
# Experimental Design for the Evaluation of Detection Techniques of Hidden Corrosion Beneath the Thermal Protective System of the Space Shuttle Orbiter

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# Outline

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- Problem Statement
- Current Detection Procedure
- Objective of This Study
- Approach Used For Study
- Evaluated Techniques- BSX, mm-Wave, THz
- Conclusions

# Problem Statement

- The United States Space Operational Space Shuttle Fleet Consists of three shuttles with an average age of 19.7 years
- Shuttles are exposed to corrosive conditions while undergoing final closeout for missions at the launch pad and extreme conditions during ascent, orbit, and descent that may accelerate the corrosion process.
- Structural corrosion under TPS could progress undetected (without tile removal) and eventually result in reduction in structural capability sufficient to create negative margins of safety and ultimate loss of local structural capability.

# Current Detection Procedure

- Thermal Protection System Components
  - Panels
  - Blankets
  - Tiles

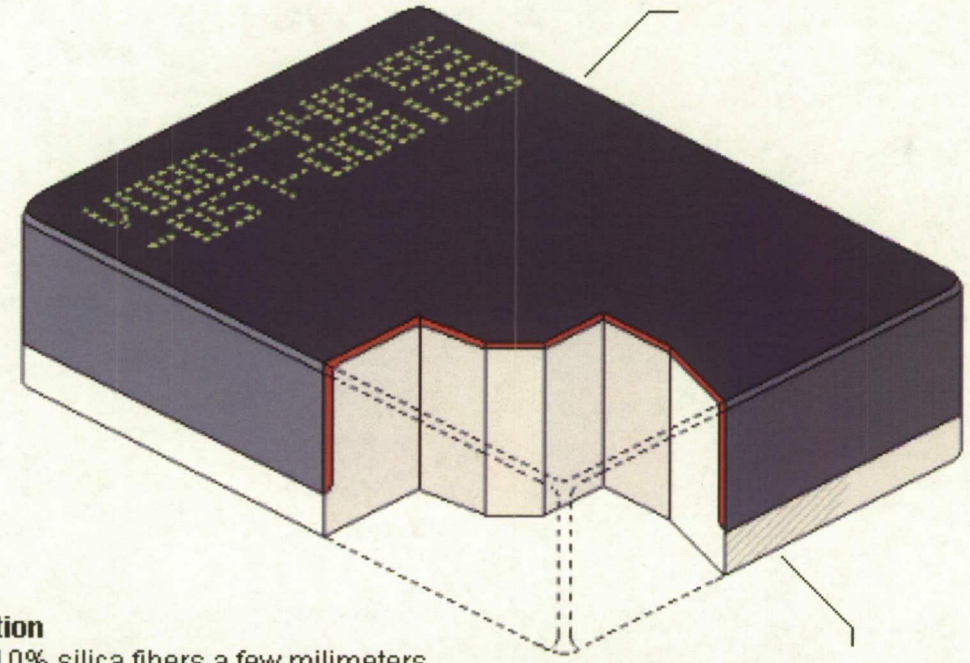
# Current Detection Procedure

1) Removal of Tile
2) Visual Inspection
3) Corrosion Rework (if applicable)
4) Corrosion Protection Reapplication
5) Rebonding of Tile

Remove Tile | Clean & Inspect Cavity | Fabricate New Tile | Install & Inspect

# High Temperature Reusable Surface Insulation

**Coating**
The outer portion of a tile is covered with a black-glazed coating of borosilicate. These tiles do most of the coating job by shedding about 95% of the heat encountered. The remaining 5% is absorbed by the tile's interior, preventing it from reaching the orbiter's aluminum skin.



**Composition**
90% air, 10% silica fibers a few milimeters thick. The tiles feels similar to plastic foam. The silica fibers are derived from high-quality sand.

**Glue**
A silicon-rubber glue similar to common bathtub caulking, bonds a tile to a felt pad, that is in turn bonded to the orbiter's skin. The felt absorbs the stresses of airframe bending that could damage the tiles.


# Objective of Study

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- Establish the ability to detect corrosion under tile without tile removal
- Determine the key factors affecting the detection process
- Roughly Quantify the Detection threshold

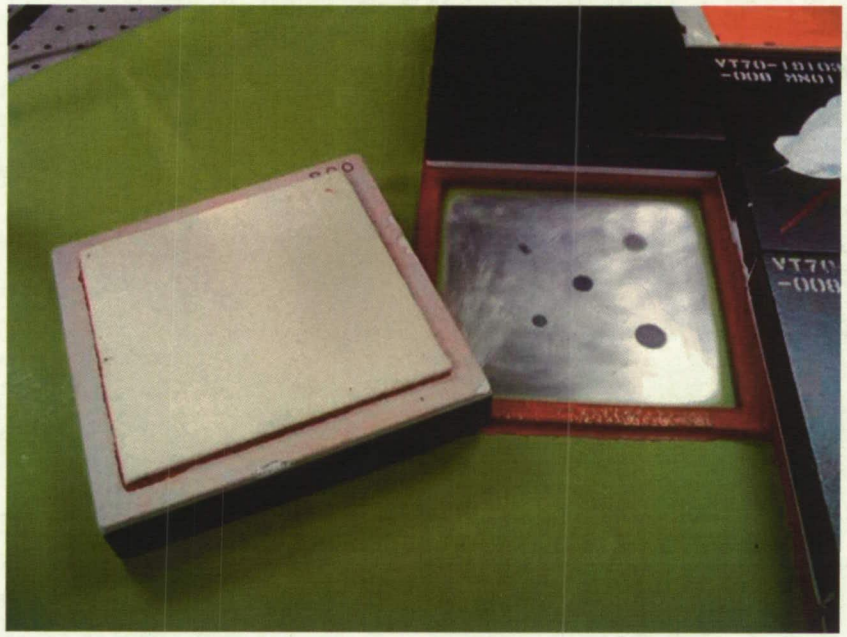
# Approach Used for Study

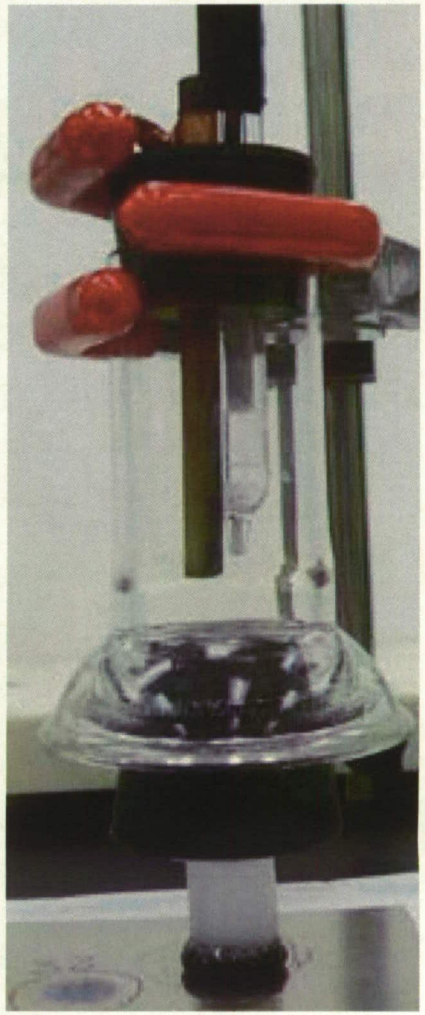
- A full factorial design with center points and replication was utilized
- The primary factors thought to affect detectability of corrosion is pit depth, diameter, or volume

| Depth \ Diameter | 0. 100” | 0. 350” | 0.600” |
|---|---|---|---|
| 0.003” | A | | B |
| 0.0115” | | E | |
| 0.020” | C | | D |

# Approach Used for Study

Two test panels were fabricated by removing tile, inducing pits of various depths and diameters, rebonding the tile back in place without removing the active corrosion

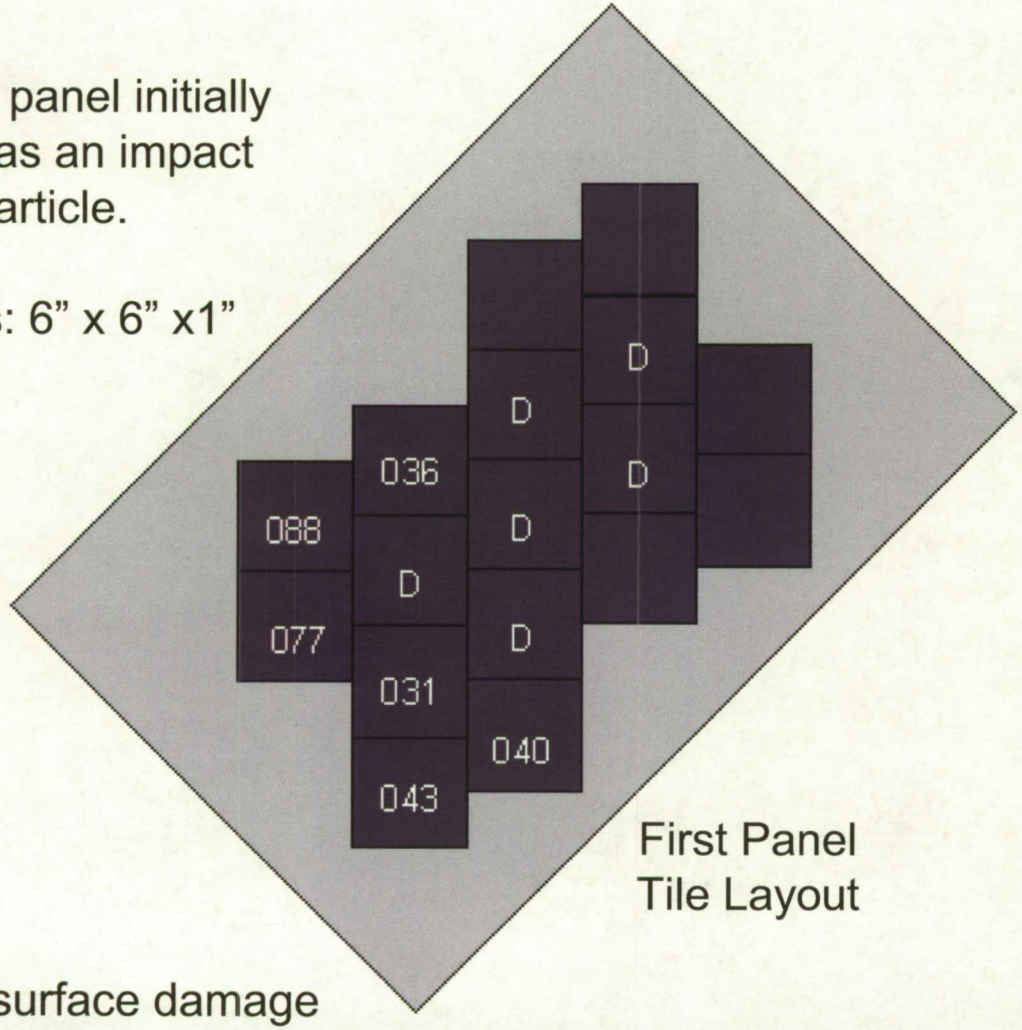




# Test Panel Layout

Test panel initially use as an impact test article.

Tiles: 6” x 6” x1”




First Panel Tile Layout

D = surface damage

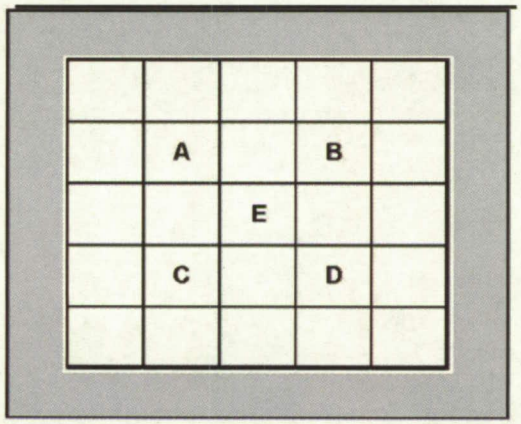
On the first panel, two tiles were removed and each had five areas of corrosion induced.

One of the tiles was re-bonded the other tile was left unattached.

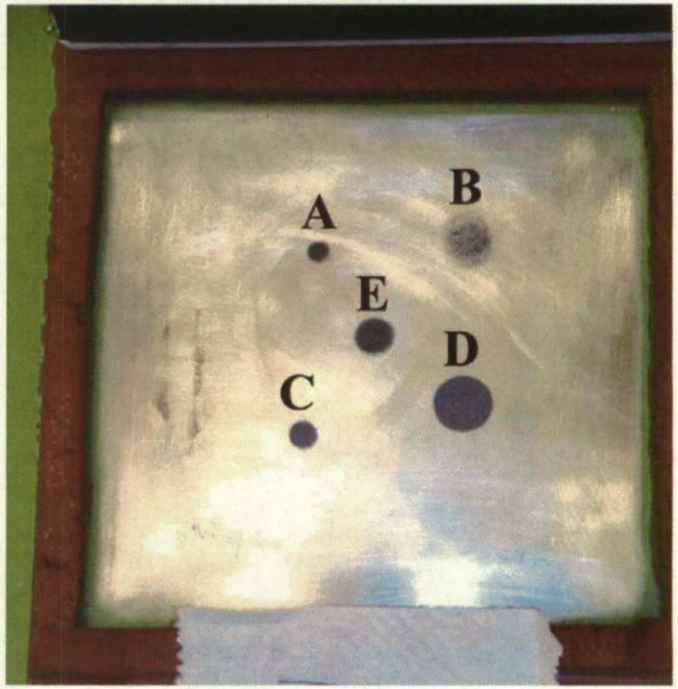
This way, the substrate could be scanned with and without a tile.

Both areas of corrosion on this panel were similar in shape and depth.

# Calibration Panel




| Pit Location | Pit Depth (inches) | Pit Diameter (inches) |
|---|---|---|
| Site A | 0.0031-0.0056 | 0.1 |
| Site B | 0.0023-0.0031 | 0.6 |
| Site C | 0.019-0.023 | 0.1 |
| Site D | 0.191-0.219 | 0.6 |
| Site E | 0.0132-0.0146 | 0.3 |

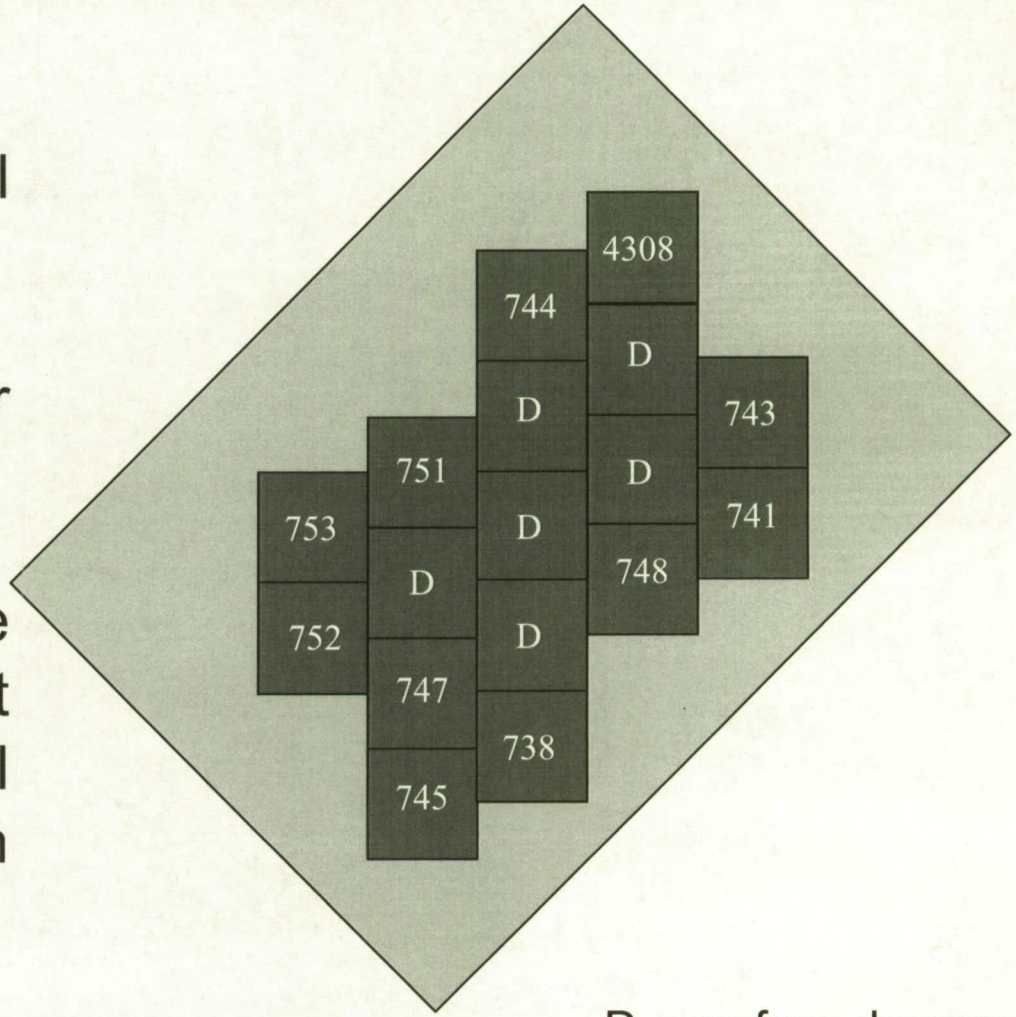


# Test Panel Layout

The second test panel was a blind test.

The panel had a similar layout as the first panel.

The tiles that were scanned have the last three digits of their serial numbers displayed on the tiles on schematic




D = surface damage

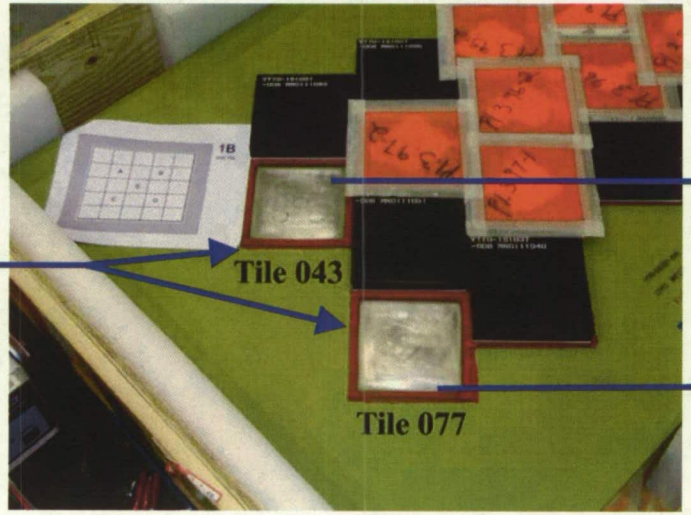
# Blind Panel

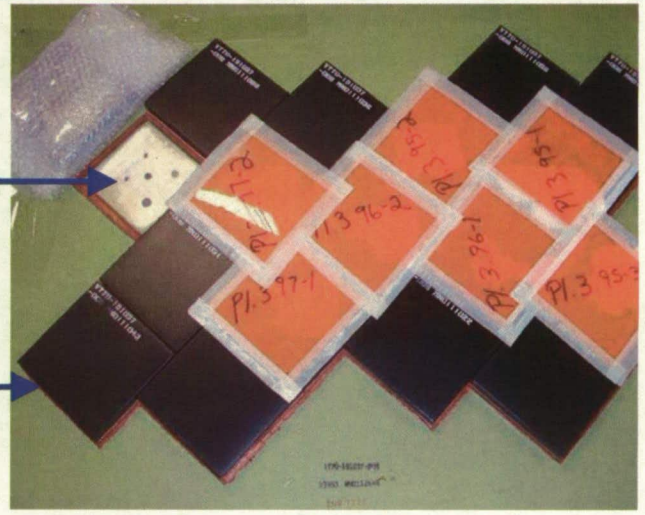

| | | | | |
|---|---|---|---|---|
| B | D | C | A | B |
| E | B | C | A | A |
| E | E | B | C | B |
| E | A | D | D | C |
| D | D | C | E | A |

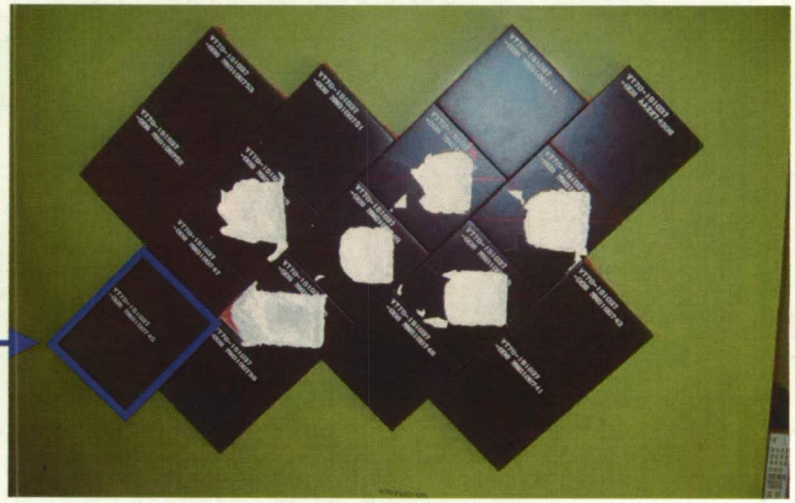
| Site | Pit | Approximate Pit Depth, inches | Pit Diameter, inches |
|---|---|---|---|
| 1 | B | 0.0015-0.0021 | 0.6 |
| 2 | D | 0.0198-0.0243 | 0.6 |
| 3 | C | 0.0144-0.0174 | 0.1 |
| 4 | A | 0.0030-0.0036 | 0.1 |
| 5 | B | 0.0014-0.0029 | 0.6 |
| 6 | E | 0.0074-0.0082 | 0.3 |
| 7 | B | 0.0021-0.0032 | 0.6 |
| 8 | C | 0.0112-0.0124 | 0.1 |
| 9 | A | 0.0022-0.0024 | 0.1 |
| 10 | A | 0.0017-0.0039 | 0.1 |
| 11 | E | 0.0043-0.0044 | 0.3 |
| 12 | E | 0.0072-0.0087 | 0.3 |
| 13 | B | 0.0018-0.0036 | 0.6 |

| Size | Pit | Approximate Pit Depth, inches | Pit Diameter, inches |
|---|---|---|---|
| 14 | C | 0.0256-0.0293 | 0.1 |
| 15 | B | 0.0018-0.0021 | 0.6 |
| 16 | E | 0.0098-0.0124 | 0.3 |
| 17 | A | 0.0033-0.0052 | 0.1 |
| 18 | D | 0.0119-0.0128 | 0.6 |
| 19 | D | 0.0085-0.0109 | 0.6 |
| 20 | C | 0.0104-0.0131 | 0.1 |
| 21 | D | 0.0199-0.0247 | 0.6 |
| 22 | D | 0.0173-0.0191 | 0.6 |
| 23 | C | 0.0117-0.0164 | 0.1 |
| 24 | E | 0.0053-0.0066 | 0.3 |
| 25 | A | 0.0025-0.0030 | 0.1 |

# Test Panel Image

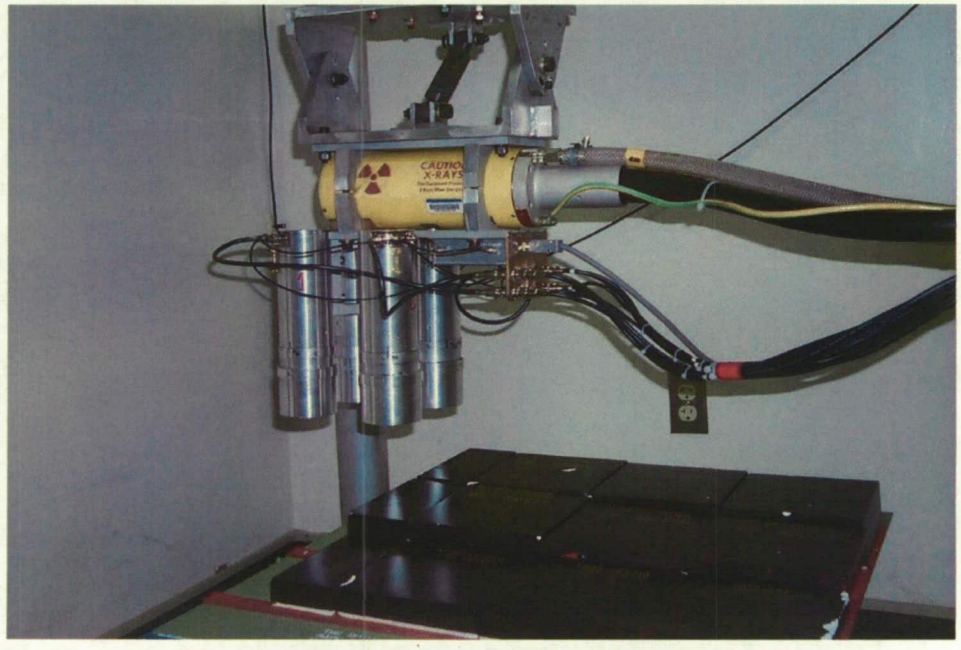


# Backscatter X-ray (BSX)

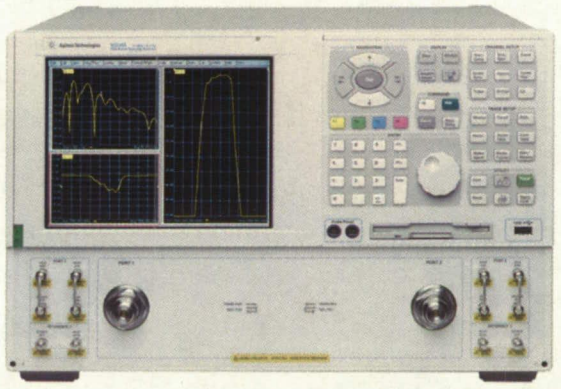
- The fundamental principle of the technique is based on Compton scattering or the inelastic scattering of x-rays.
- A collimated beam of x-rays impinges on the part and the scattered radiation is measured by detectors mounted around the source.



**MSFC BSX Imaging System**

# MM-Wave Imaging

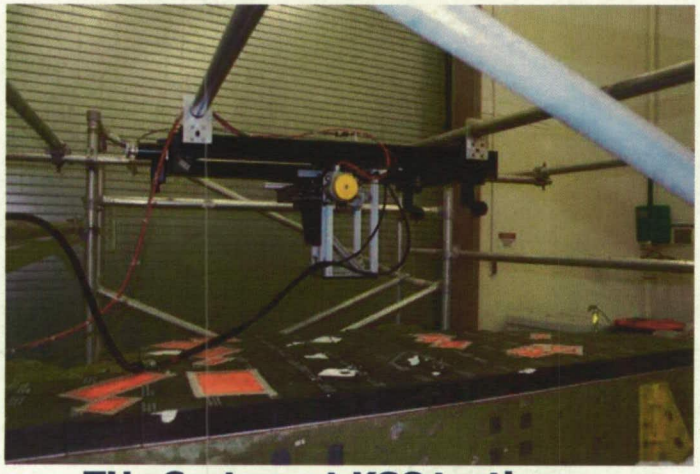
- In contrast to the BSX which operates at wavelengths of less than 1 nanometer, mm-wave imaging operates at wavelengths ranging from 1 to 10 mm
- Radio Frequency (RF) - Microwave system operates in the extremely high frequency Q-band of the electromagnetic spectrum between 30 and 300 GHz.
- System is economical and doesn't require the multitude of safety precautions that BSX requires.



**MM-Wave Imaging System at MSFC**

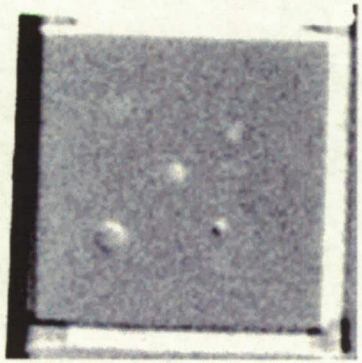
# THz Imaging

- The "Terahertz gap" forms the boundary in the electromagnetic spectrum between radio and light roughly between 300 GHz and 10 THz
- 1 Terahertz (THz) is $10^{12}$ cycles per second or 3 mm in wavelength
- Advances in opto-electric and semiconductor technology have enabled THz radiation to be economically generated and detected
- THz waves work well in NDE due to their high transparency in dielectric materials



**THz System at KSC testing an orbiter wing mockup section**

# NDE Results



55 Kv, 11.6 mA,
1.1 mm focal spot

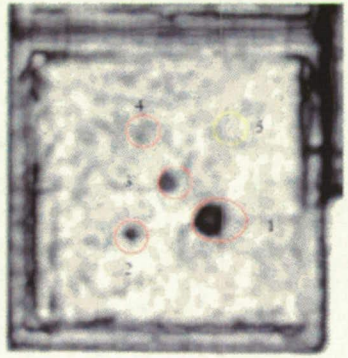
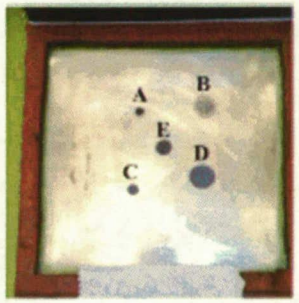
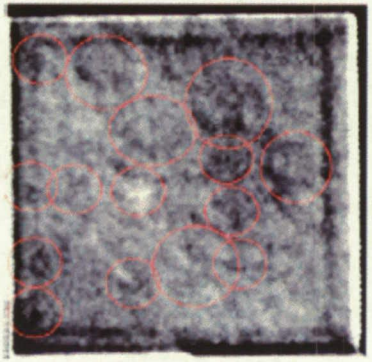
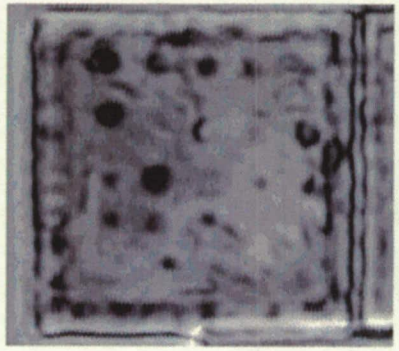


Image missing

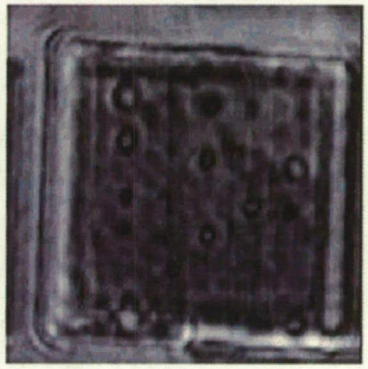


55 Kv, 40 mA,
5.5 mm focal spot



FFT at 125 GHz



Q-Band (33 to 50 GHz)

## BSX

Slow (1 hr/ft$^2$)
Poor Detection

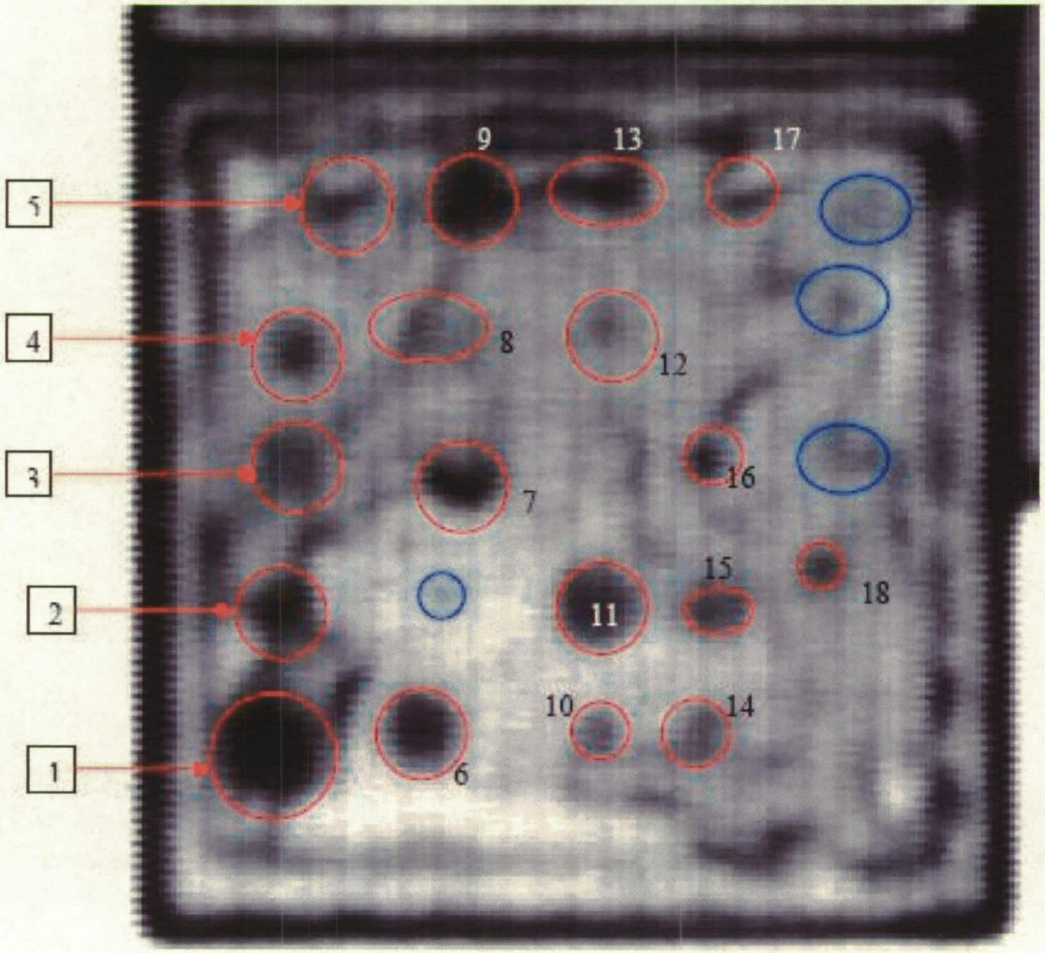
## THZ

Quick (0.5 hr/ft$^2$)
Adequate Detection

## MM-Wave (SAFT)

Slow (24hr/tile)
Not Practical (Requires moving part)

# NDE Results - Terahertz



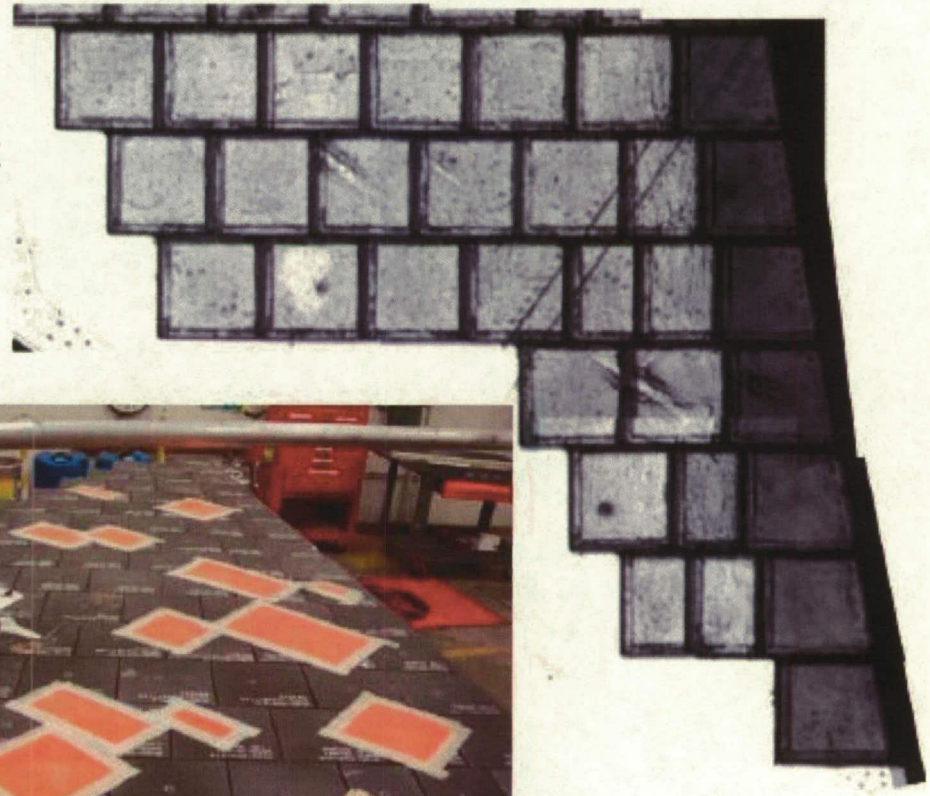

**Left:** Peak to Peak amplitude image from high resolution scan. Focus of 13" Zoom of 300%.

**Key**

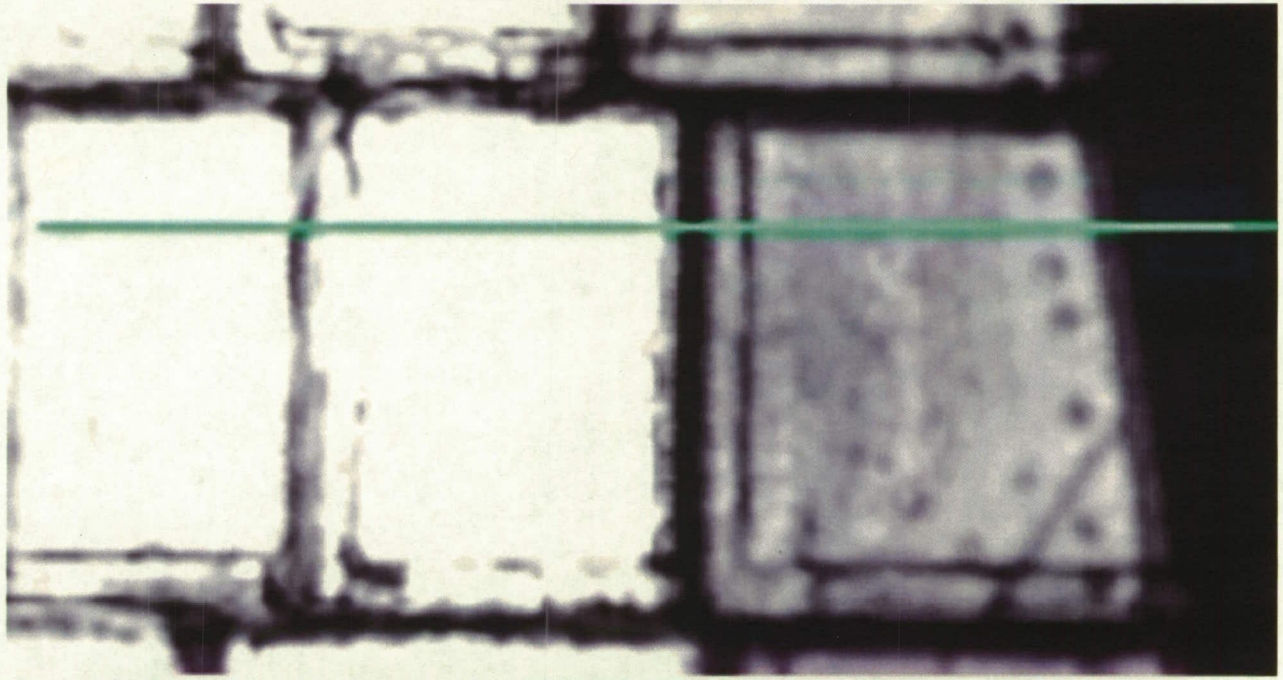
- Corrosion Indication
- Low Confidence Indication
- Indication from unknown factor

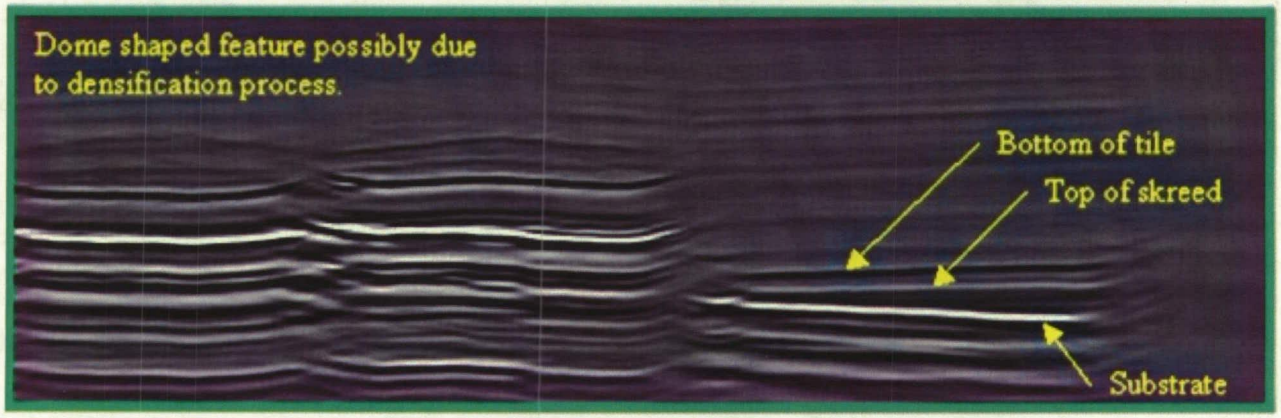
# NDE Results - Terahertz

Because of the success on the test panels, the THz System was used to scan a mock wing section



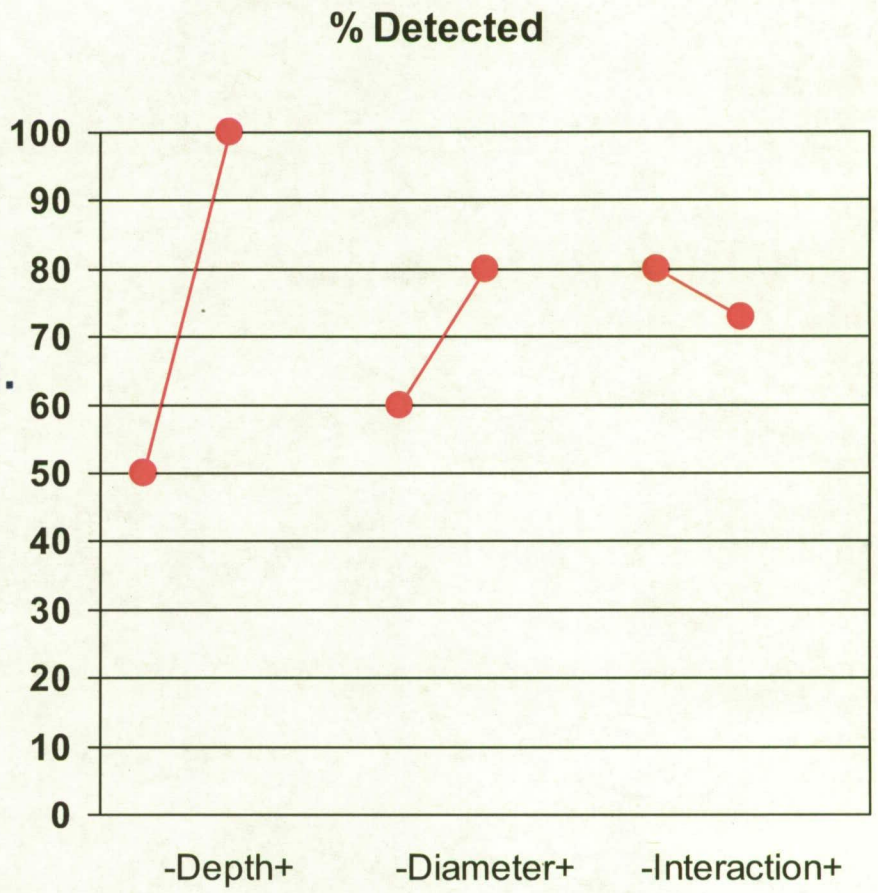
# THz Imaging Results





# Main Effects Mean Plot

- Qualitatively, the depth of the corrosion pit is the most important factor effecting the ability to detect corrosion with terahertz and millimeter imaging.
- The interaction between corrosion area depth and diameter is not a key factor.
- As expected, the greater the depth and diameter, the more detectable the area of corrosion is.




# Conclusions

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United Space Alliance

- The test panels proved to be beneficial for proof of concept testing
- Inspection of the corrosion panels showed that corrosion on bare aluminum could easily be detected, however when a tile covered the corrosion, the corroded areas were more difficult to detect.
- Detection is primarily dependant on corrosion pit depth
- Measurements and analysis indicate that artificially induced corrosion areas hidden by HRSI tile with depths greater than 0.005" are detectable with Terahertz Imaging.

# THE END

Many thanks to Eric Maderas, Steve Smith, Jeff Seebo, James Walker and Brad Regez for their NDE expertise.

# Questions or Comments?

## Experimental Design for the Evaluation of Detection Techniques of Hidden Corrosion Beneath the Thermal Protective System of the Space Shuttle Orbiter

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