Terahertz Imaging and Backscatter Radiography Probability of Detection Study for Space Shuttle Foam Inspections

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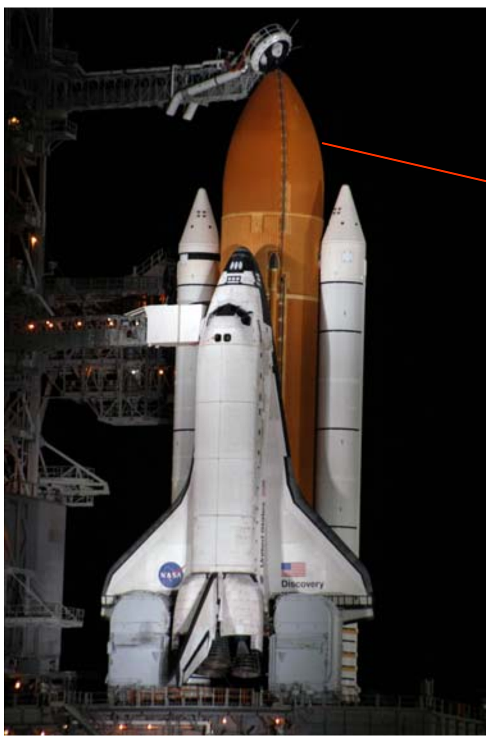
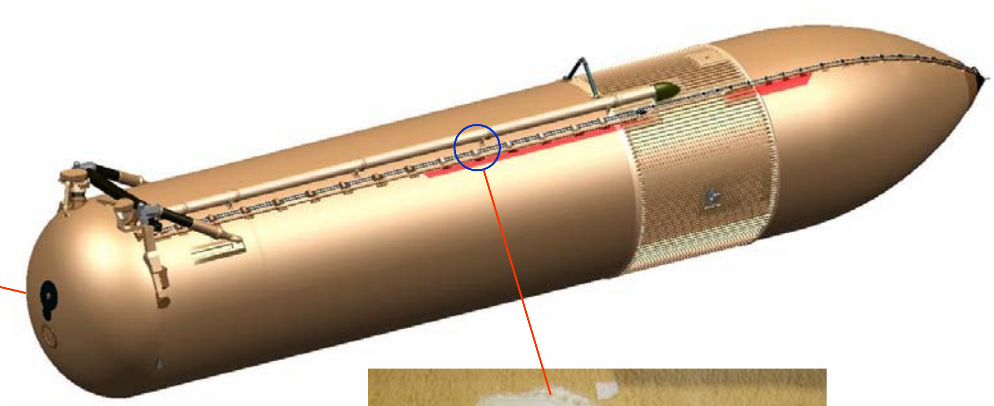
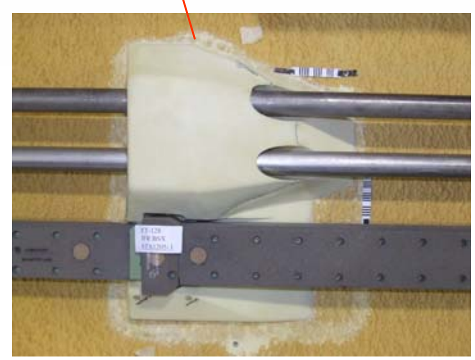
- **External Propellant Tank (ET) Background**
  - **ET holds cryogenic liquid hydrogen and oxygen fuel for shuttle main engines**
  - **Polyurethane foam insulation prevents cryogenic fuel from boiling as well as ice formation**
  - **Aero loads during launch can produce foam debris potentially damaging the shuttle orbiter**
  - **After the Columbia accident, ET foam debris was identified as a likely cause of the orbiter wing damage**
  - **NDE is performed on ET foam as one method of preventing critical foam debris during launch**



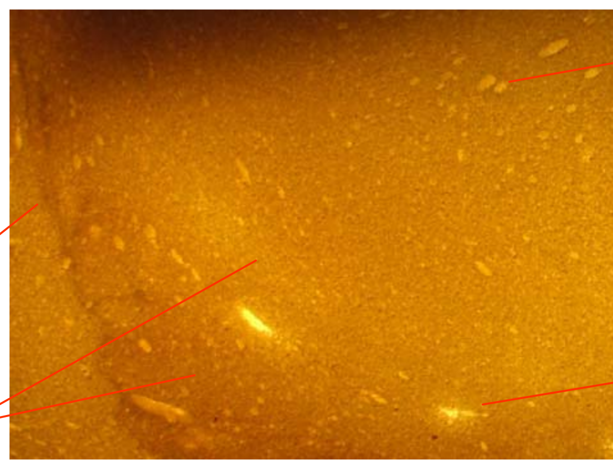




Ice frost ramps are one application that currently undergoes NDE on each External Tank.

- **NDE Difficulties in Polyurethane Foam Inspection**
  - Does not lend itself to conventional NDE methods
  - Very low density (~2.5 lbs/cu ft) so air voids do not exhibit significant density change
  - Non homogeneous material with density variations
  - Inspection must be single sided due to access restrictions
  - No history of industrial inspection of foam

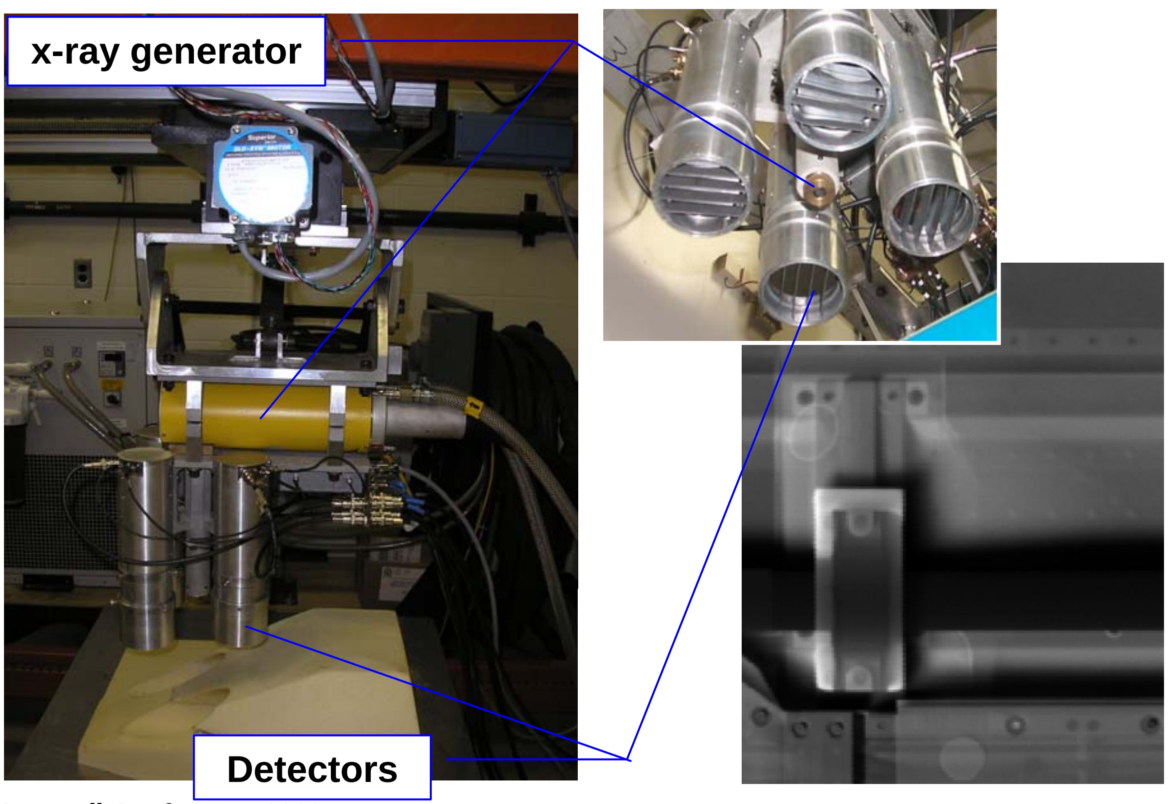
- **Conventional NDE Method Assessment**
  - UT: Foam attenuates UT
  - X-ray: Requires two sided access
  - Thermography: Foam is an insulator
  - Air-Coupled, Low Freq. UT: Non-homogeneous foam structure impairs technique

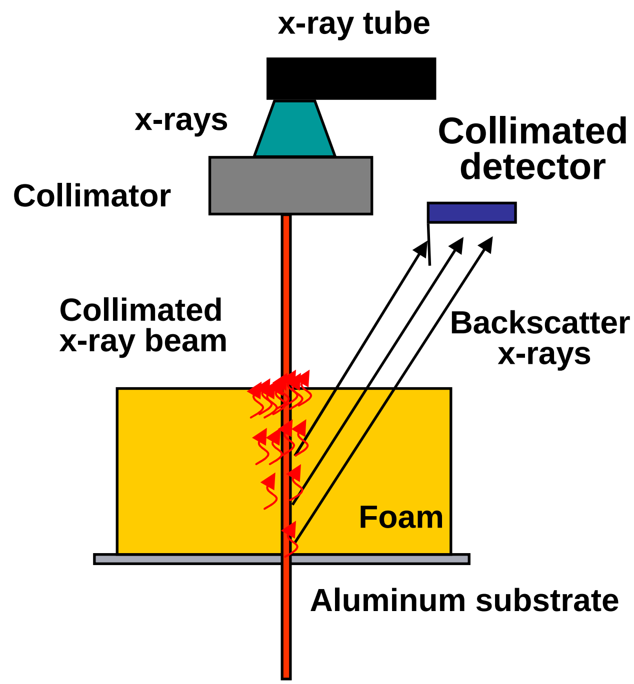


Typical Slice of ET Foam (Backlit to Emphasize Density Variations and Voids)

Background: Backscatter Radiography (BSX)

- Collimated beam of x-rays (55-70 kV) interact with sample molecules
- Backscatter x-rays are emitted (Compton Scattering), possibly after multiple subsequent scattering events, and detected by NaI or YSO detectors
- Collimation provides some preferential sensitivity to selected depth
- The x-ray beam and detectors are scanned across the part to generate a 2-D presentation of the internal make-up of the foam

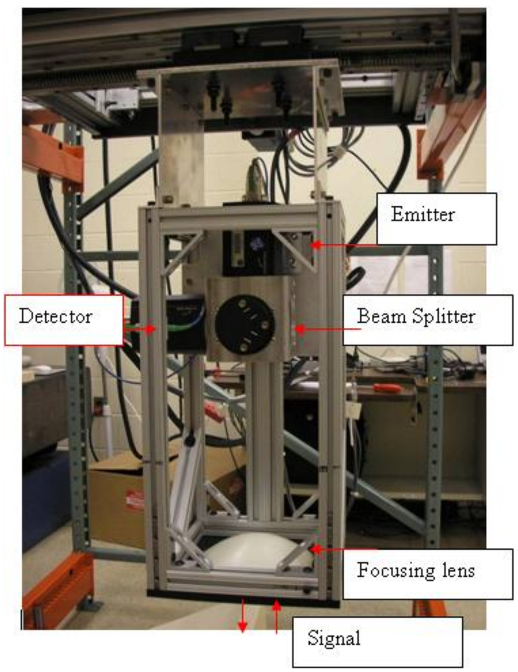




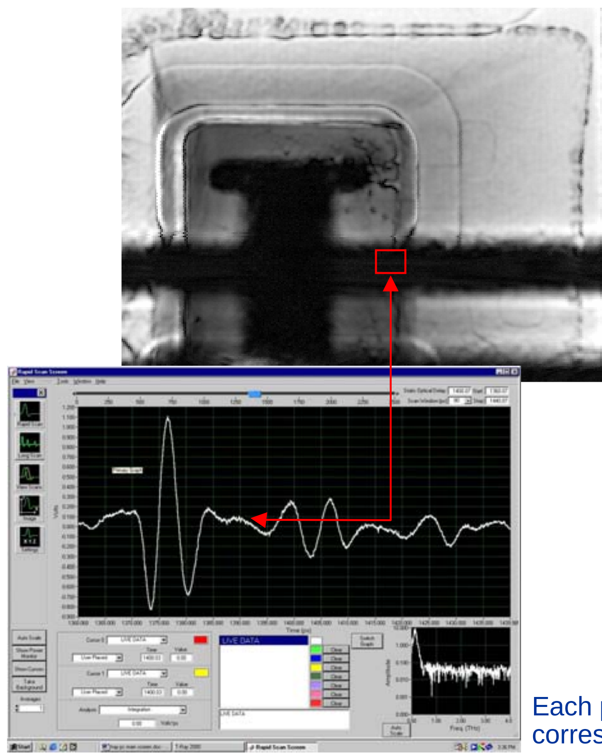
BSX Image

Background: Terahertz Imaging

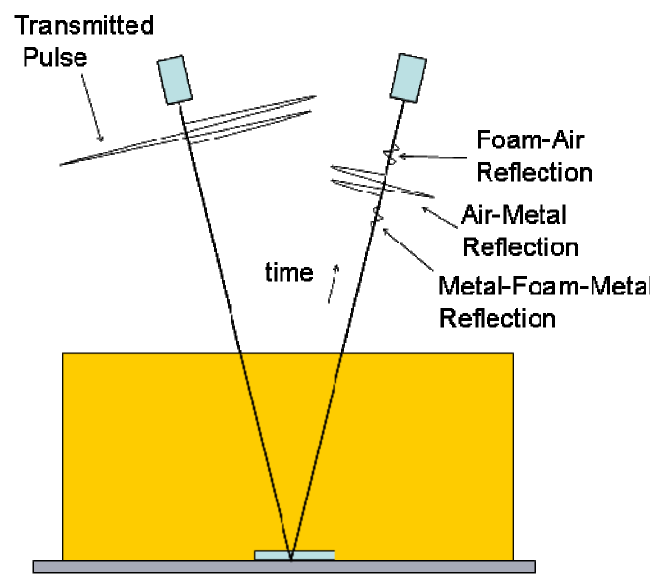
- Terahertz (THZ) inspection uses energy in the high frequency RF band between microwave and infrared
- THZ beam is transmitted through object and reflects off the aluminum substrate
- Due to foam attenuation, received pulse is approx. 0.1 to 0.3 THz (100 GHz to 300 GHz)
- Presence of defects produces changes in amplitude, phase and frequency of received beam
- Less attenuation can indicate less material such as the presence of a void
- THZ beam is scanned across the part to generate a 2-D presentation of the internal make-up of the foam



Terahertz Transceiver

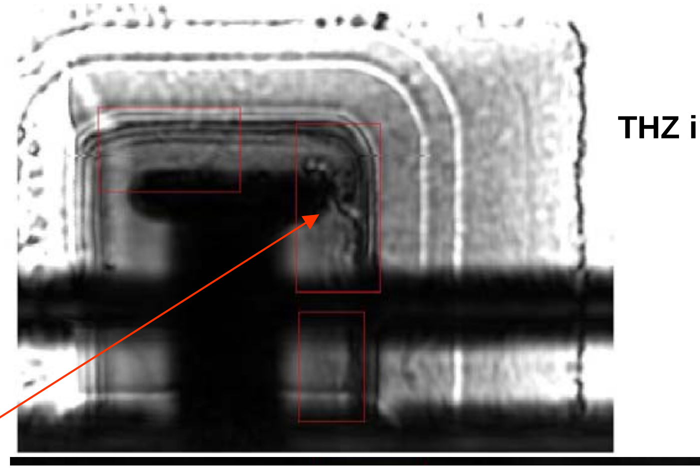


Each pixel in the Terahertz image corresponds to an individual waveform

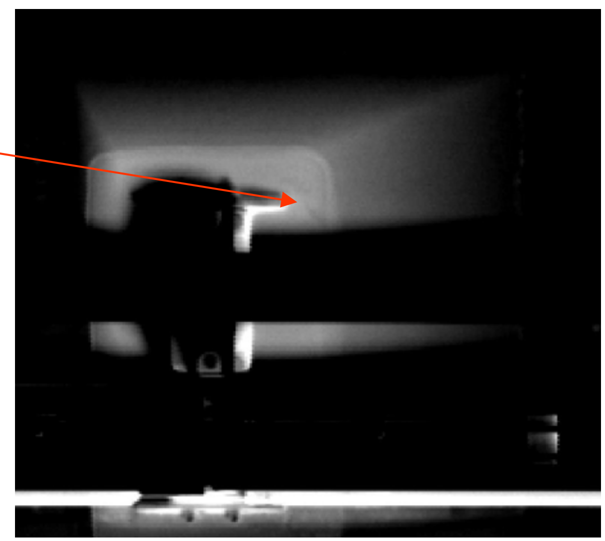


Background: BSX and THZ Examples

- **Example 1**
  - THZ image has distinct response from void
  - BSX image has marginal response from void



THZ image

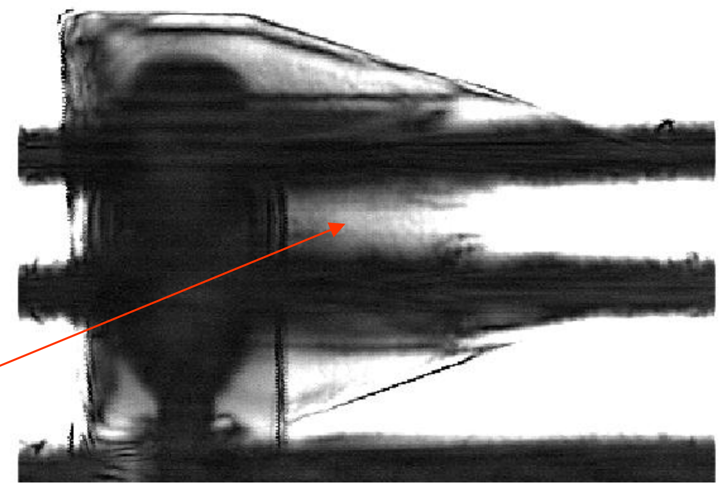


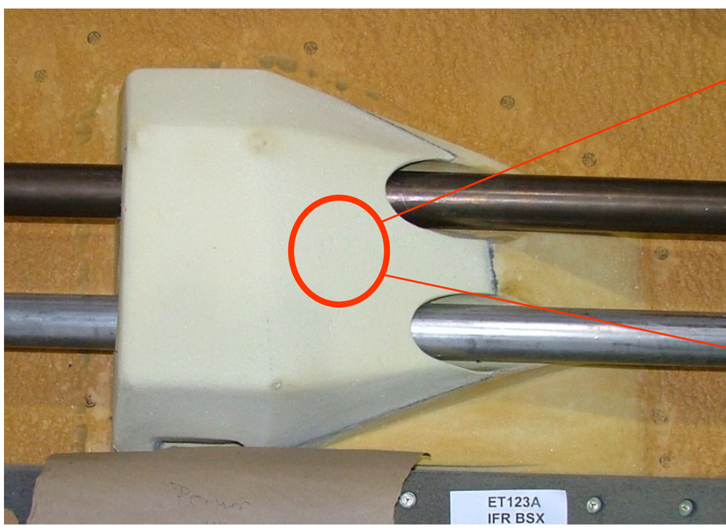
BSX image

Background: BSX and THZ Examples

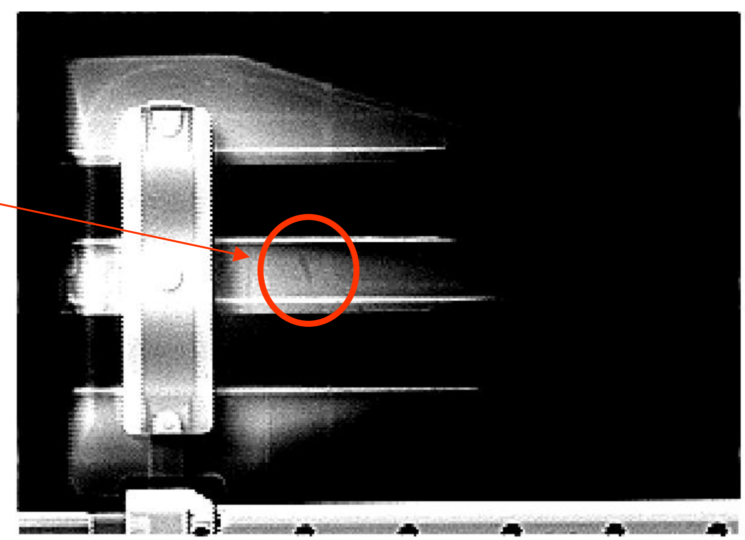
- **Example 2**
  - BSX image has distinct response from void
  - THZ image has marginal response from void

THZ image

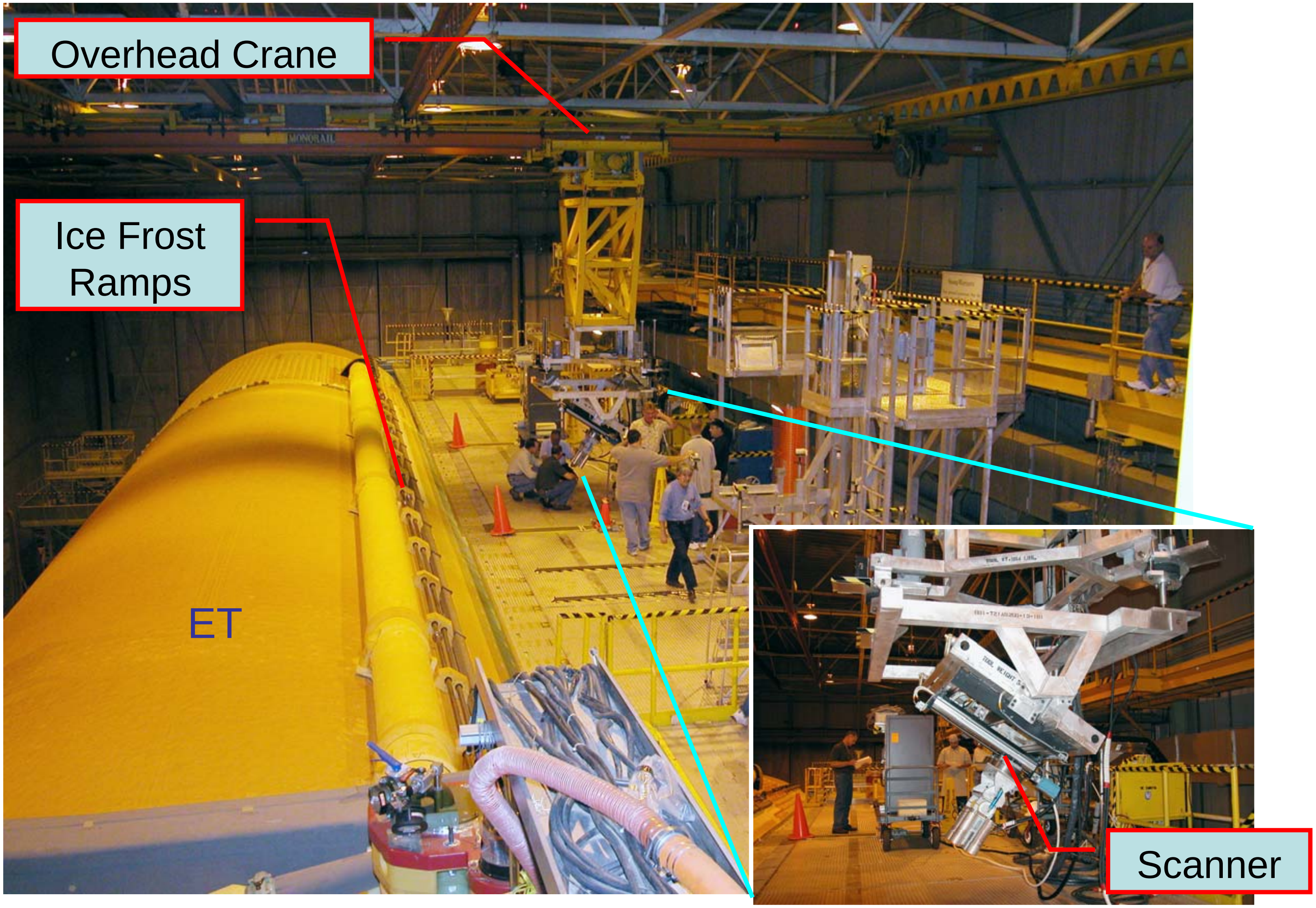




BSX image



EXTERNAL TANK FOAM INSPECTION SYSTEM



NDE Activity in Building 420 at the Michoud Assembly Facility

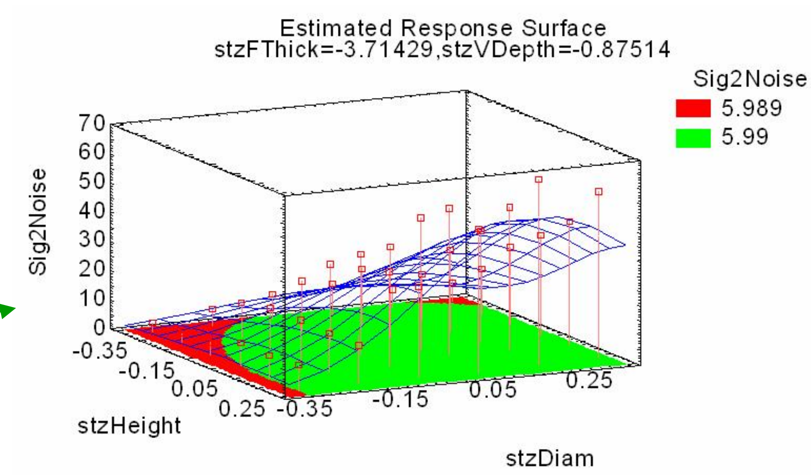
BSX/THZ POD Study

- Purpose of Probability of Detection (POD) Study
  - Statistical study used to assess performance and reliability of an NDE method
  - 90/95 detectability/confidence is common requirement in NASA, Air Force, etc.
  - BSX and THZ are used in a unique application with no existing POD history
  - POD result is necessary for future certification

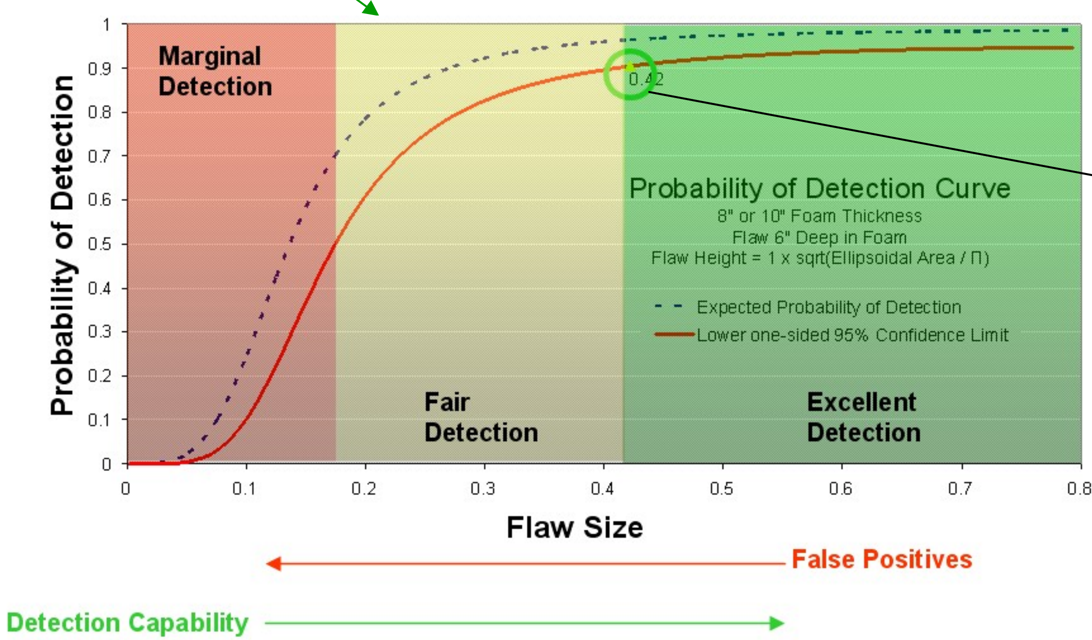
- Goals for the BSX/THZ POD Study
  - Follow guidelines in MIL-HNBK-1823
  - Follow production requirements in inspection procedure
    - BSX and THZ methods are combined for a single result
    - Certified personnel
    - Material configuration
    - Production test procedures
    - Production equipment configuration
  - Establish 90/95 POD result
    - Multiple material thicknesses
    - Multiple defect depths
    - Exceed critical defect requirement of 0.9“ by 0.4” voids
  - Establish false positive rate
  - Provide pedigree to techniques and personnel

BSX/THZ POD Study

- **POD Study Characteristics**
  - **Designed Experiment**
  - **Hit or Miss Data**
  - **Multi-Variable Logistic Regression**
  - **Cumulative Distribution Function**



Single variable versus multi-variable POD response



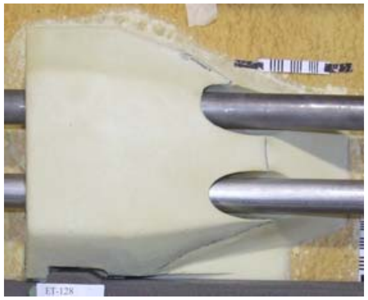
90/95 Value: Intersection of 95% confidence curve with 90% probability of detection

BSX/THZ POD Study

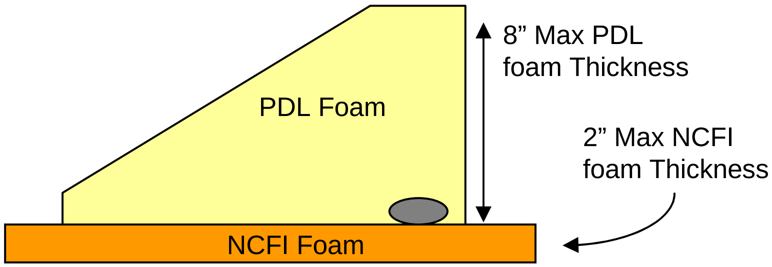
– POD Approach for BSX/THZ of Ice Frost Ramps (IFRs)

- **Test article consisted of flat blocks with inserted semi-natural defects**
- **This design allowed POD calculation for different defect depths and foam thicknesses**
- **Sample population of 400 composed of 100 defects and 300 blanks**
- **A POD sample consisted of a BSX and THZ inspection of one coupon**
- **Three interpreters analyzed the 400 samples for a total of 1200 discrete results**

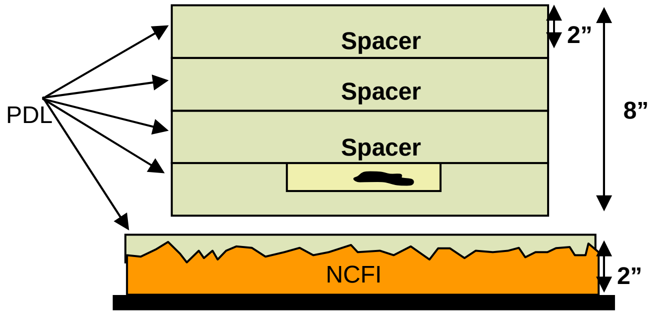
POD test article



ET Ice Frost Ramp



Key materials and dimensions

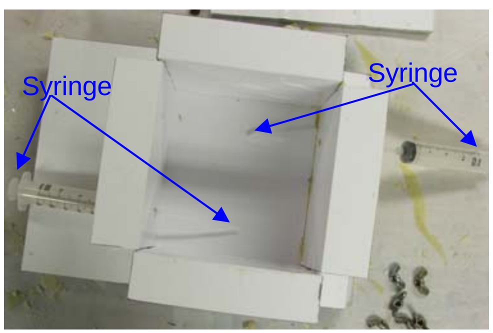


POD test article configuration

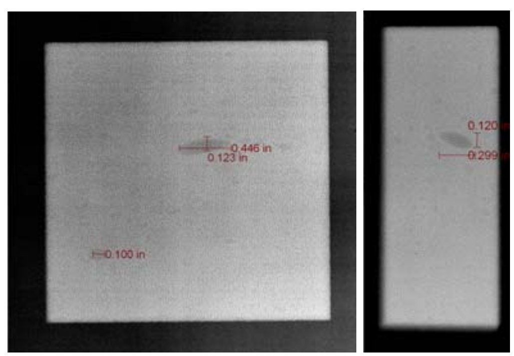
BSX/THZ POD Study

- **POD Approach for BSX/THZ of IFRs**
  - **Test matrix and experimental design:**
    - **Ken Johnson (MSFC Statistics and Trending group)**
    - **Ward Rummel (Independent Contractor)**
  - **Randomized inspection order**
  - **Interpreters were blind to sample contents**
  - **Three Level II certified radiographers evaluated data**
  - **All 400 samples were dissected to confirm defect sizes or false positives**

Coupon with defects after final dissection



Mold and syringes used to produce voids.

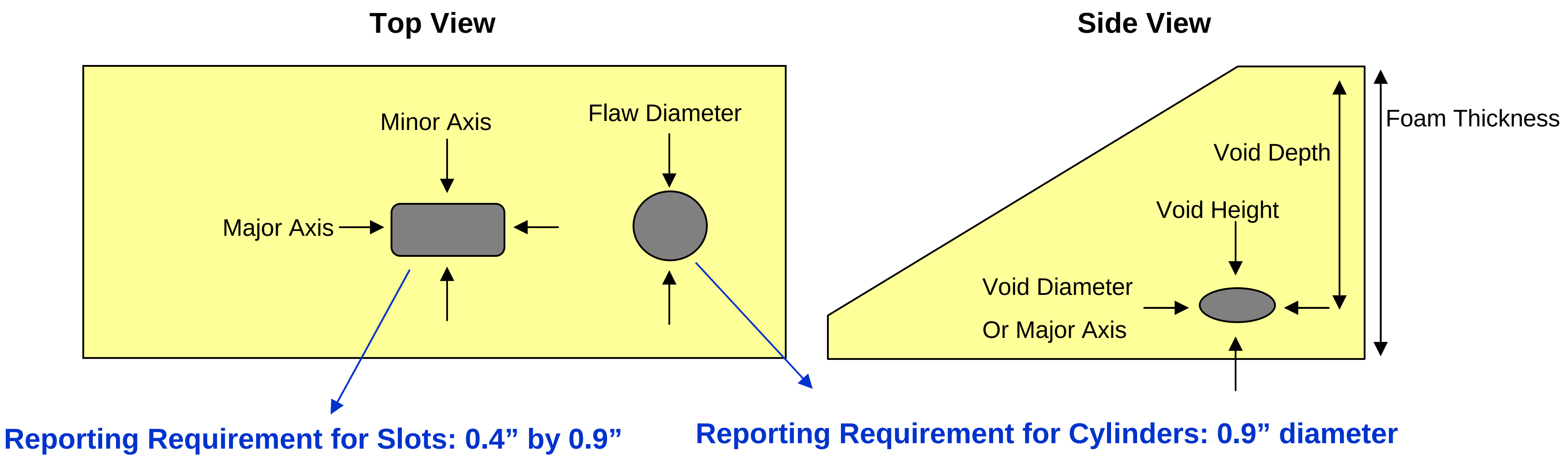


X-ray images of internal voids in coupon

Coupon with defects marked after x-ray inspection

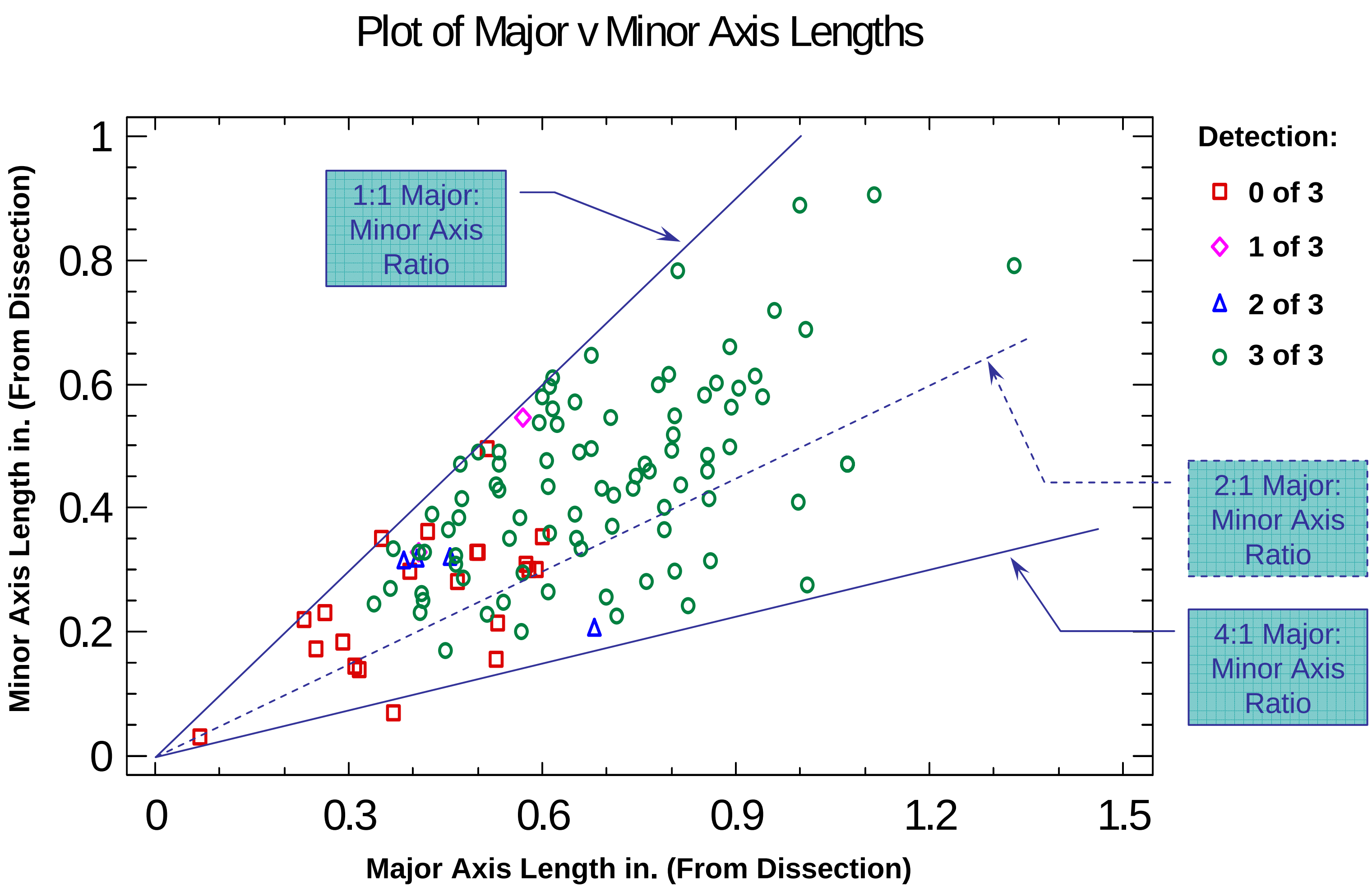
BSX/THZ POD Study

- **POD Variables**
  - **POD results are computed for multiple values of these variables**
    - **Interpreter: Three interpreters were used in the study**
    - **Foam thickness: Total foam thickness that contained the defect**
    - **Void depth: How far below the surface the void was located**
    - **Void height: Air gap or thru thickness of void**
    - **Void diameter: Diameter of cylinder void**
    - **Void major axis: Length of major axis of a slot void**



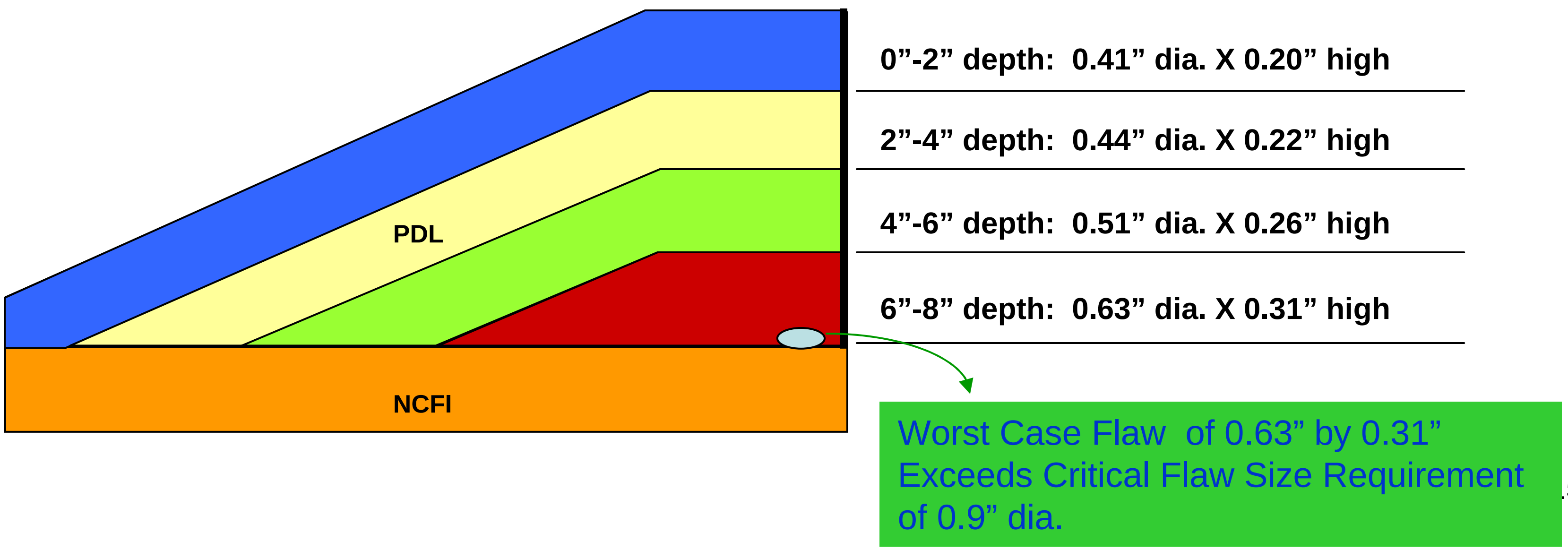
BSX/THZ POD Study

- **Observations**
  - **More elongated flaws require larger major axis dimension for detection**
  - **Thinner flaws (smaller height or thru-thickness) require larger major axis dimension for detection**
  - **Deeper flaws (under larger amounts of foam) require larger major axis dimension for detection**



- **POD Results for Combined BSX/THZ Inspection: Cylinders**

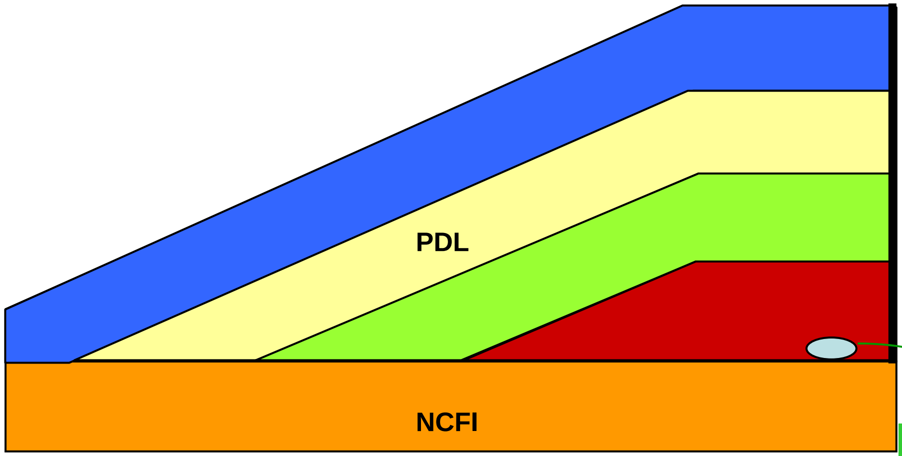
Inputs			90/95 POD Value
Foam Thickness (in)	Void Depth (in)	Flaw Height (in)	Flaw Diameter (in)
10	2	0.20	0.41
10	4	0.22	0.44
10	6	0.26	0.51
10	8	0.31	0.63



BSX/THZ POD Study

- **POD Results for Combined BSX/THZ Inspection: Slots**

Inputs			90/95 POD Value
Foam Thickness (in)	Void Depth (in)	Flaw Height (in)	Flaw Maj. Axis (in)
10	2	0.29	0.58
10	4	0.31	0.62
10	6	0.36	0.72
10	8	0.44	0.89



0”-2” depth: 0.58” major axis X 0.20” high

2”-4” depth: 0.62” major axis X 0.22” high

4”-6” depth: 0.72” major axis X 0.26” high

6”-8” depth: 0.89” major axis X 0.31” high

Worst Case Flaw of 0.89” by 0.44” Meets Critical Flaw Size Requirement of 0.9” by 0.4”

BSX/THZ POD Study

- **BSX/THZ false positive results**
  - False positive rate was approx. 0.24 per square foot or approx. one false positive per IFR
  - However, all false positives were below the reportable size of 0.4” x 0.9”
  - No false positive indications from this study would have been formally reported based on their small size

All false positives were below reportable size of 0.4” x 0.9”

Inter-preter	Spl No.	ID	Lab Cpn. No.	Foam Thickness	BSX Hit/Miss	BSX Long Axis Dim.	BSX Short Axis Dim.	THz Hit/Miss
1	023a	Blank260	62B1X	4	1	0.580	0.220	0
1	023b	Blank260	62B1X	4	1	0.250	0.180	0
1	027	Blank046	76BX	4	1	0.930	0.250	0
3	082	Blank064	191X	4	1	0.235	0.235	0
2	181b	84.625	198BX	2	1	0.480	0.140	0
2	181c	84.625	198BX	2	1	0.550	0.210	0
1	295	Blank038	334X	4	1	0.250	0.120	0
3	362a	Blank175	384B1X	6	1	0.325	0.300	0
3	362b	Blank175	384B1X	6	1	0.300	0.300	0
1	400	Blank030	444X	2	1	0.160	0.160	0
2	382	Blank101	396B1X	8	1	0.360	0.260	0
2	400	Blank030	444X	2	1	0.170	0.150	0

BSX/THZ POD Study

- **POD Summary**
  - POD Test Plan was developed following the guidelines of MIL-HNBK-1823
  - ET production procedures were used in the POD study
  - POD studies completed for combined BSX and THZ detection of voids
  - Worst case 90/95 POD value for BSX/THZ:
    - Cylinders: 0.63” diameter by 0.31” thick void under 8” of foam
    - Slots: 0.89” x 0.45” slot by 0.31” thick void under 8” of foam
  - False positive rate established
    - No false positive results at or above critical flaw size