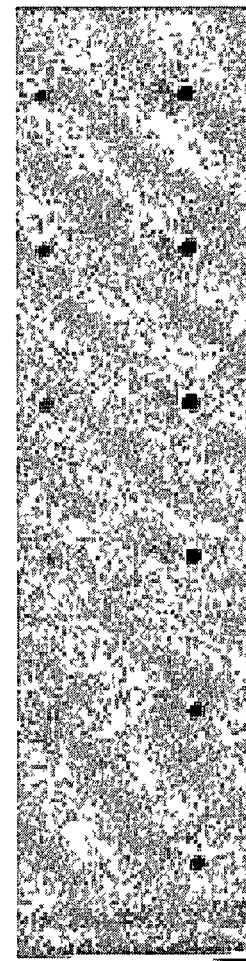
Multiple scans, smaller than 1mm apertures and a finer than 1mm scanning resolution are options to enhance the capability of the BSX system to detect smaller flaws



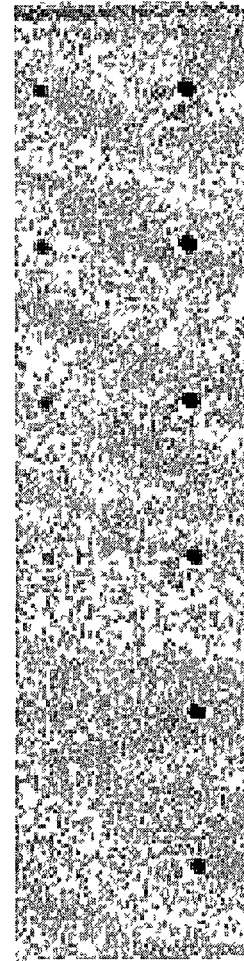
Detector 1



Detector 2



Detector 3



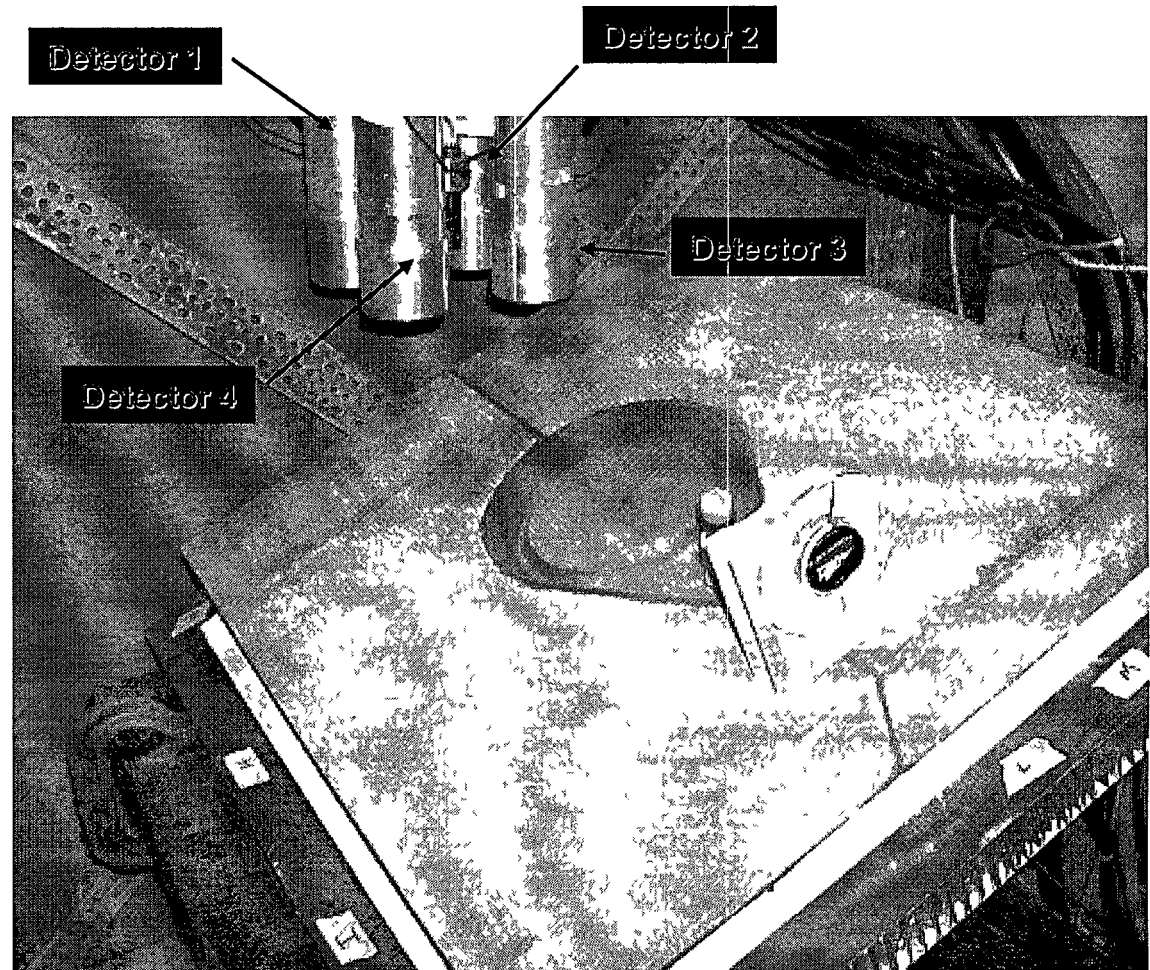
Detector 4



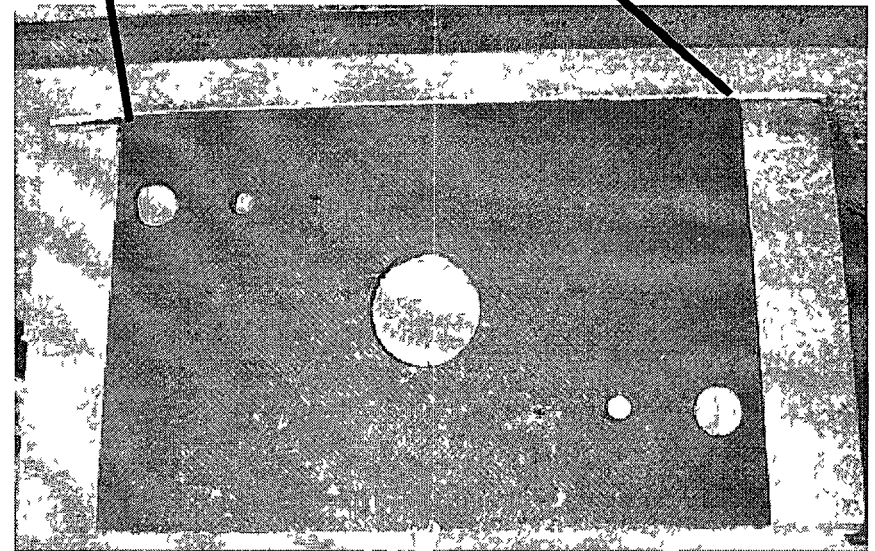
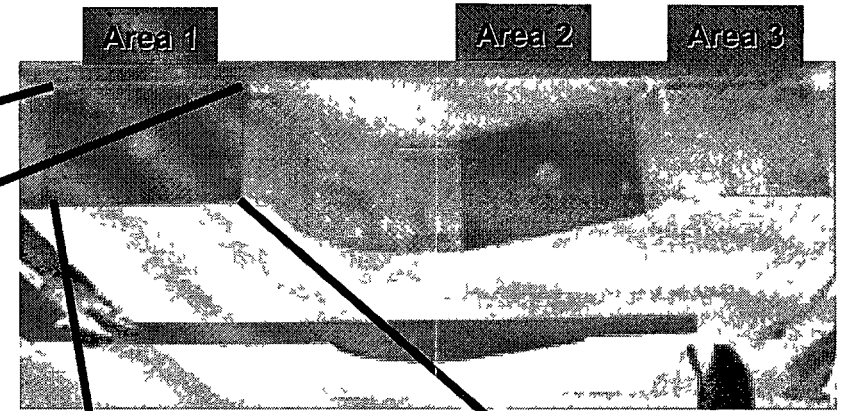
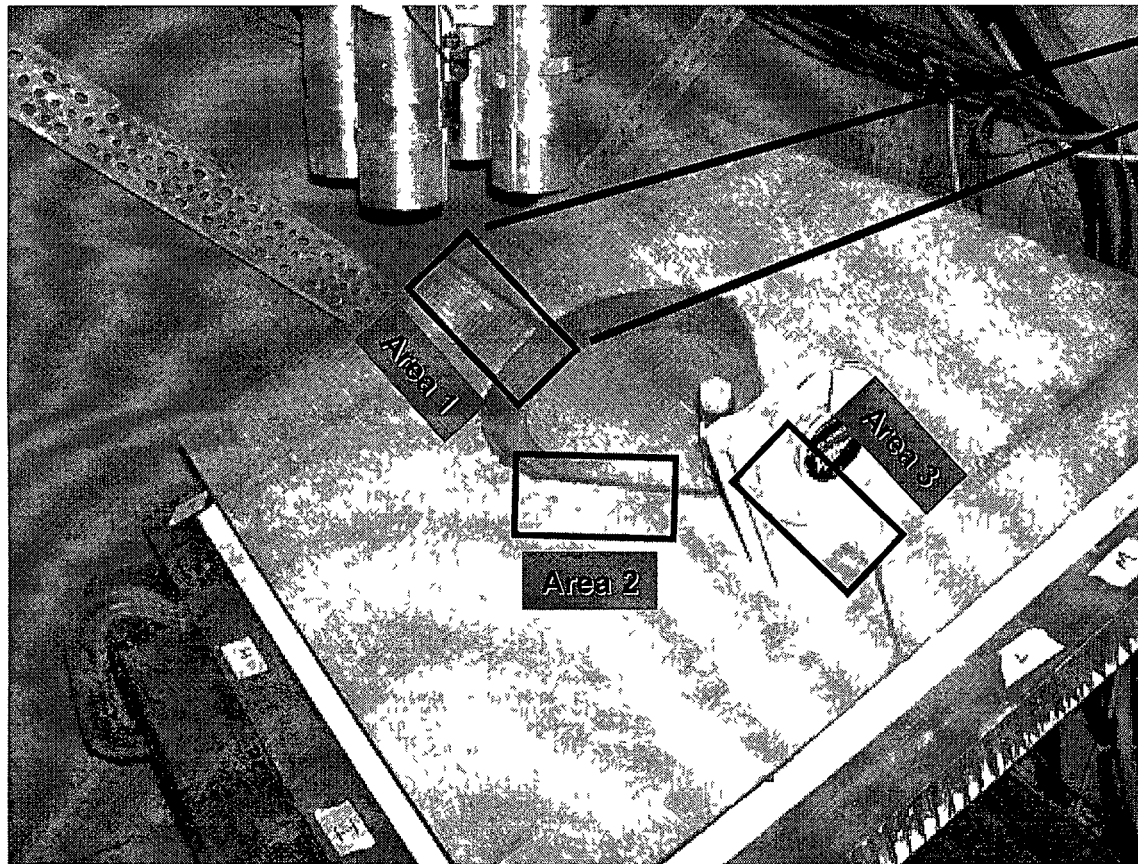
Kalman Filter

LDDU Experimental Setup

- LDDU scans were conducted with a step size of 0.52mm, scan speed of 2.6mm/s, 90degree fin rotation, 112mm source to object distance and LDDU tilt angles of 0, 11, and 23 degrees
- Three areas of interest were investigated in the RTV seams that joined the PICA pieces together

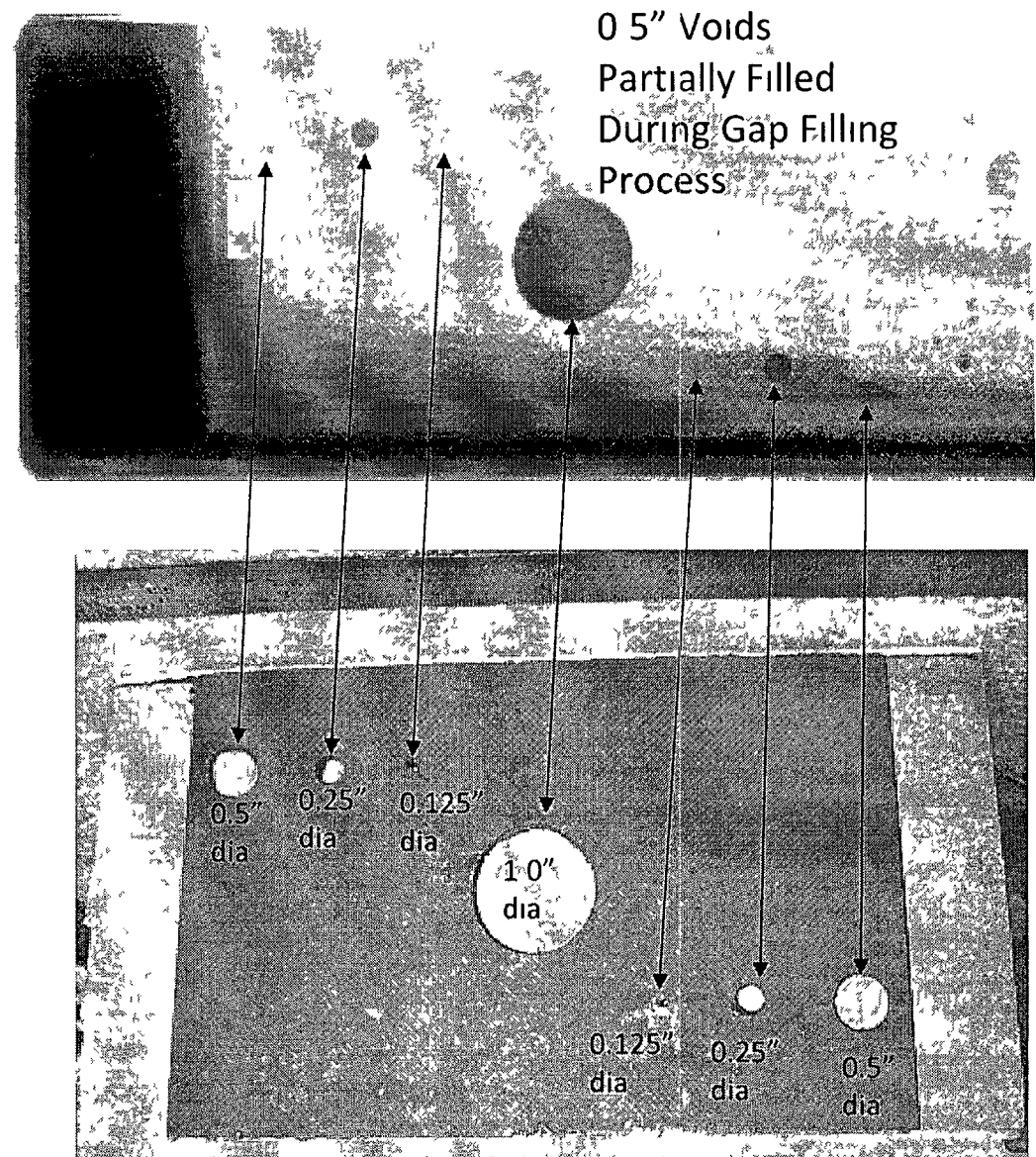


LDDU Regions of Interest

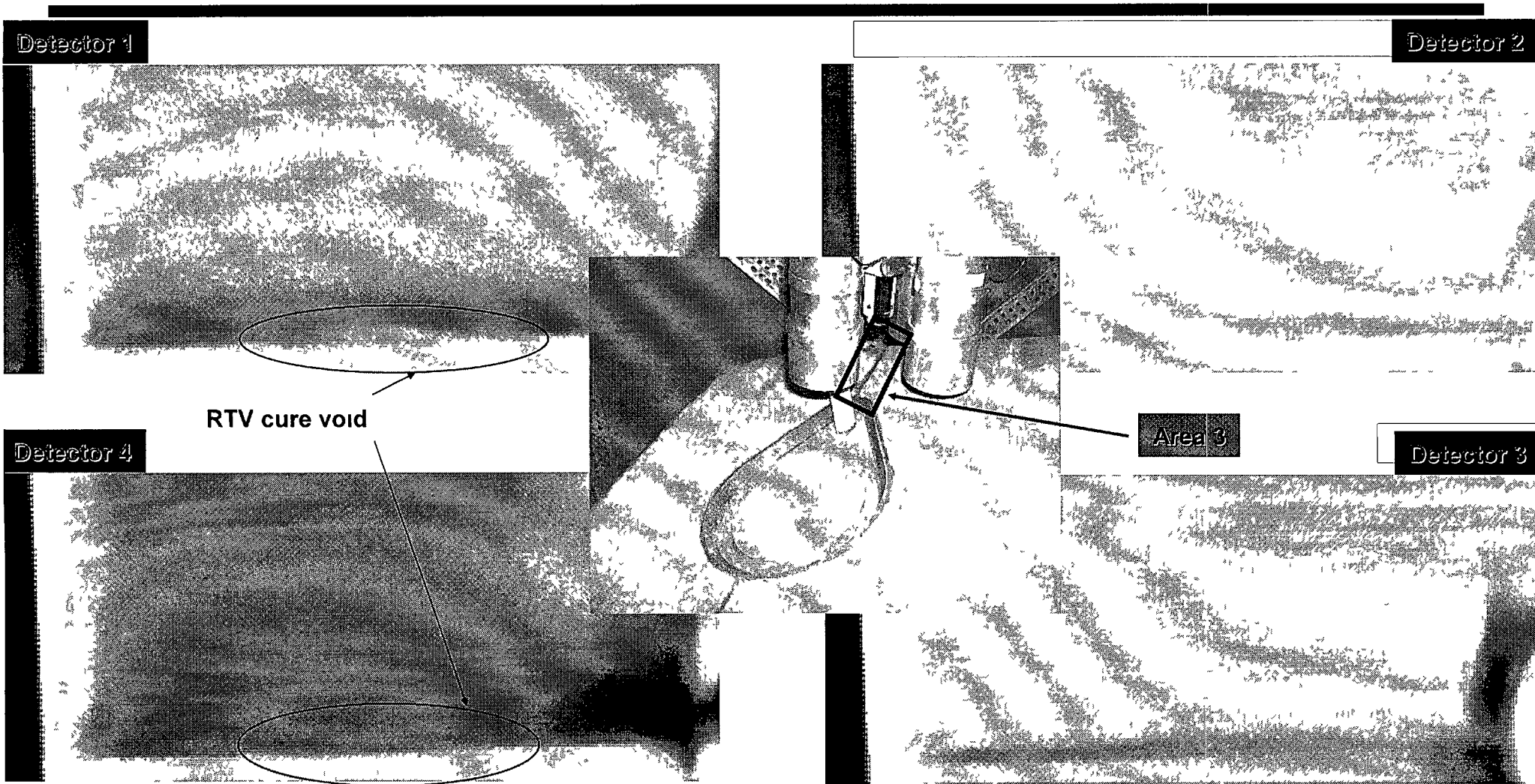


RTV hole position and orientation

- RTV voids exist outside of the pre-cured RTV region
- The 0.5in holes are shown to be partially filled
- It must be noted that the voids labeled 0.125in are realistically at the most 0.0625in which is near the limit of the current system configuration of 0.039in source beam diameter (1mm)



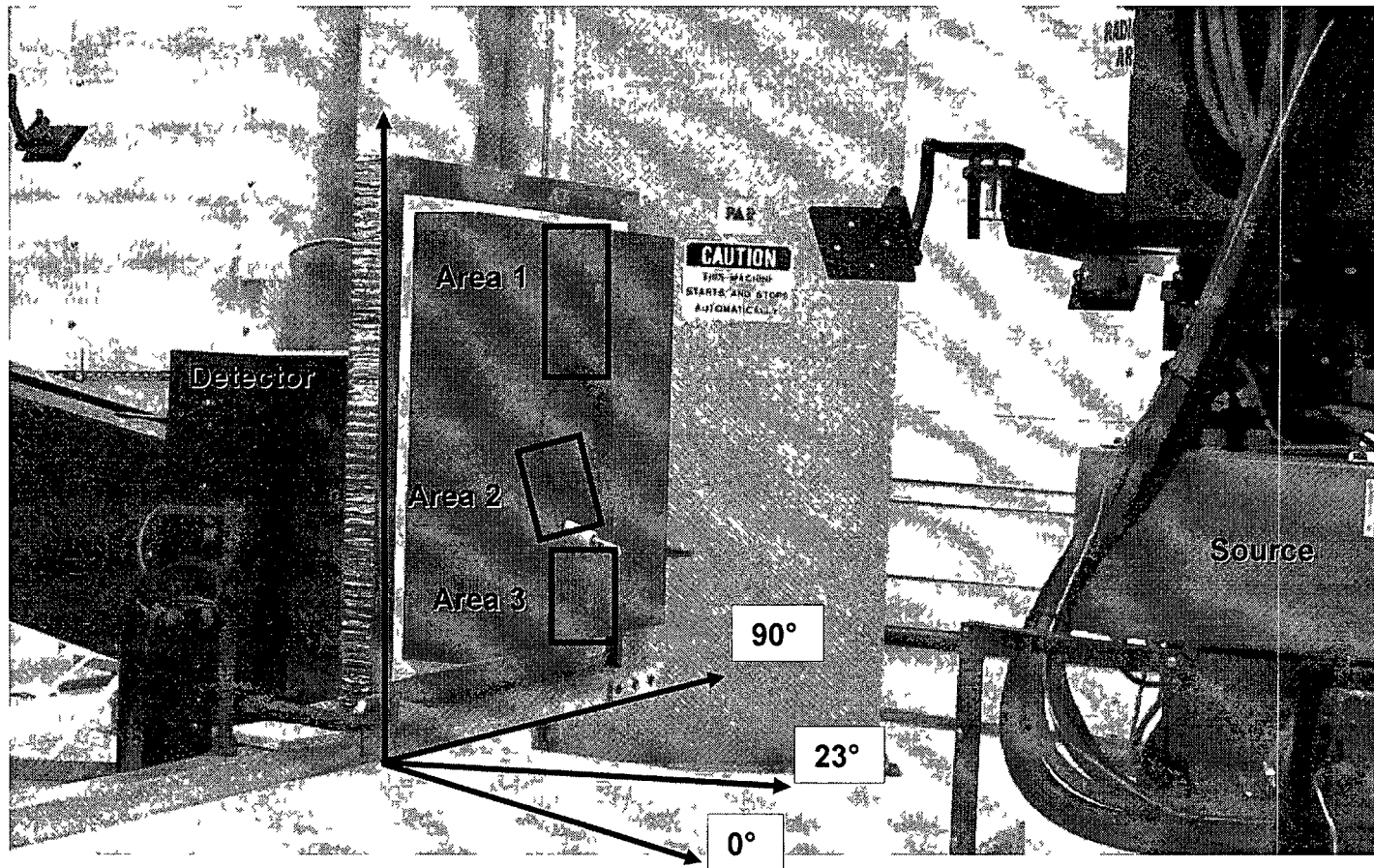
LDDU BSX 23° Tilt Scan Area 3



- Void detected near subsurface of non pre-cured RTV section of the LDDU

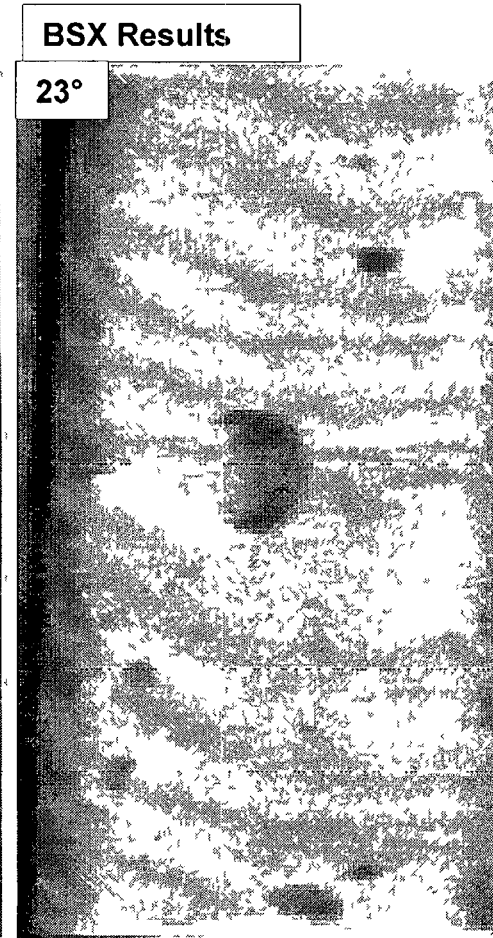
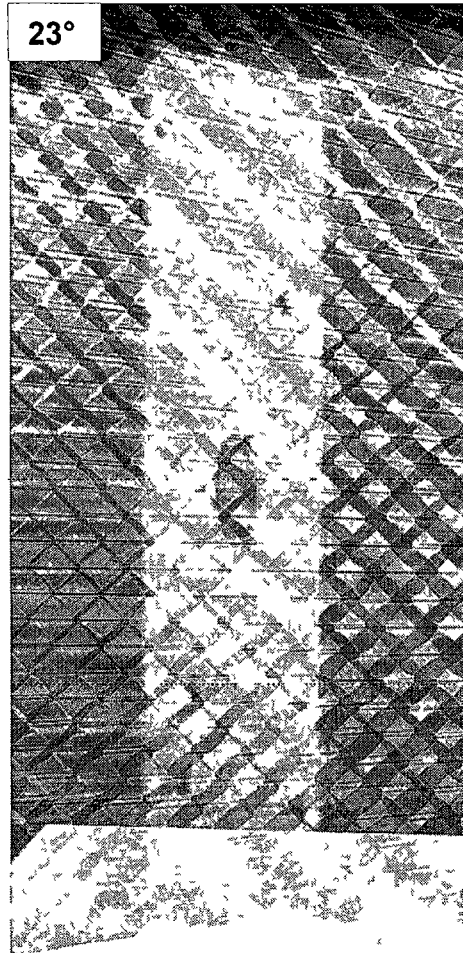
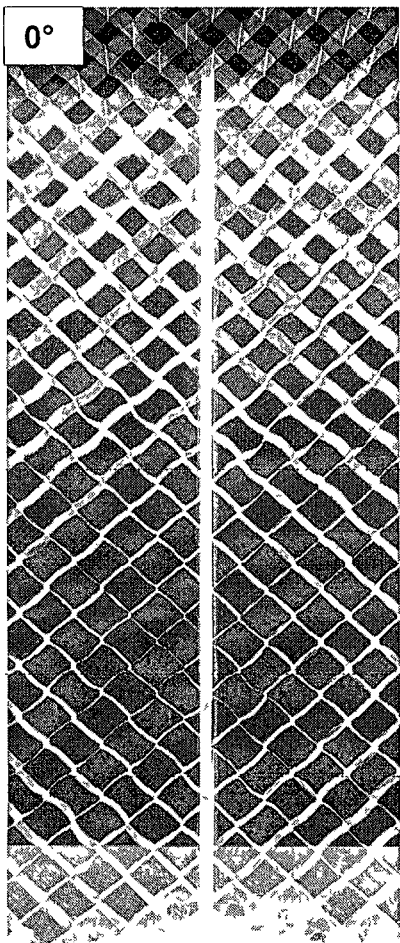
LDDU Through Transmission X-Ray Setup

- Through Transmission X-Ray scans were conducted at 130kV and 60in source to object distance on the two pre-cured RTV areas and one non pre-cured RTV area for three separate angles
- The LDDU was set flat on the table for the 90 degree scans



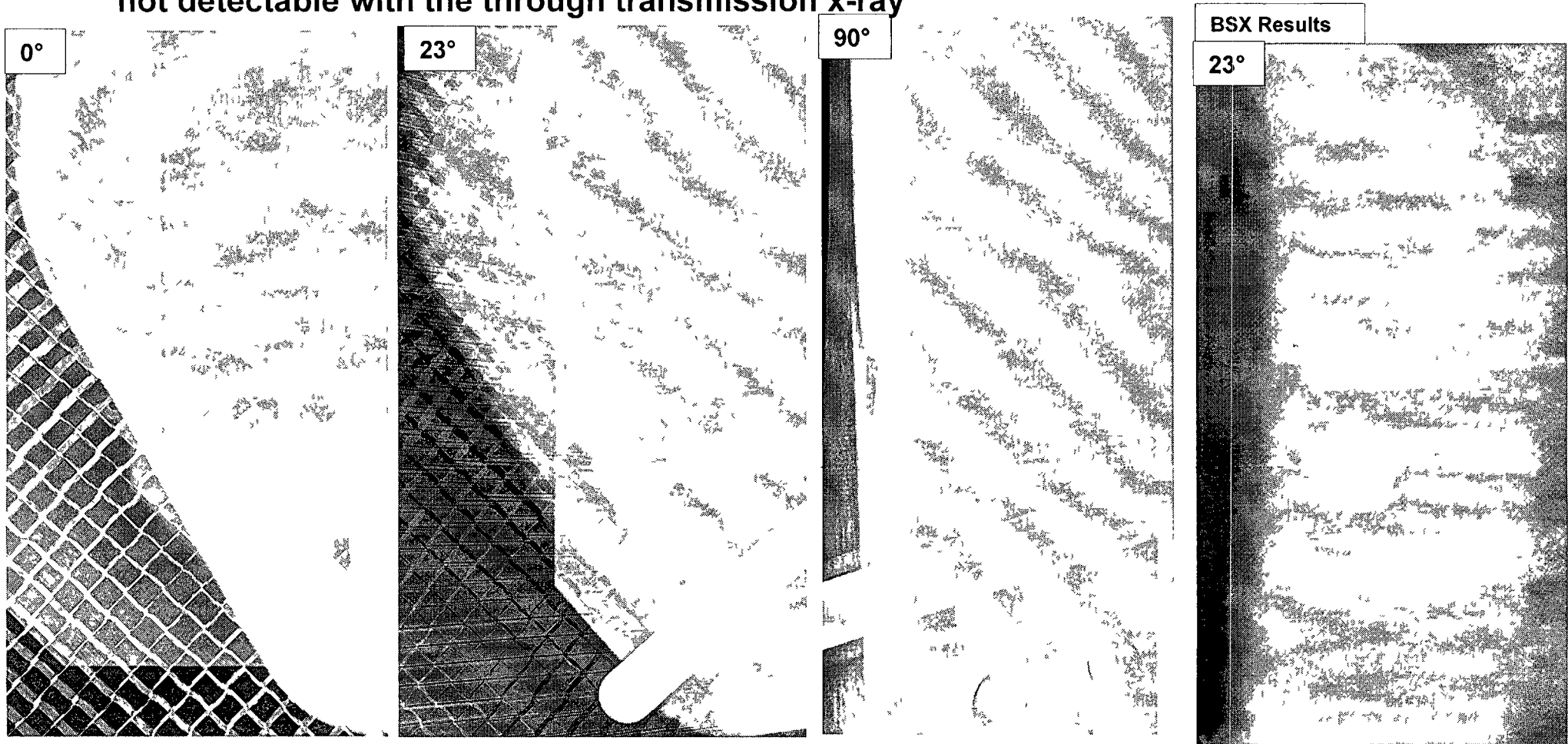
LDDU Through Transmission X-Ray Area 1 Results

- Results compare well to BSX Results
- A disbond in the RTV seam is detected and may explain why the 0.5in RTV voids were filled in during processing
- 0 and 23 degree results show the honeycomb substructure in the image that interferes with the detection of some of the RTV voids



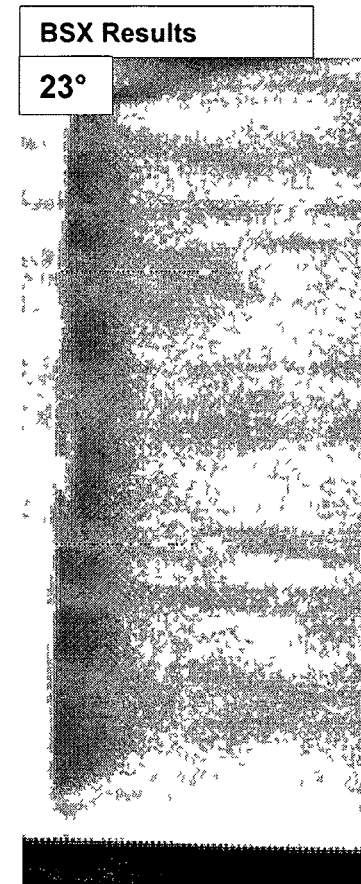
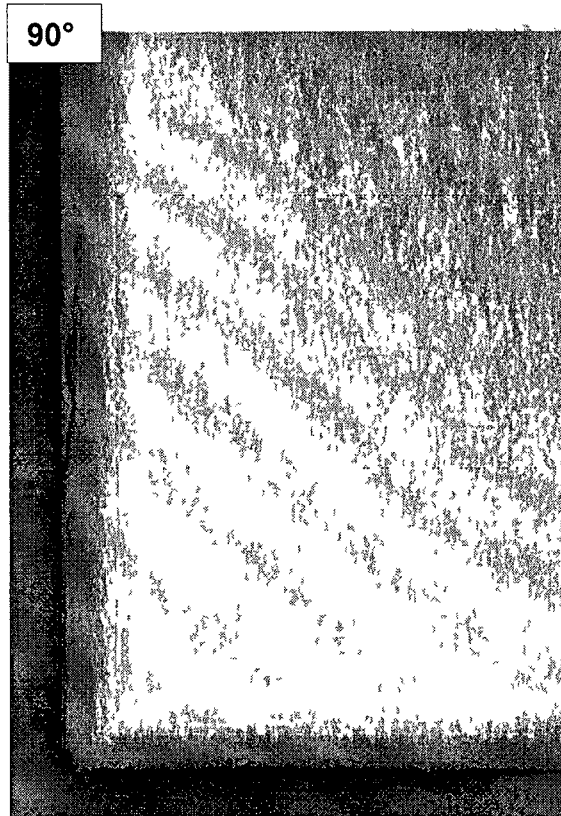
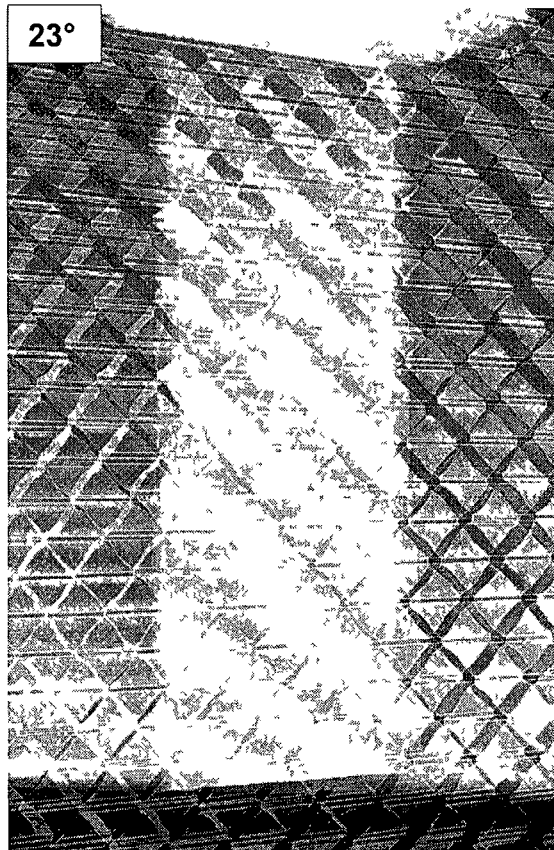
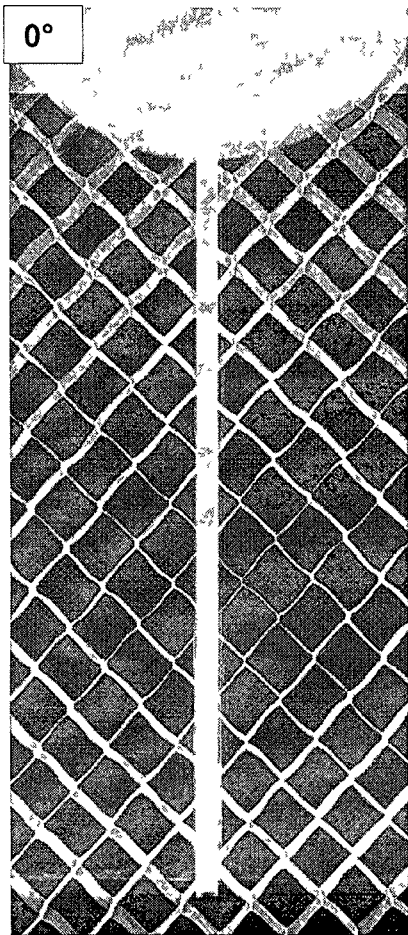
LDDU Through Transmission X-Ray Area 2 Results

- RTV voids are difficult to detect with the through transmission x-ray due to the density and the thickness of the compression pad
- Backscatter x-ray results clearly show the 0.5 and 0.25in diameter voids that are not detectable with the through transmission x-ray



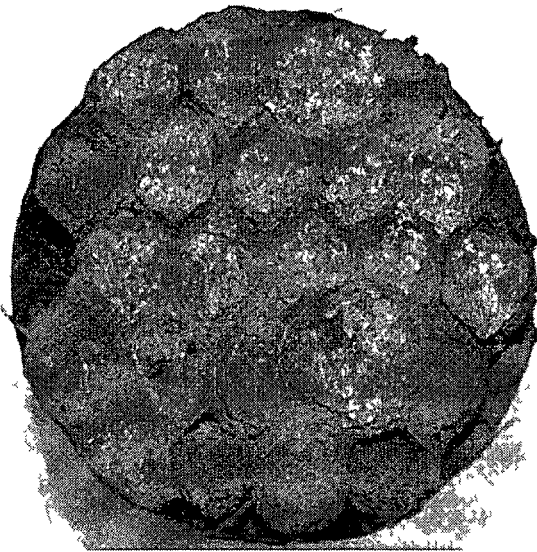
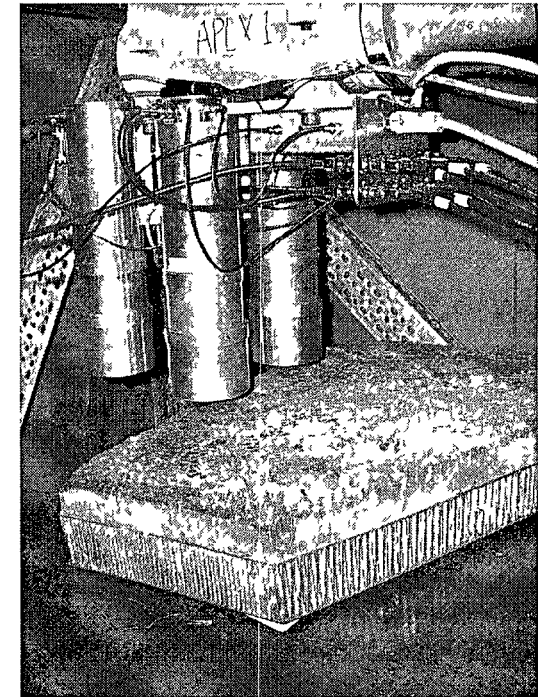
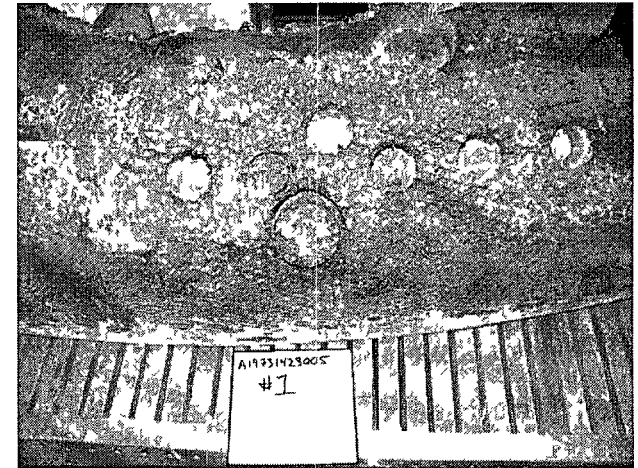
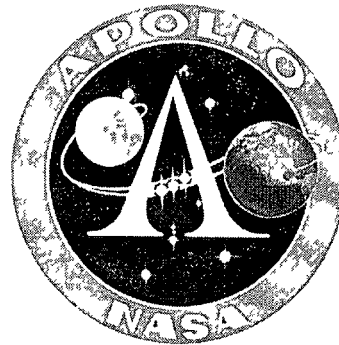
LDDU Through Transmission X-Ray Area 3 Results

- Void in the non pre-cured RTV was detected with both x-ray systems near the surface of the PICA



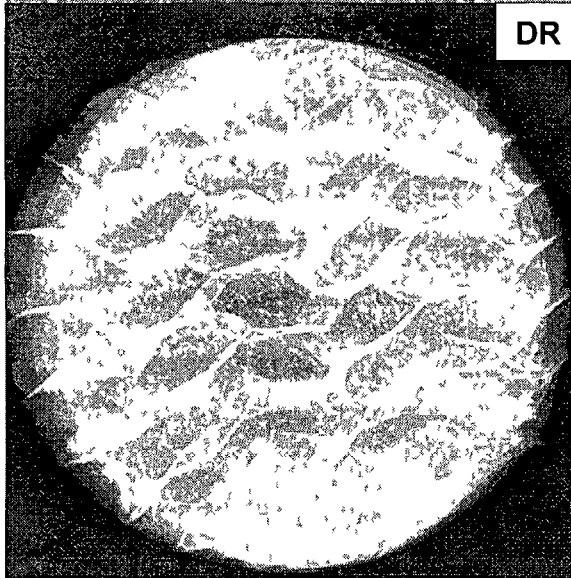
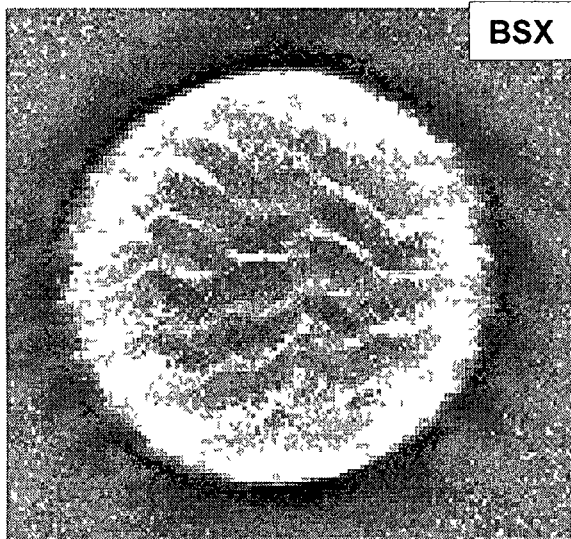
Avcoat Components

- Apollo AS-202 (8-1966) Avcoat plugs
- New Avcoat calibration block
- Apollo AS-202 Avcoat heat shield components



Avcoat Plugs

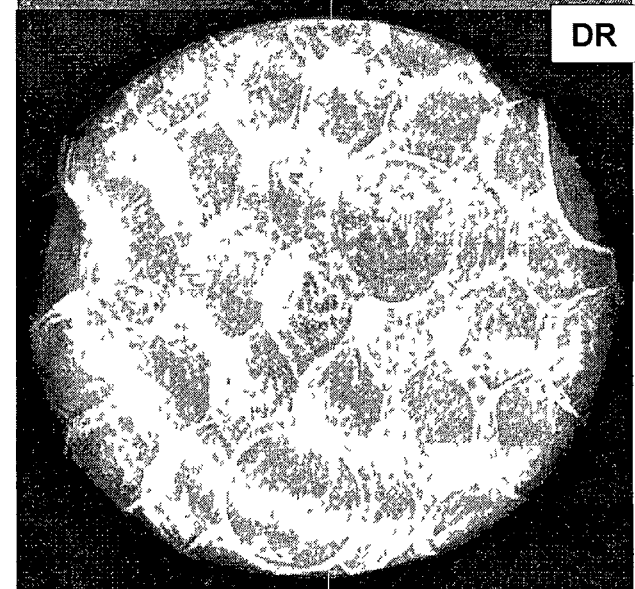
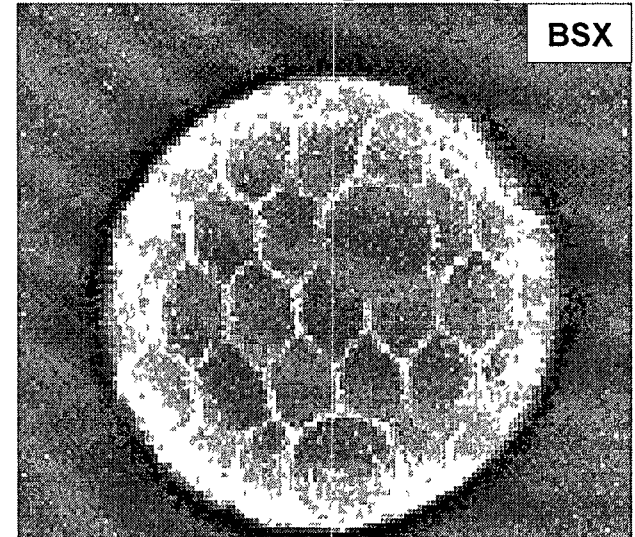
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Cells at angle to x-ray beam



117kV
17mA
1mm Aperture

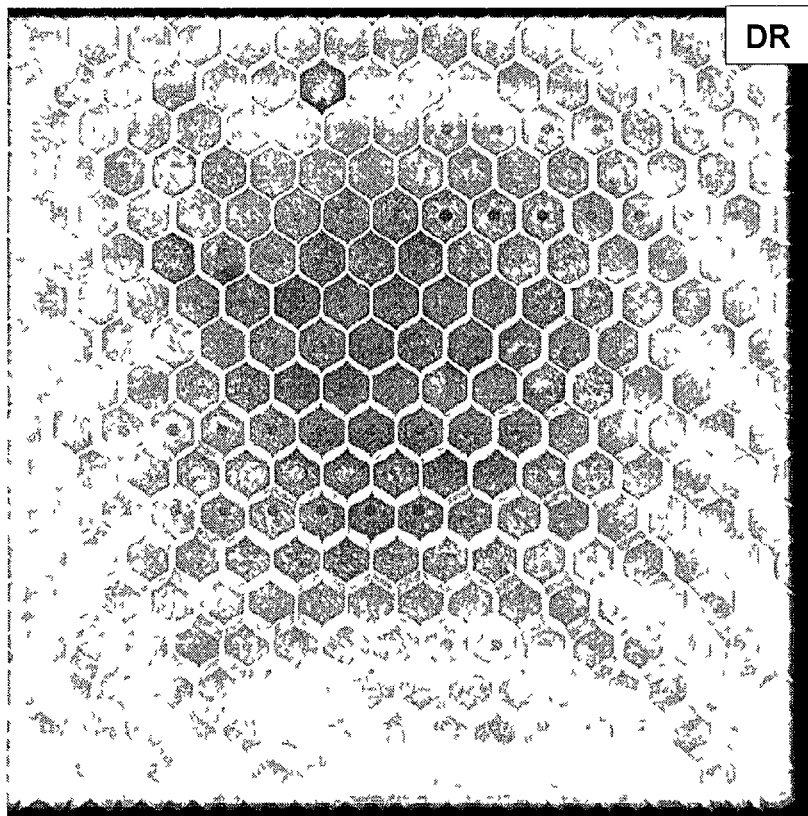


A197314230006
Cells at 0 degree angle to x-ray beam

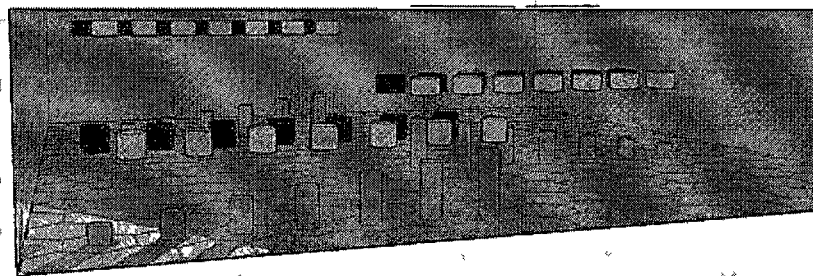
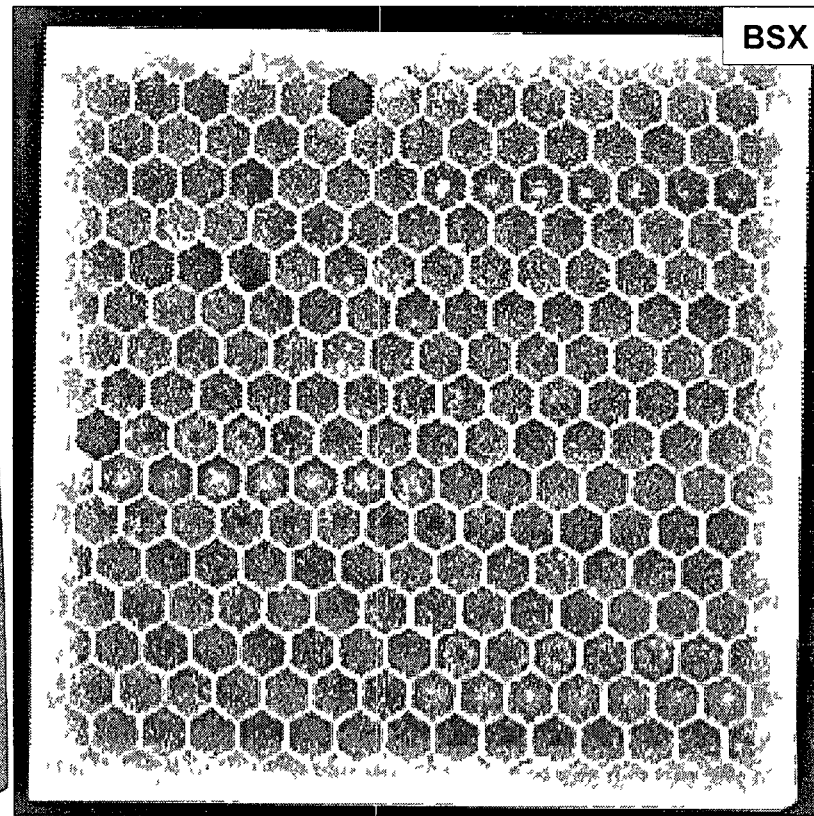
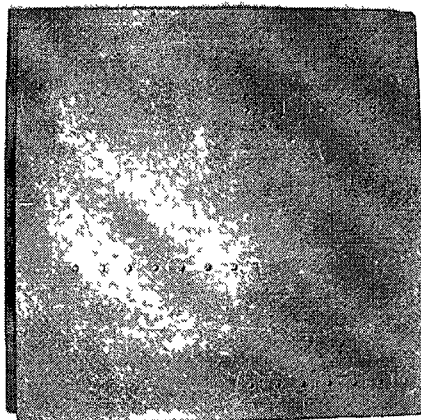


Avcoat Reference Block

Sum of 4 detectors and filter



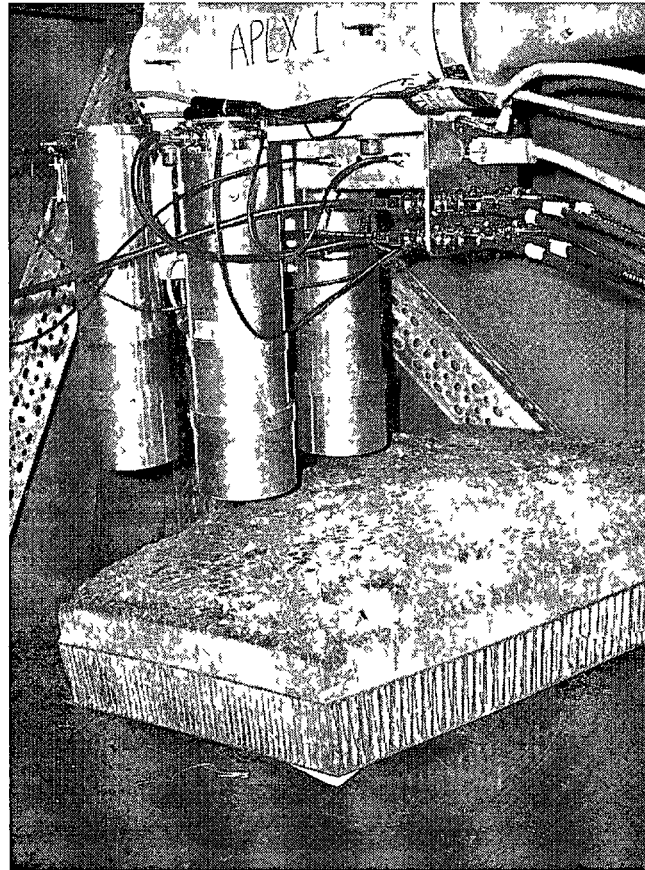
114kV
15mA
1mm Aperture



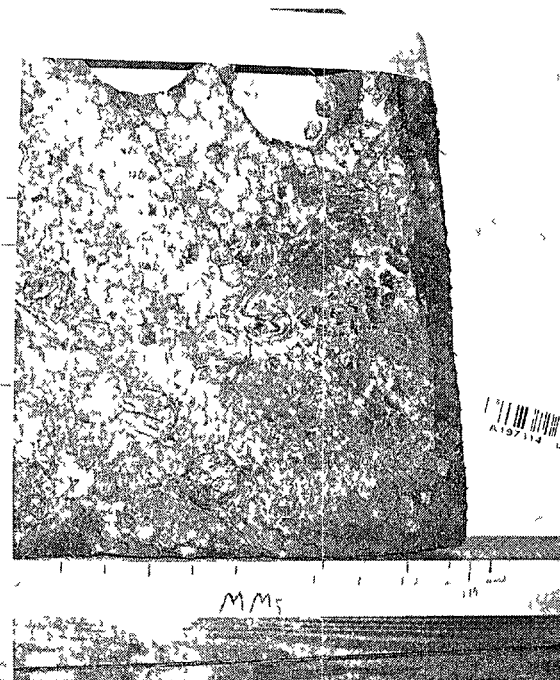
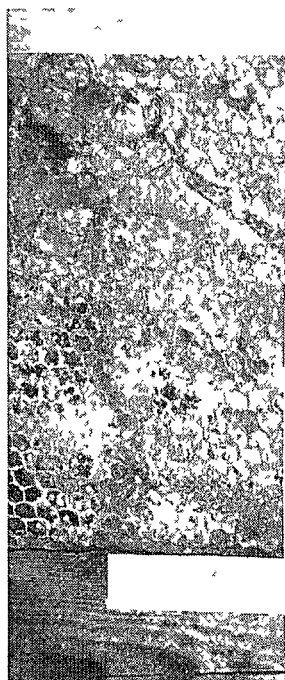
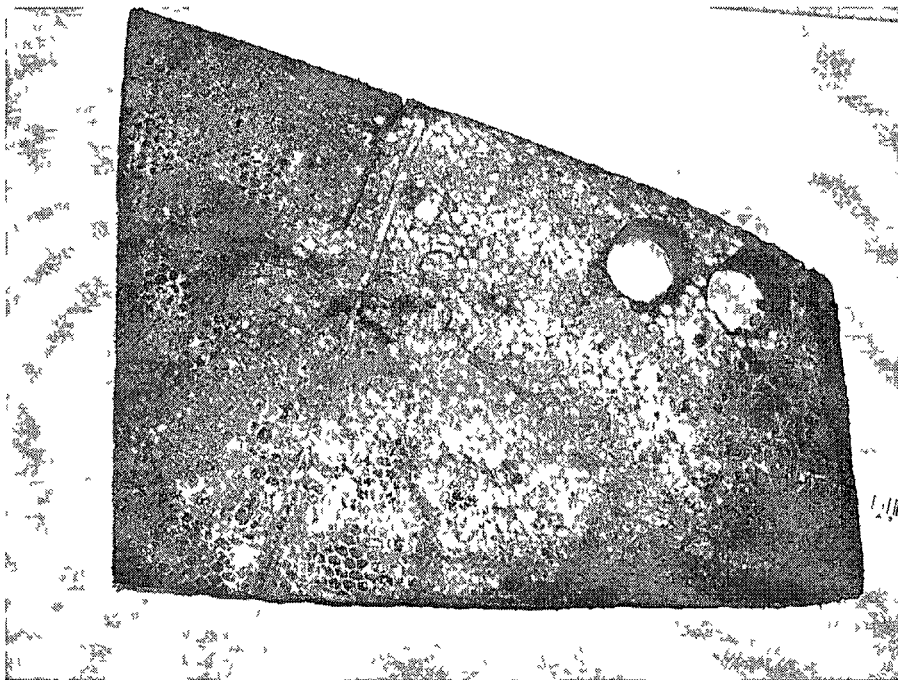
Able to detect all flat FBH and gap fills

Apollo sample A19731423006

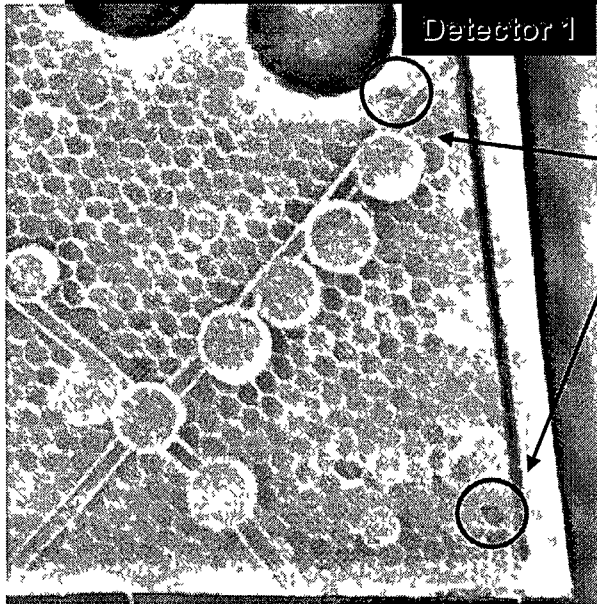
- Apollo sample A19731423006 was scanned to provide any available information on repairs to the TPS material as well as any apparent defects from the original manufacturing. Evaluations to be determined.



APOLLO SAMPLE/ SCANNED AREA

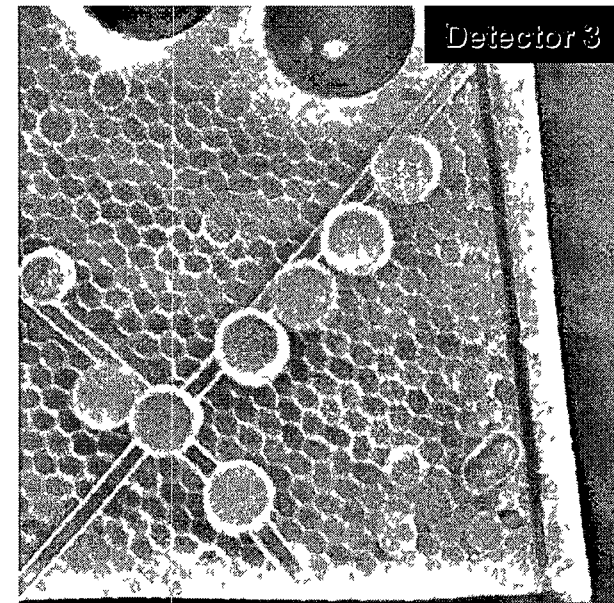
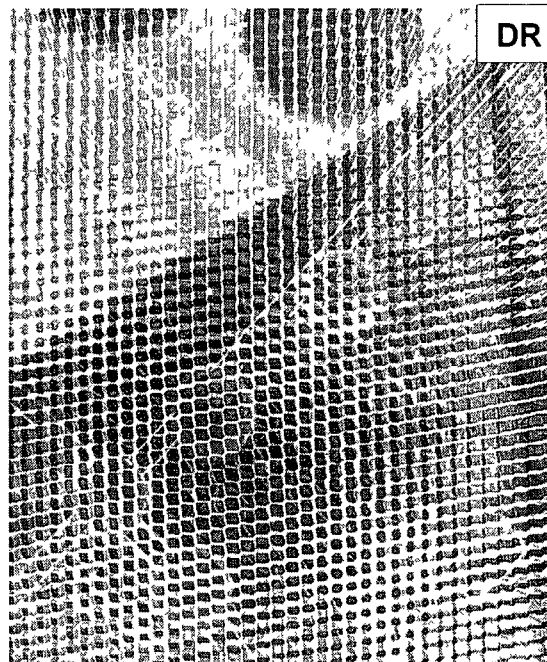
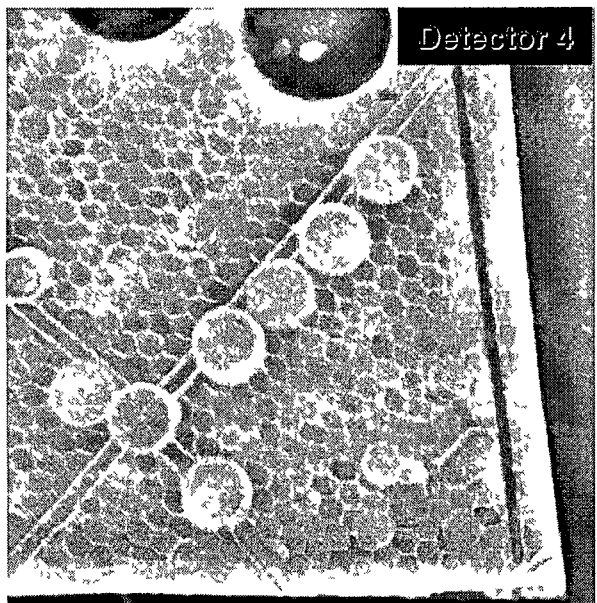
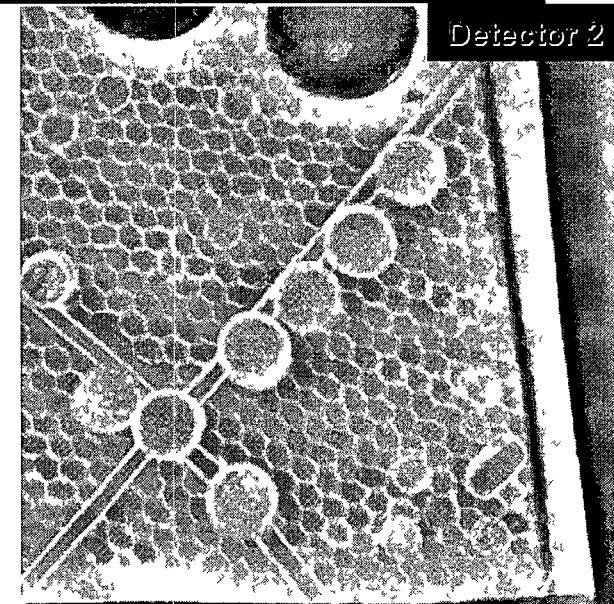
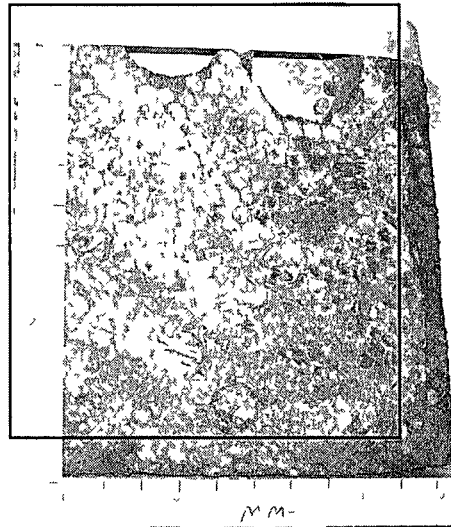


Large Scan Area 1mm Spot Resolution



•Possible void in Avcoat Honeycomb Cell

90kV
30mA
0.75mm Aperture



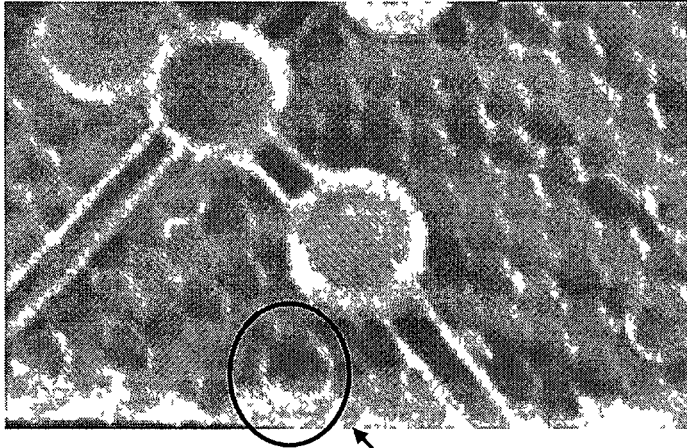
Small Scan Area 0.52mm Step Size 20 Degree Tilt

100kV

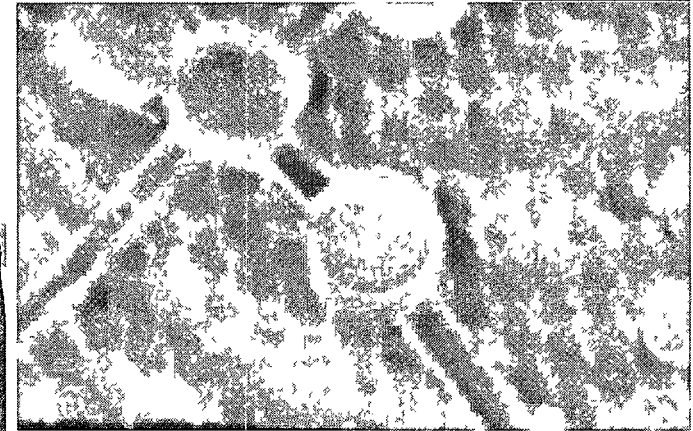
30mA

0.75mm Aperture

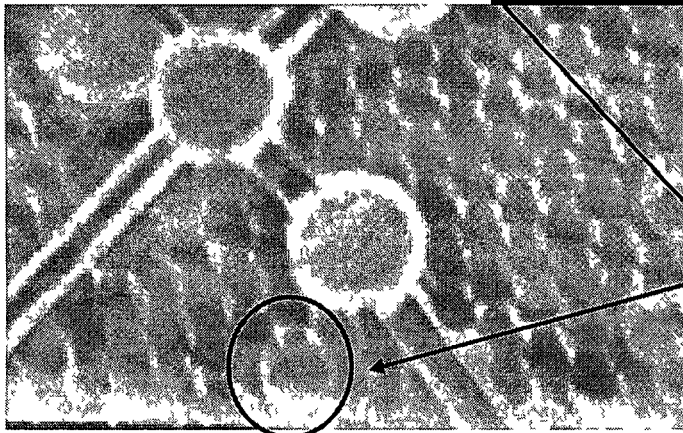
Detector 1



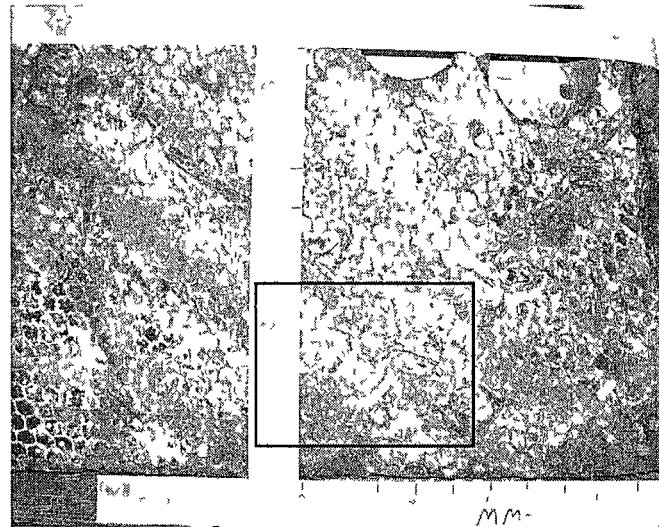
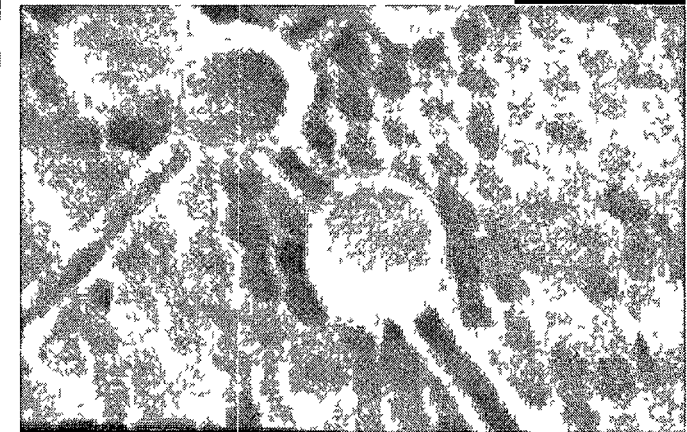
Detector 2



Detector 4



Detector 3



- Ability to detect honeycomb liner
- Possible steel honeycomb core detected as darker regions with detectors 1 and 4 near edge of specimen

Small Scan Area 0.52mm Step Size 45 Degree Tilt

Detector 1

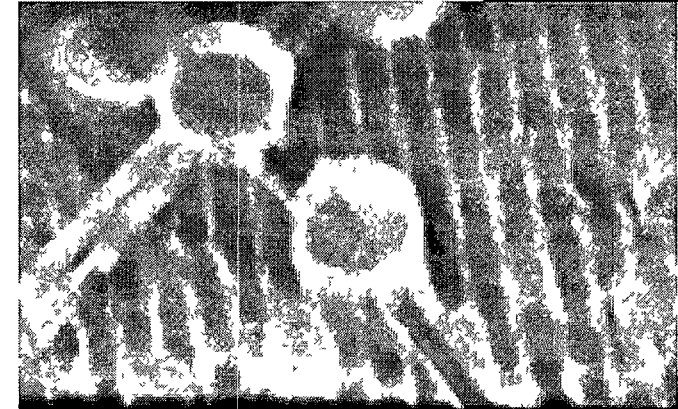


100kV

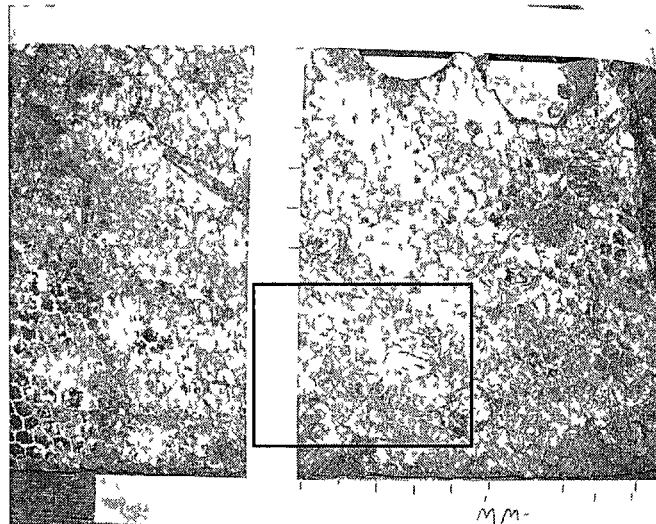
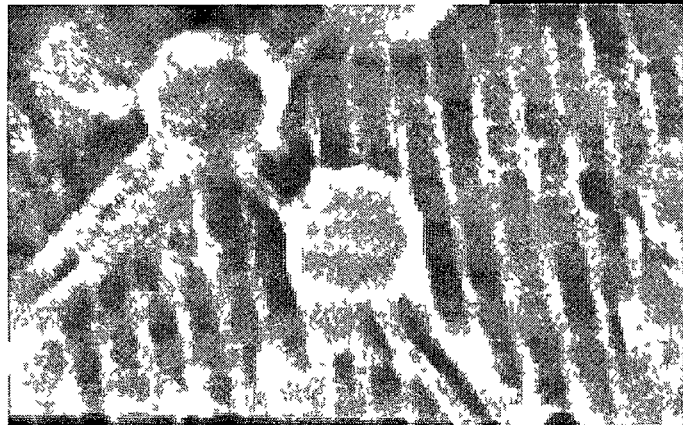
30mA

0.75mm Aperture

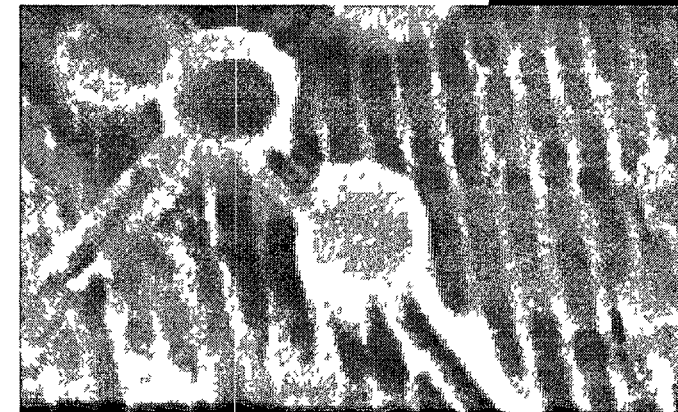
Detector 2



Detector 4

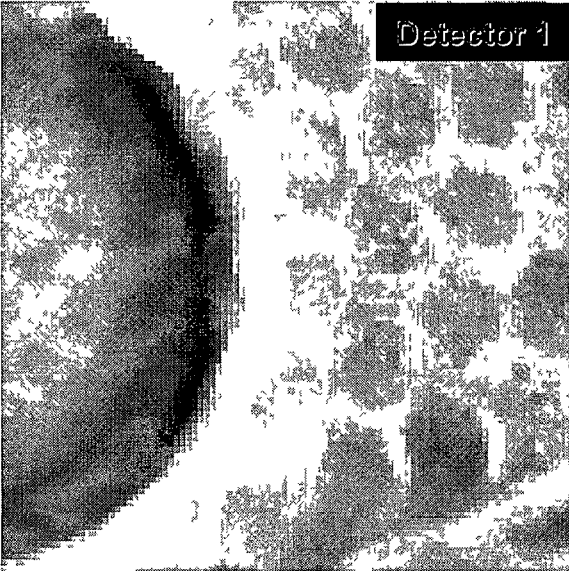


Detector 3

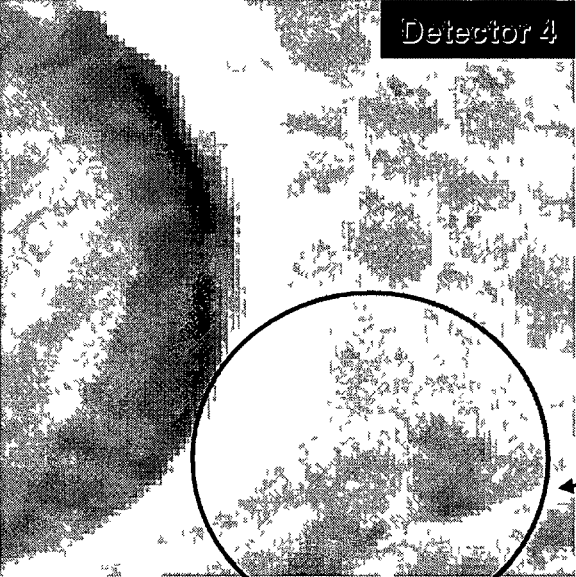
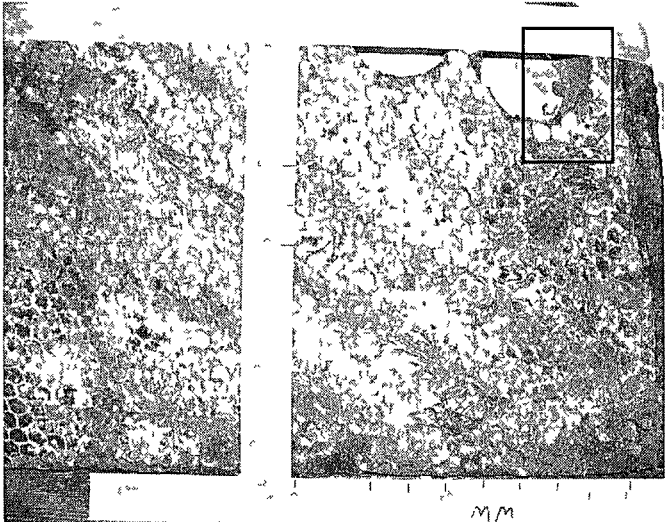


- Tilt allows to see honeycomb to penetration depth limit of system at 100kV
- More energy is needed to detect indications at avcoat honeycomb and steel facesheet interface

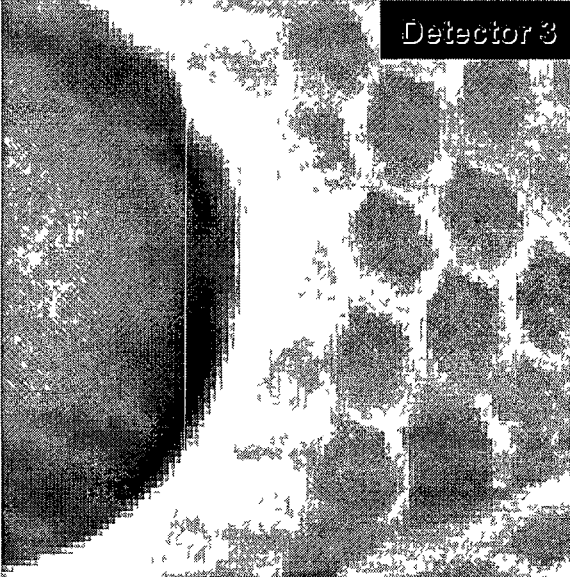
Small Scan Area 1mm Spot Resolution Large Aperture



100kV
30mA
1mm Aperture



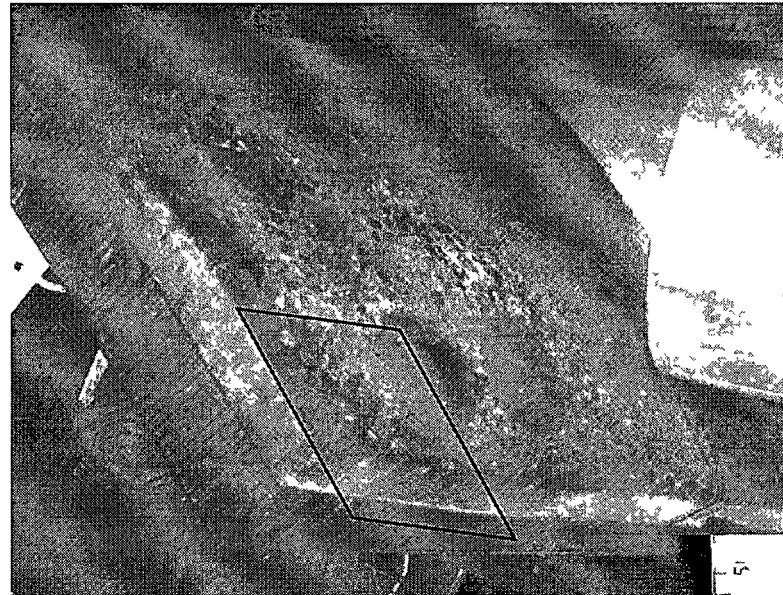
- **Detector 4 shows slight indication of underlying steel honeycomb near edge of Apollo piece**



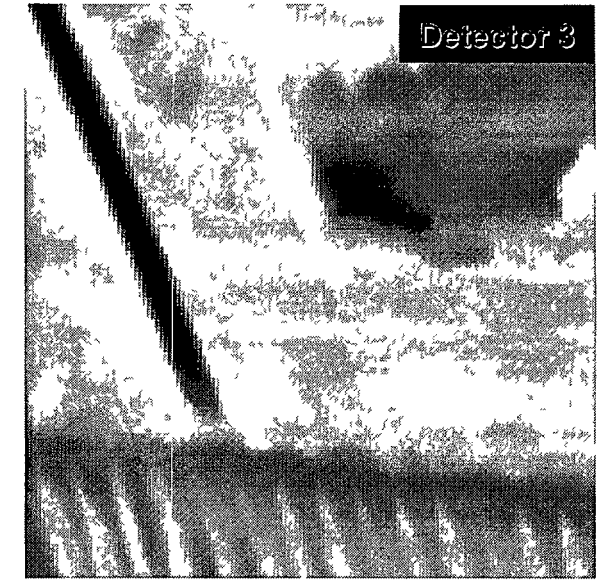
Small Area 45 Degree Tilt Near Edge



100kV
30mA
1mm Aperture
Slow Scan 2 6mm/sec

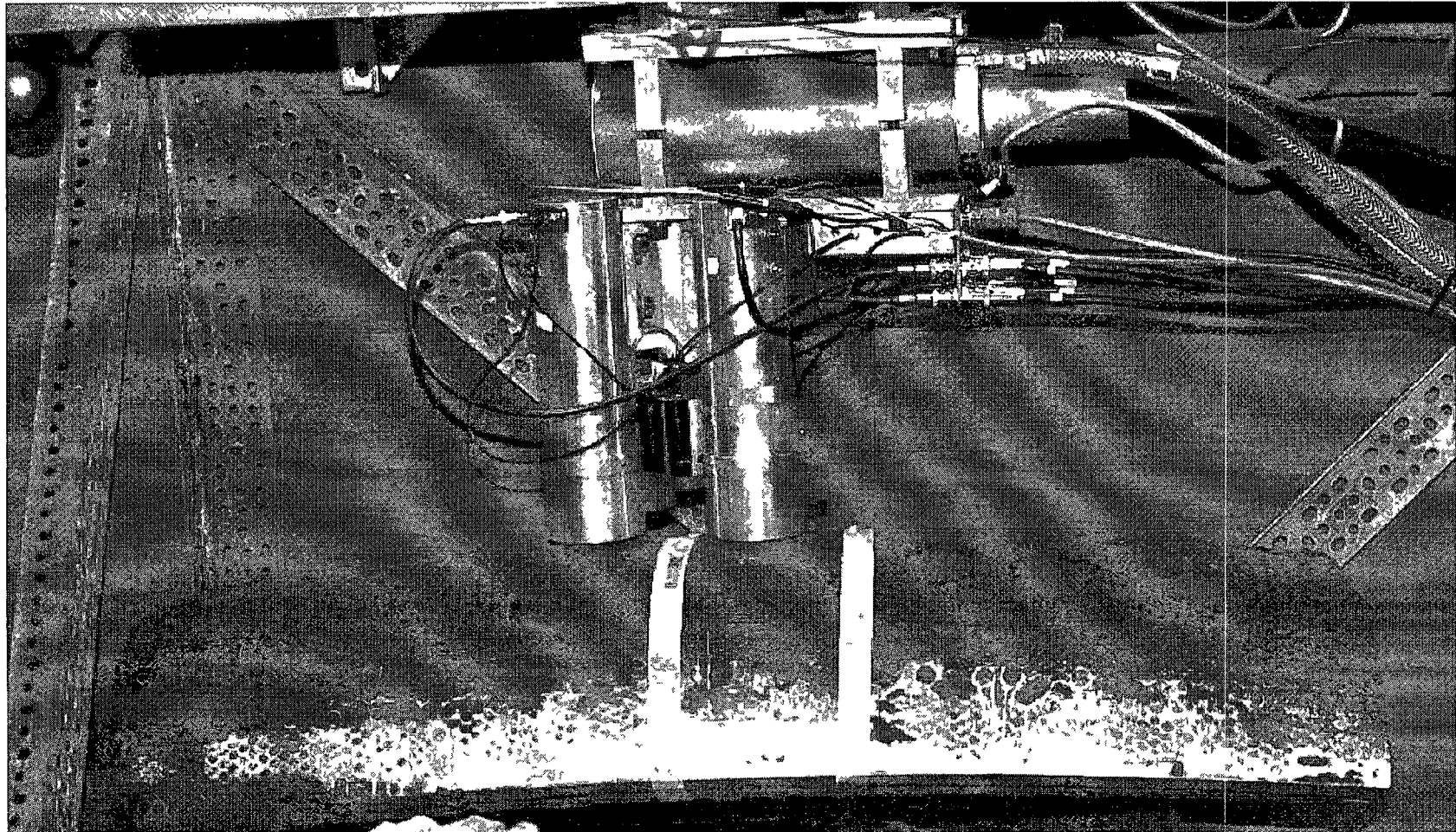


- Depth of penetration is approximately 0.5 inch maximum with optimum settings

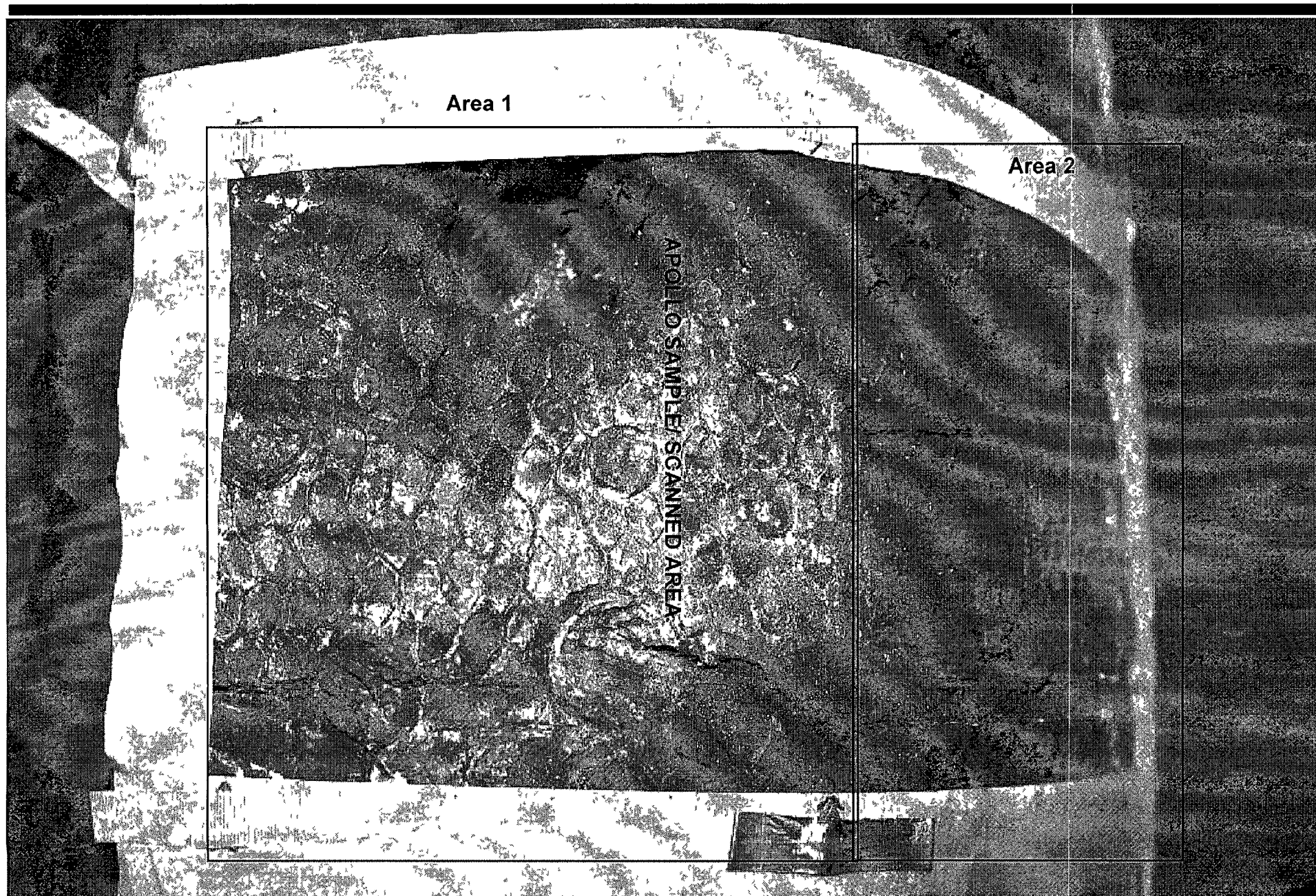


Apollo sample A19731423005

- Apollo sample A19731423005 was scanned to provide any available information on repairs to the TPS material as well as any apparent defects from the original manufacturing Evaluations to be determined



APOLLO SAMPLE/ SCANNED AREA



SCAN PARAMETERS

- Apollo sample A19731423005 was scanned 0.52mm step size with 0.75mm aperture at a scan rate of 10mm/s
- X-Ray parameters were 115kV and 15mA
- Fin settings were at 90 degrees with sleeves at 1.25" height

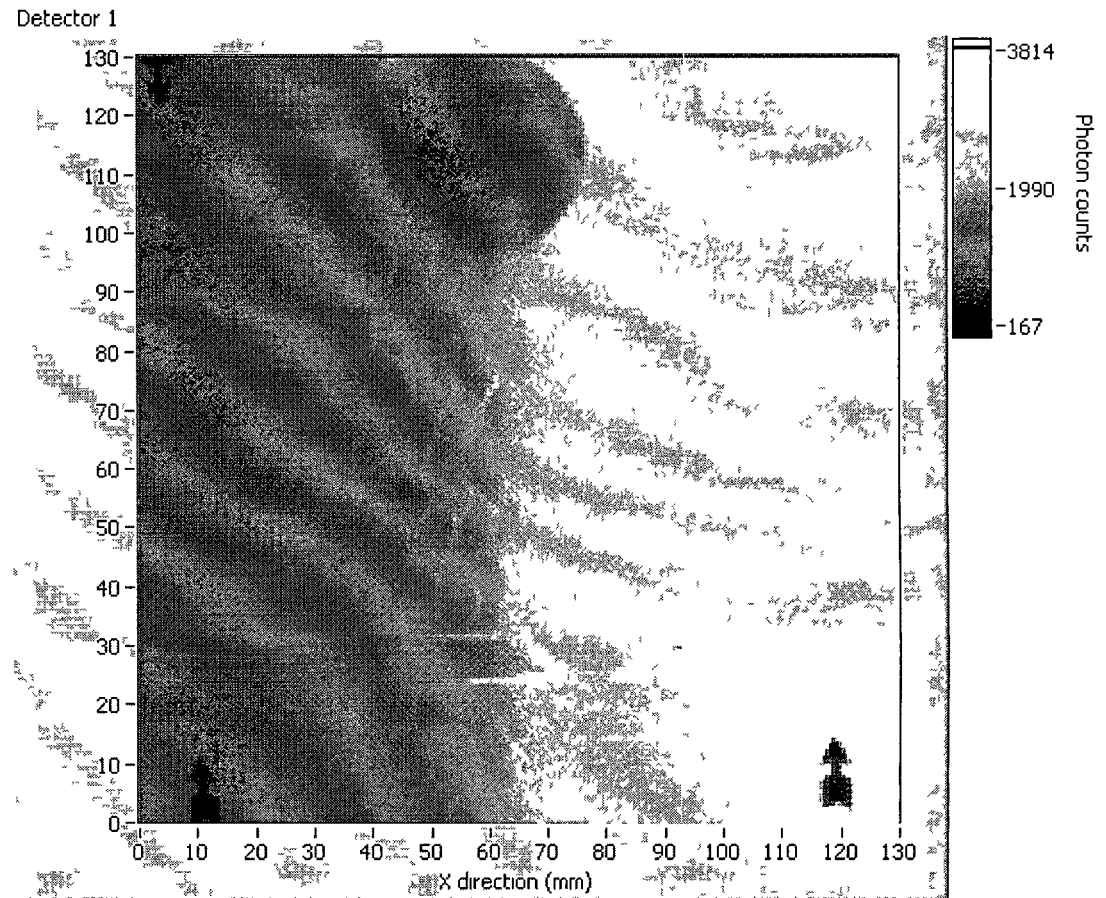
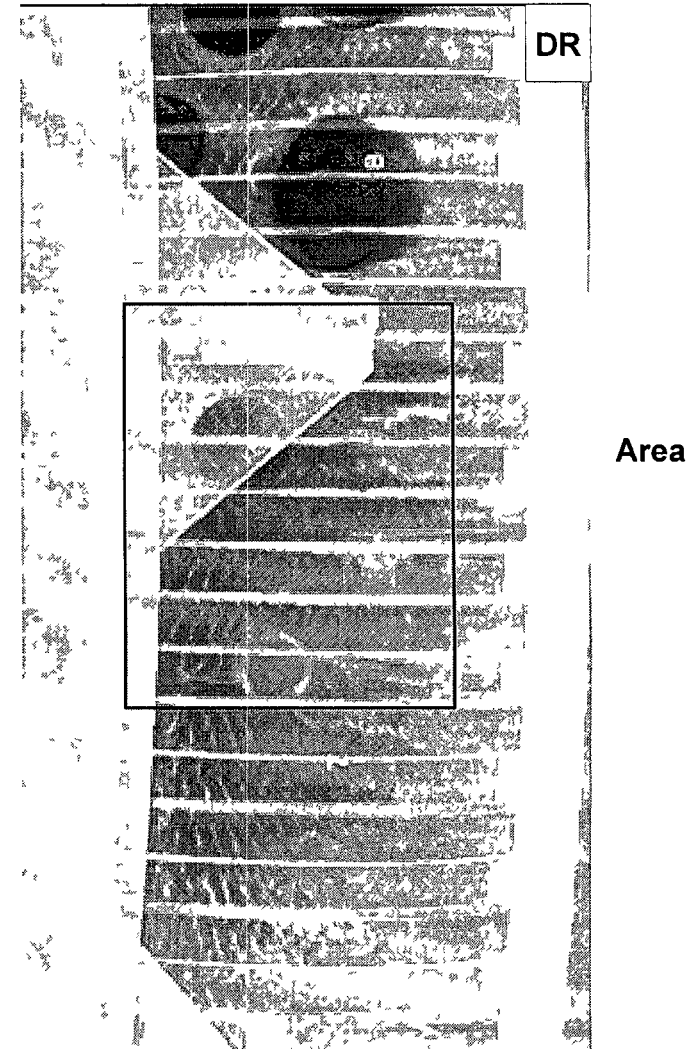
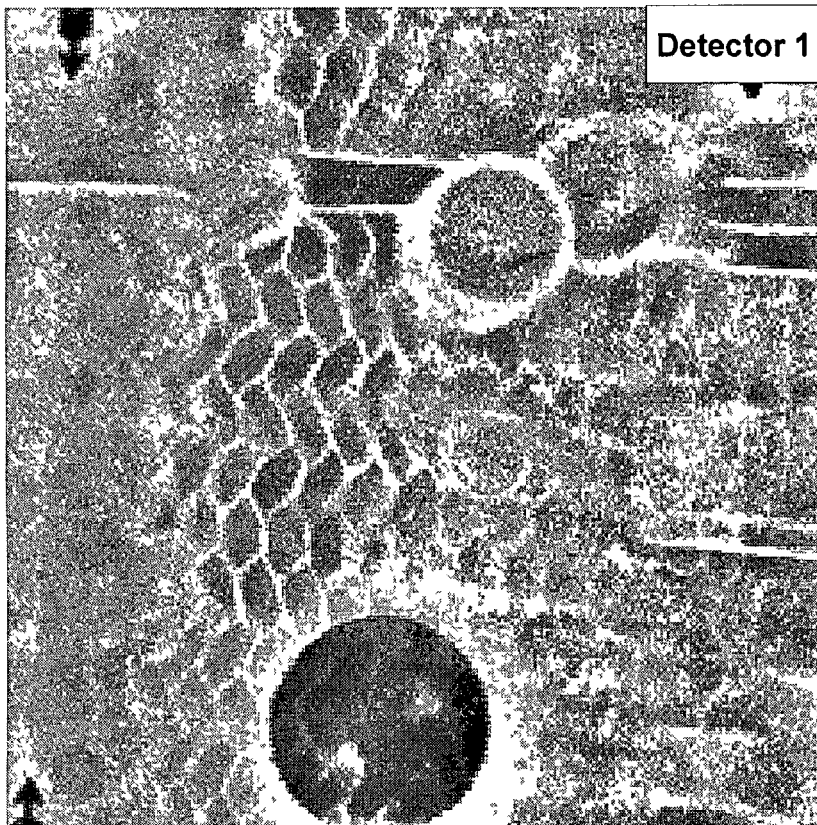
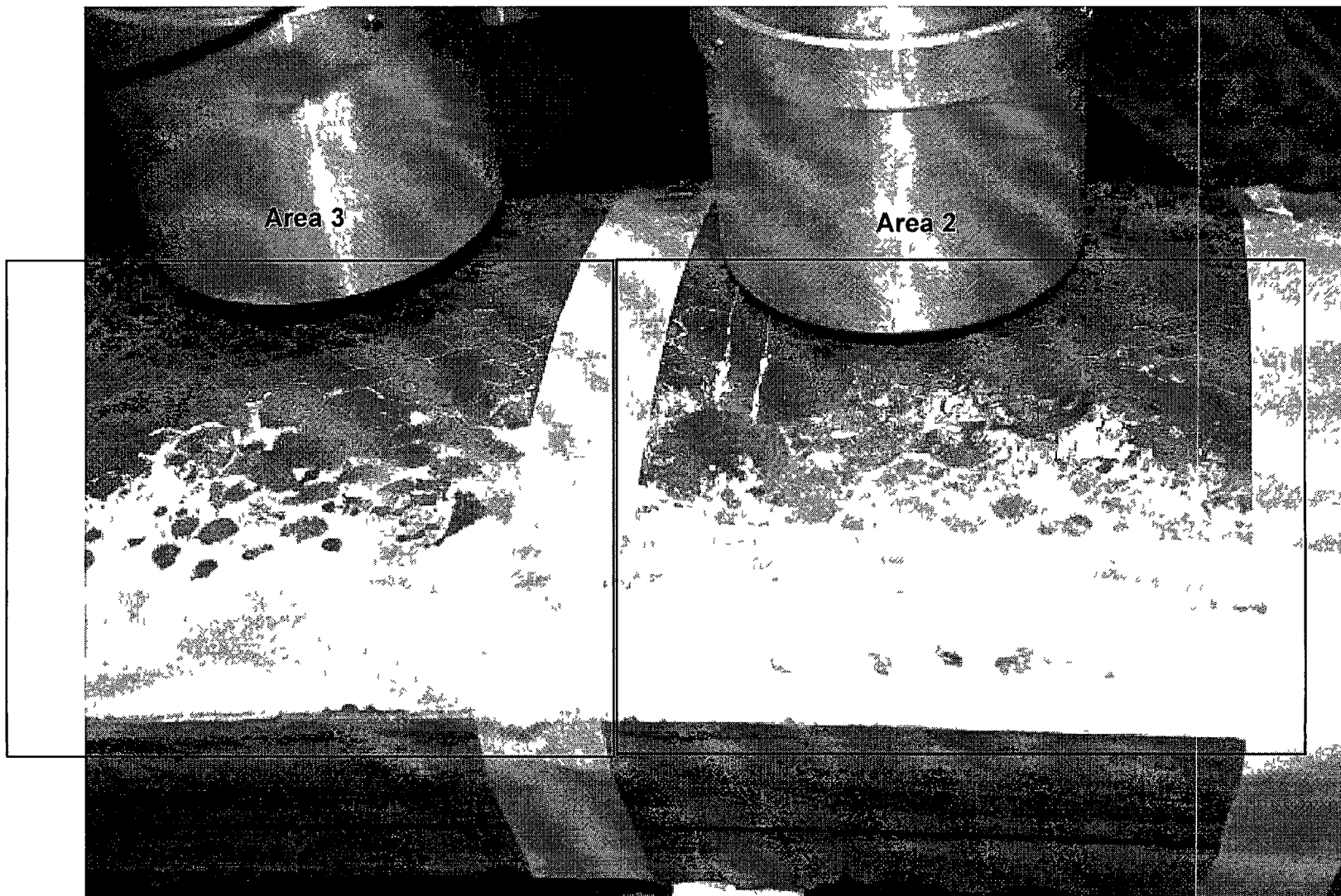


IMAGE RESULTS Area 1

- Images were processed using FFT band pass filter and contrast enhancement
- Able to see through Avcoat sample using 115kV unlike in previous Avcoat Piece

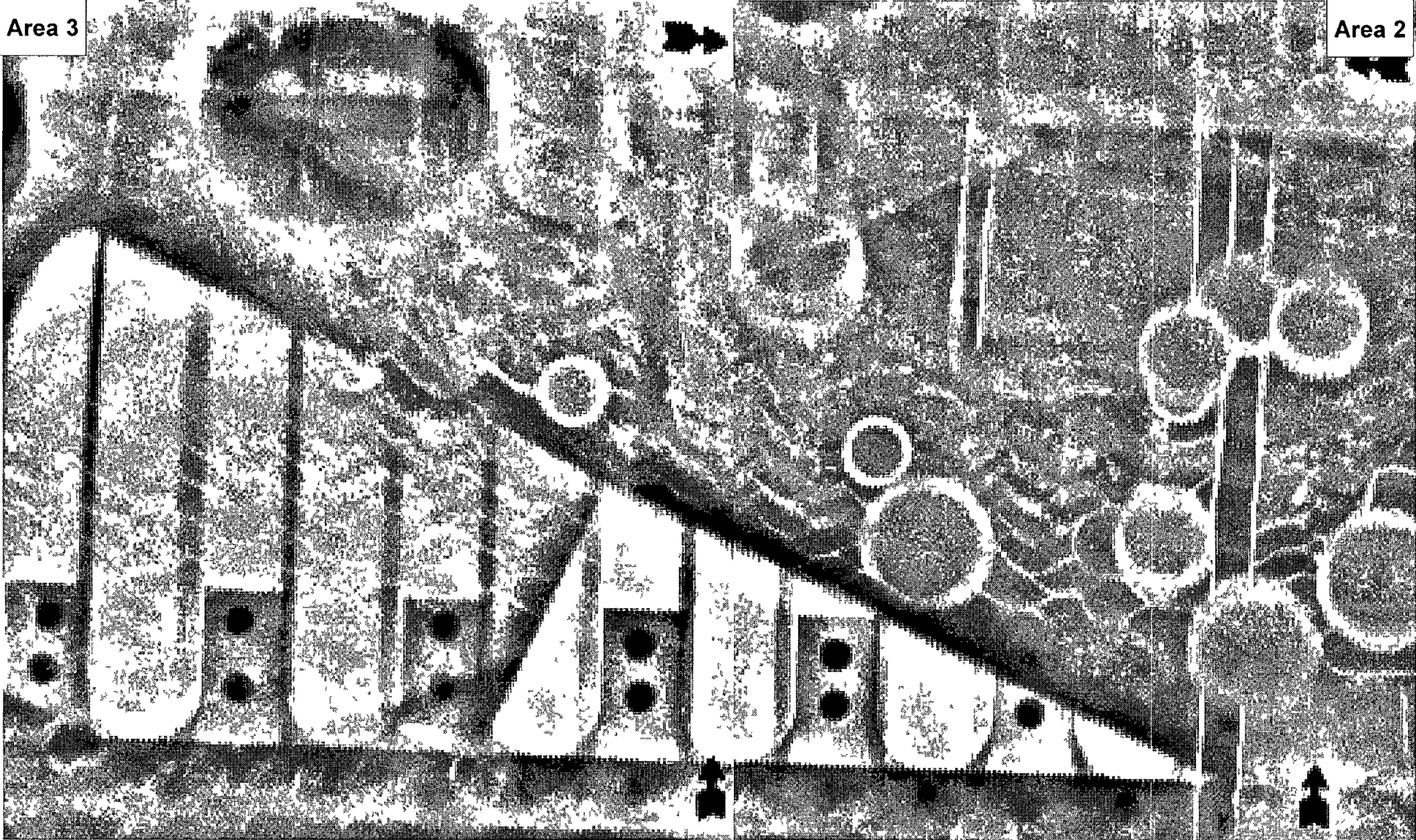


APOLLO SAMPLE/ SCANNED AREA



BSX Image results Area 2 and 3

Combination of scans show large triangular area due to wooden shim underneath sample



Conclusions and Future Work

- **Conclusions**

- **Single sided nature of BSX allows for x-ray of large complex components**
- **Not necessary to transmit x-rays through object**
- **BSX system able to detect voids and other indications in various heat shield materials**
- **Increased resolution is necessary to obtain resolution on the scale of DR**

- **Future Work**

- **Development needed to scan along curved surfaces**
 - **The x-ray beam needs to be parallel to honeycomb cells to image core and minimize interference from cell wall**
- **System calibration is necessary to transition technology to floor operations**
 - **Correct kV energy must be chosen to image each material and not the honeycomb substructure, or wooden shims**
- **Modifications and development necessary to quantitatively detect composition and depth information with current setup**