

*Nondestructive Evaluation Sciences Branch*

# Thermal Inspection for the Assessment of Adhesively Bonded Metal Adherends

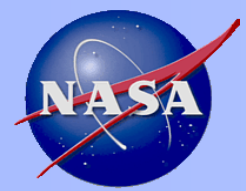
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<sup>2</sup>National Research Council, Ottawa, ON, Canada

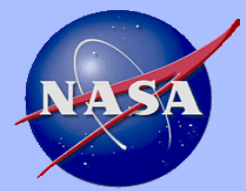
SPIE Thermosense Conference April 27 - 30, 2026



# Outline

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- Introduction
- Thermal Measurements on Single Lap Joint Samples
  - Aluminum Adherends Grit Blasted to Enhance Emissivity
  - Bonds Weakened Chemically at Bondline Interface
- Thermal Modeling and Measurement for Estimation of Bondline Thickness
  - Porosity Incorporated into Three Layer Thermal Model
  - Model Fit to Data for Estimation of Bondline Thickness
- Comparison to X-ray CT and Optical Microscopy
  - X-ray CT for Volume Fraction of Porosity and Effective Bondline Thickness
  - Optical Microscopy for Edge Bondline Thickness
- Conclusions



# Introduction

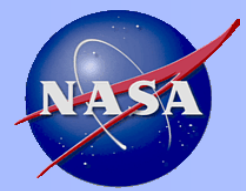
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## Background

- Bondline strength is affected by bondline thickness
- NASA developed phased based ultrasound (UT) techniques requires calibration for bondline thickness
- Investigate large area and rapid thermal inspection technique to measure bondline thickness in bonded metal adherends

## Payoffs

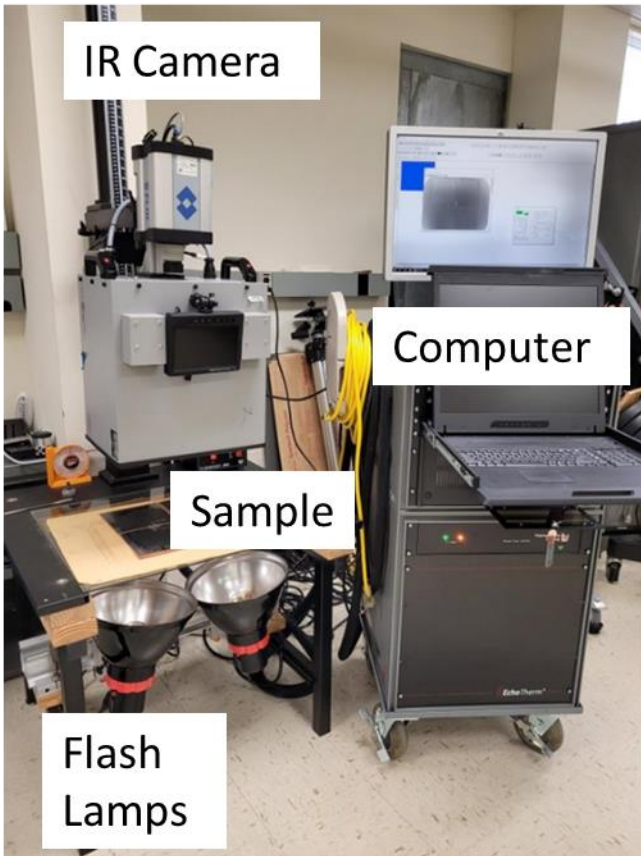
- Rapid large area nondestructive evaluation (NDE) assessment of bondline thickness
- Develop complementary NDE technique (thermal) to be used with phased based UT measurement for bond strength
- Transition thermal technique for application to bonded composites



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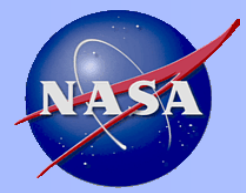
# Through Transmission Thermal Inspection Setup

## Through Transmission Thermal Inspection Setup



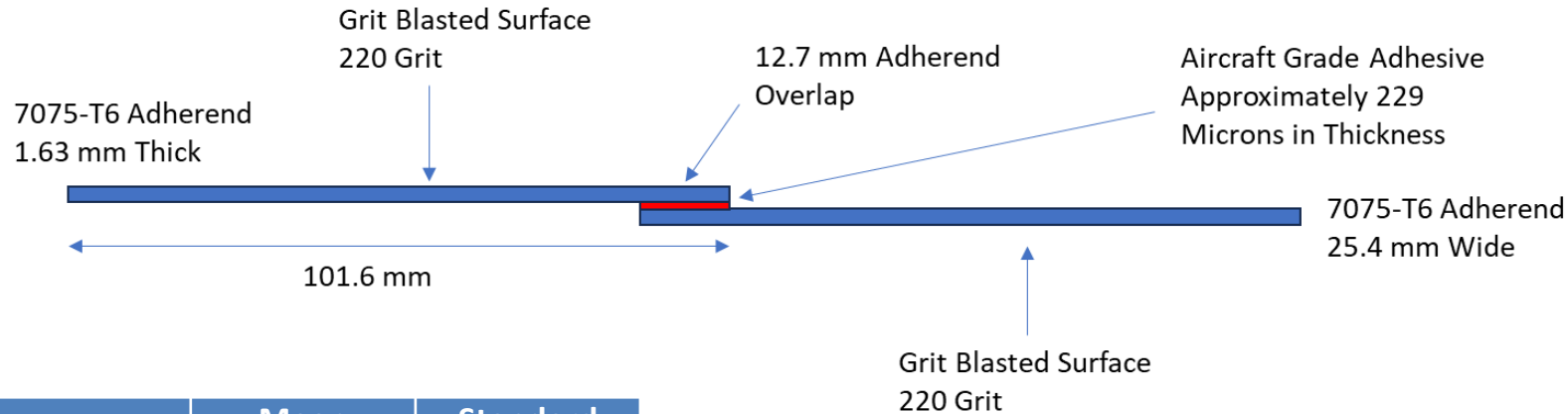
### Thermal Inspection System Specifications:

- Mid-wave Cooled Infrared Camera, 120 Hz Full Frame Acquisition (1344 x 784 Pixel Array)
- Dual 4800 Joule Flash Lamp Power Supplies
- Flash Lamp Synchronized to Data Acquisition
- Frosted Acrylic Glass Light Diffusers



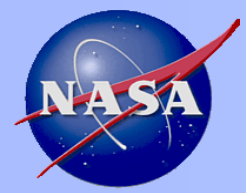
# Single Lap Joint Bonded Sample Configuration

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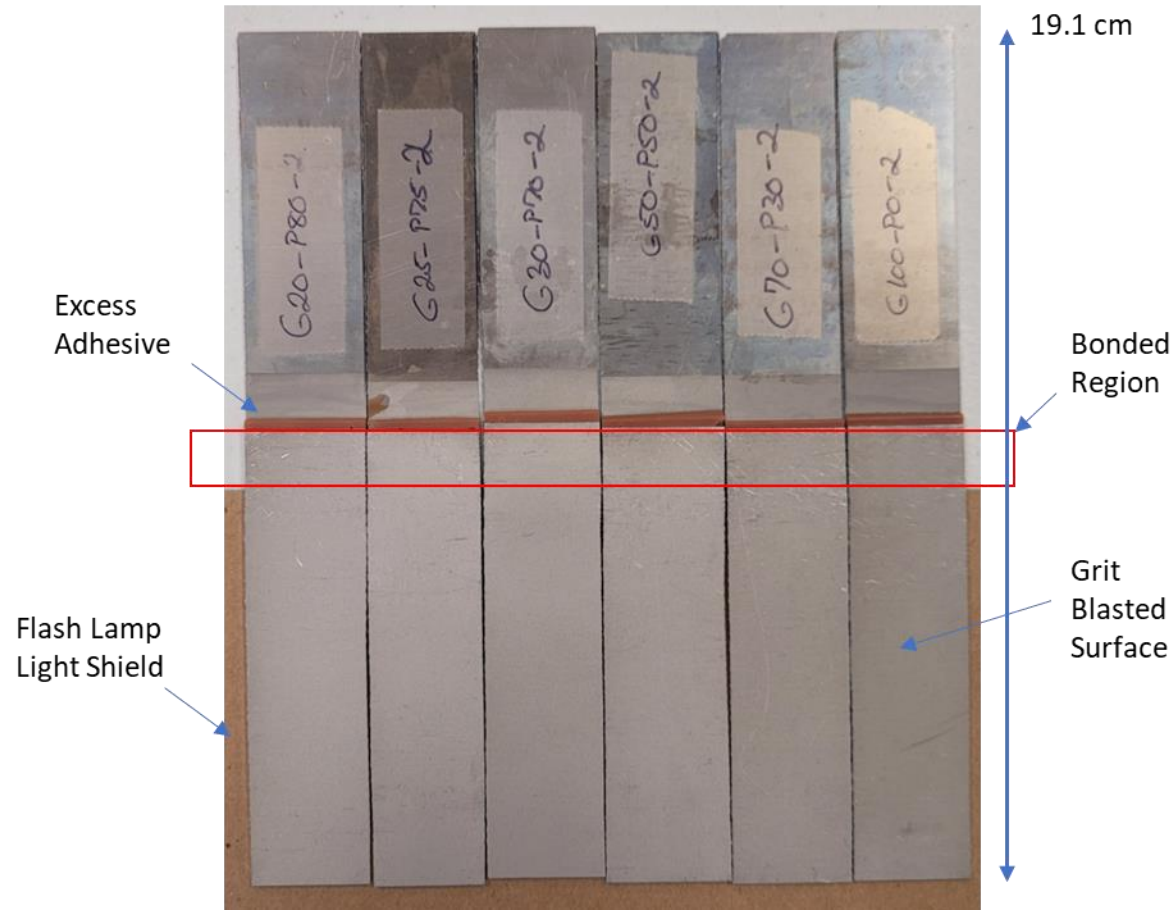
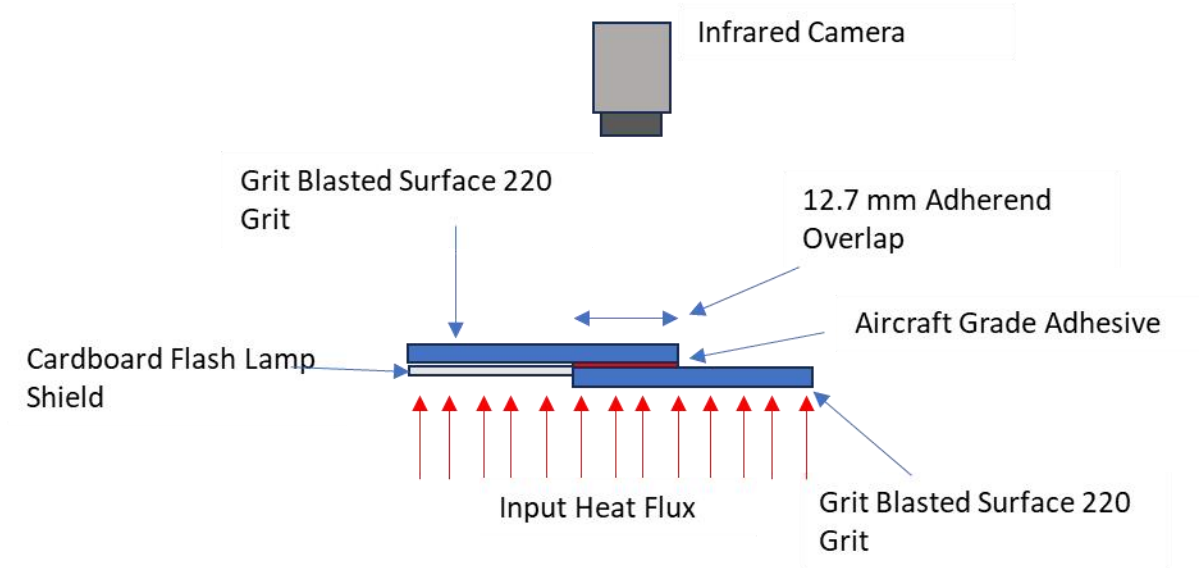
| Sample<br>G: γ-GPS (%)<br>P: PTMO (%) | Mean<br>Shear<br>Stress<br>(psi) | Standard<br>Deviation<br>(psi) |
|---------------------------------------|----------------------------------|--------------------------------|
| G100-P0                               | 4973                             | 354                            |
| G70-P30                               | 4373                             | 169                            |
| G50-P50                               | 3870                             | 262                            |
| G30-P70                               | 2162                             | 100                            |
| G25-P75                               | 1152                             | 464                            |
| G20-P80                               | 1782                             | 240                            |

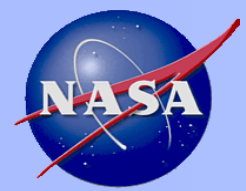
| Sample                           | Average Surface<br>Temperature (Celsius) | Measured Emissivity |
|----------------------------------|------------------------------------------|---------------------|
| Unpainted Aluminum<br>Surface    | 55.6                                     | 0.132 +/- 0.0032    |
| Grit Blasted Aluminum<br>Surface | 45.7                                     | 0.478 +/- 0.0079    |
| Painted Aluminum Surface         | 34.3                                     | 0.90 +/- 0.0080     |



# Thermal Inspection Configuration for Single Lap Joint Bonded Sample

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# Thermal Model of a Three Layer System

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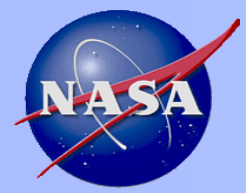
$$\begin{bmatrix} V_1 \\ 0 \end{bmatrix} = \begin{bmatrix} \cosh(q l_2) & \frac{-\sinh(q l_2)}{K q} \\ -K q \sinh(q l_2) & \cosh(q l_2) \end{bmatrix} \begin{bmatrix} \cosh(q_a l_a) & \frac{-\sinh(q_a l_a)}{K_a q_a} \\ -K_a q_a \sinh(q_a l_a) & \cosh(q_a l_a) \end{bmatrix} \begin{bmatrix} \cosh(q l_1) & \frac{-\sinh(q l_1)}{K q} \\ -K q \sinh(q l_1) & \cosh(q l_1) \end{bmatrix} \begin{bmatrix} V_0 \\ F \end{bmatrix}$$

$$q = \sqrt{s/\alpha} \quad q_a = \sqrt{s/\alpha_a}$$

$$V_1(s) = \frac{\alpha K_a F}{(\alpha K_a \cosh[l_2 \sqrt{\frac{s}{\alpha}}] (K \sqrt{\frac{s}{\alpha}} \cosh[l_a \sqrt{\frac{s}{\alpha_a}}] \sinh[l_1 \sqrt{\frac{s}{\alpha}}] + K_a \sqrt{\frac{s}{\alpha_a}} \cosh[l_1 \sqrt{\frac{s}{\alpha}}] \sinh[l_a \sqrt{\frac{s}{\alpha_a}}]) + K \sinh[l_2 \sqrt{\frac{s}{\alpha}}] (\alpha K_a \sqrt{\frac{s}{\alpha}} \cosh[l_1 \sqrt{\frac{s}{\alpha}}] \cosh[l_a \sqrt{\frac{s}{\alpha_a}}] + \alpha_a K \sqrt{\frac{s}{\alpha_a}} \sinh[l_1 \sqrt{\frac{s}{\alpha}}] \sinh[l_a \sqrt{\frac{s}{\alpha_a}}]))}$$

$$K_a = K_{adhesive} (1 - \sqrt{Pore_{Fraction}}) + \frac{K_{adhesive} \sqrt{Pore_{Fraction}}}{(1 - \sqrt{Pore_{Fraction}}) (1 - \frac{K_{adhesive}}{K_{pore}})}$$

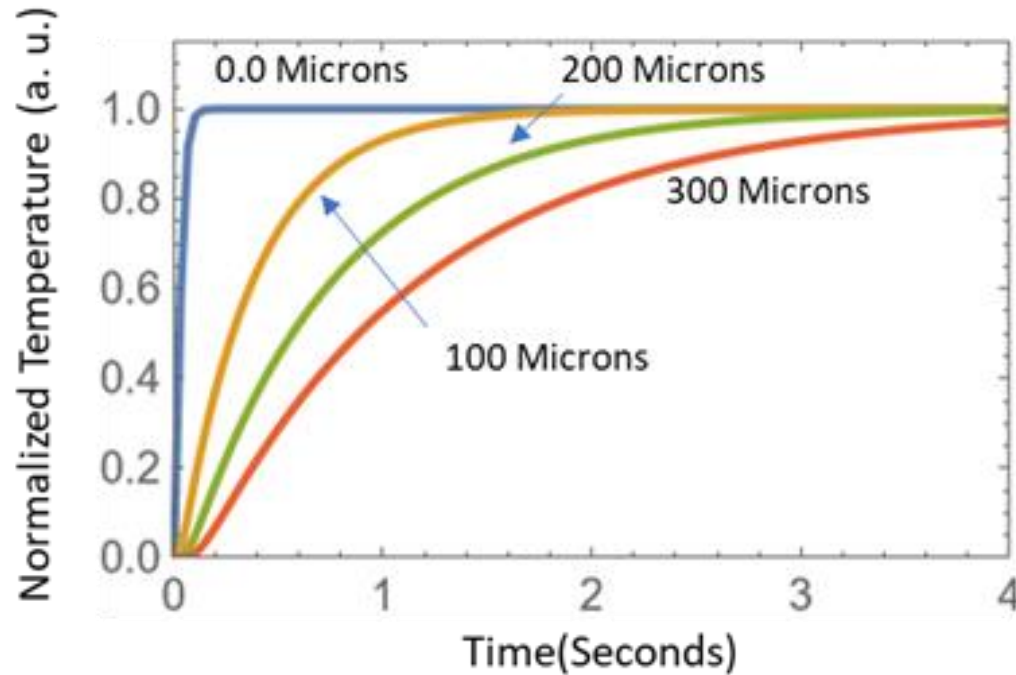
- Model assumes perfect thermal contact between the layers and no convection losses



# Thermal Model for Bondline Thickness

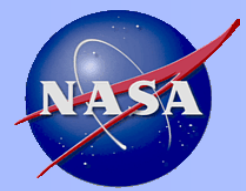
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Through Transmission Thermal Model Results



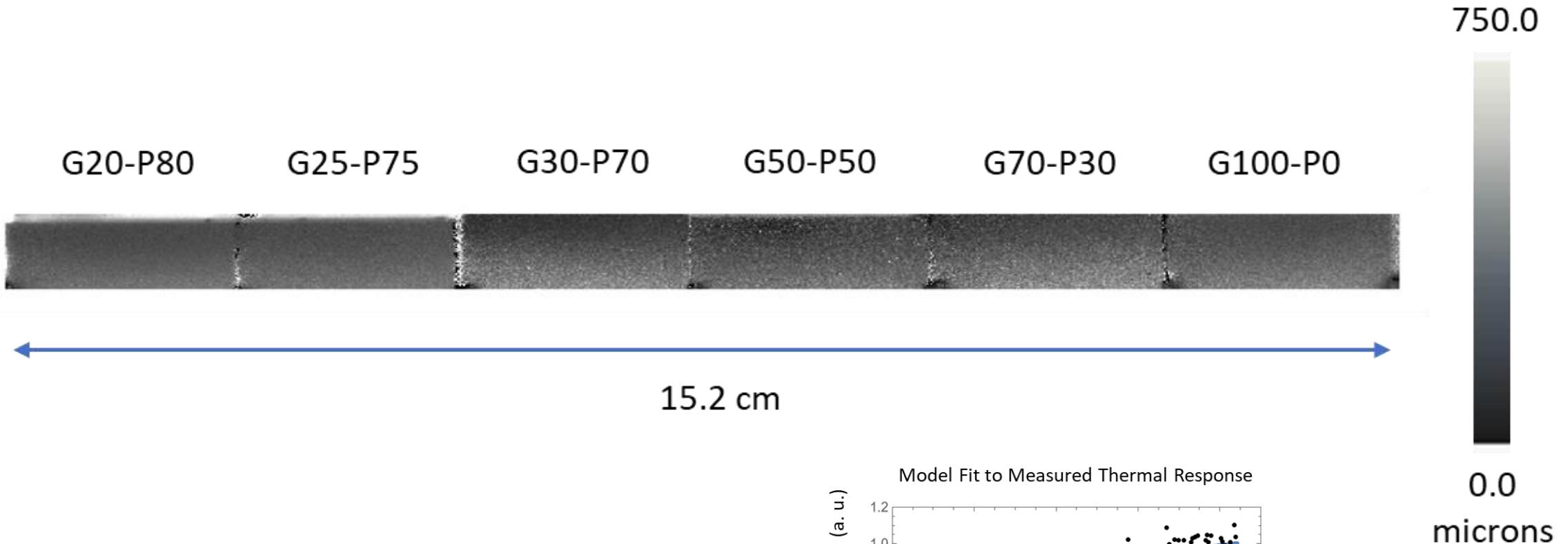
| Bond Line Thickness (microns) | Approximate Time to Reach Maximum Steady State Temperature (seconds) |
|-------------------------------|----------------------------------------------------------------------|
| 0.0                           | 0.2                                                                  |
| 100                           | 1.5                                                                  |
| 200                           | 3.0                                                                  |
| 300                           | 4.5                                                                  |

- Large difference in the thermal diffusivity between the adherends (aluminum) and the adhesive (approximately 400 times)

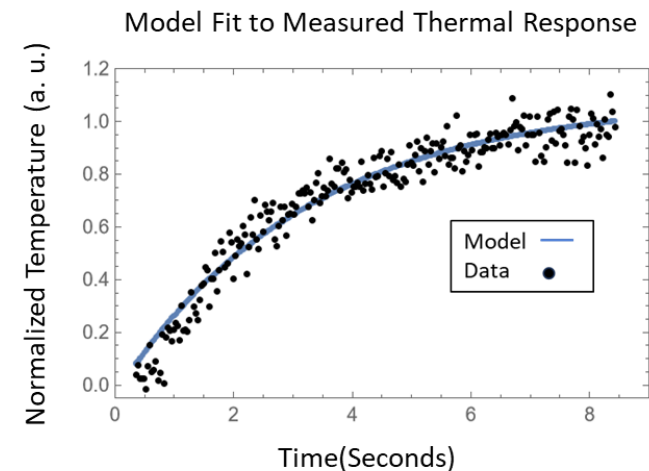


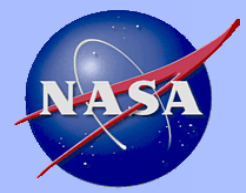
# Thermal Estimation of Bondline Thickness

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- Model is fitted to data pixel by pixel





# Thermal Estimation of Thickness with Histogram Distribution

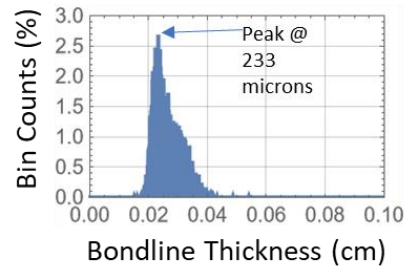
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G20-P80 Thermal Thickness Image G25-P75 Thermal Thickness Image G30-P70 Thermal Thickness Image

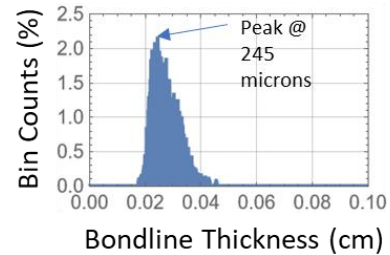


21.0 mm

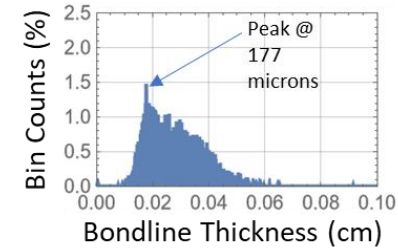
Bondline Thickness Histogram



Bondline Thickness Histogram



Bondline Thickness Histogram

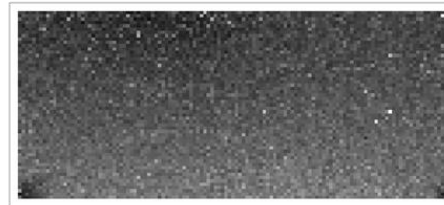
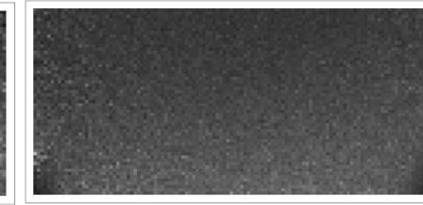


750.0

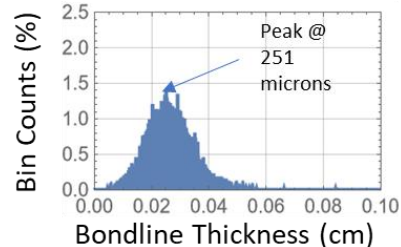


0.0 microns

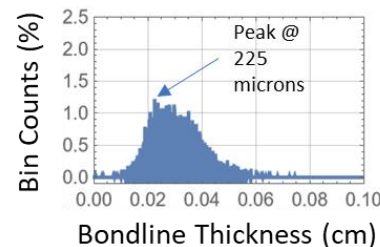
G50-P50 Thermal Thickness Image G70-P30 Thermal Thickness Image G100-P0 Thermal Thickness Image



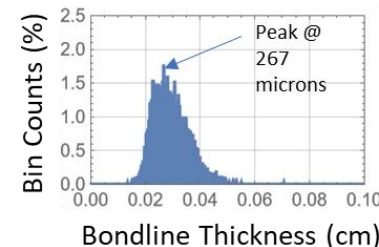
Bondline Thickness Histogram

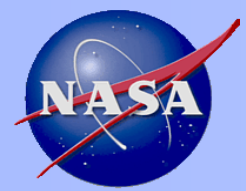


Bondline Thickness Histogram



Bondline Thickness Histogram



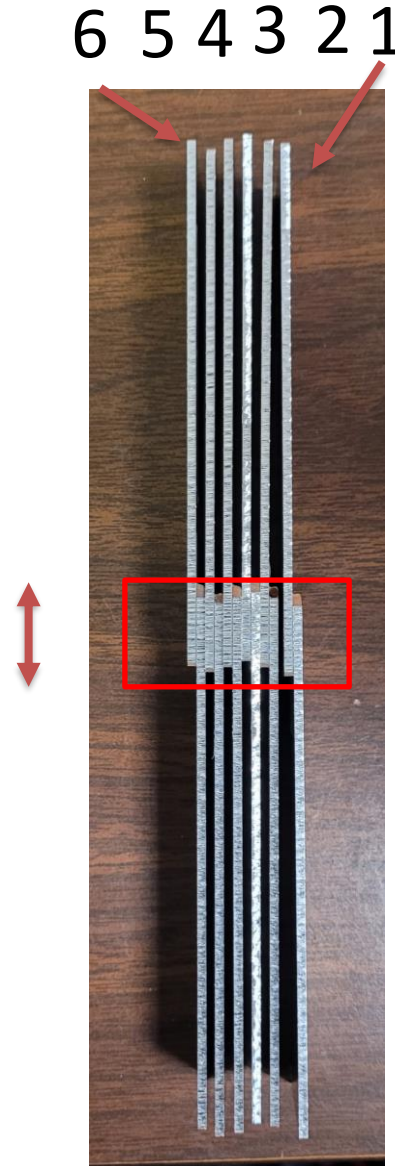


# Configuration for X-ray CT Measurements

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## Full Stack X-ray CT Scan Orientation

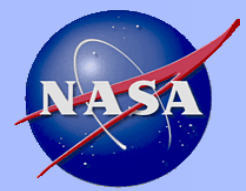
Scan Volume:  
2.54 cm<sup>3</sup>,  
Resolution  
approx. 19.9  
microns per  
voxel in X, Y,  
and Z.



### Key

- 1: G20-P80-2
- 2: G25-P75-2
- 3: G30-P70-2
- 4: G50-P50-2
- 5: G70-P30-2
- 6: G100-P0--2

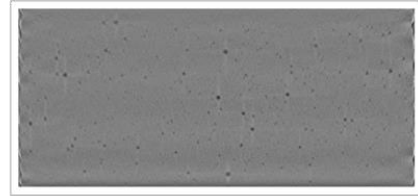
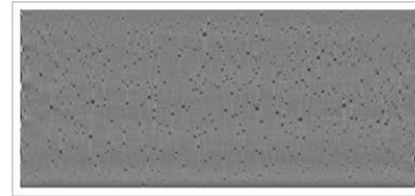
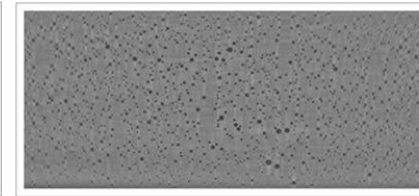
X-ray Detector  
Side



# X-ray CT for Bondline Porosity Assessment

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G20-P80 Averaged X-ray CT Image   G25-P75 Averaged X-ray CT Image   G30-P70 Averaged X-ray CT Image

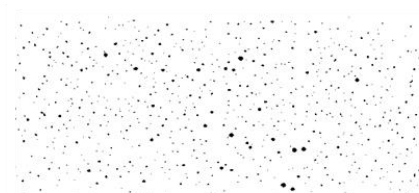


21.0 mm

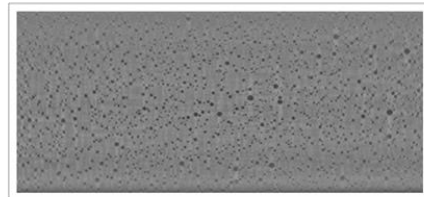
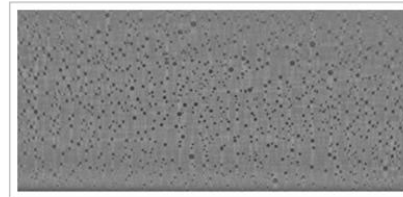
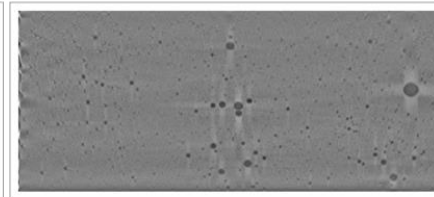
G20-P80 Segmented X-ray CT  
Image, Porosity 1.00%

G25-P75 Segmented X-ray CT  
Image, Porosity 3.18%

G30-P70 Segmented X-ray CT  
Image, Porosity 6.93%



G50-P50 Averaged X-ray CT Image   G70-P30 Averaged X-ray CT Image   G100-P0 Averaged X-ray CT Image

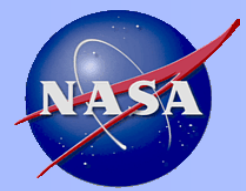


G50-P50 Segmented X-ray CT  
Image, Porosity 7.91%

G70-P30 Segmented X-ray CT  
Image, Porosity 7.48%

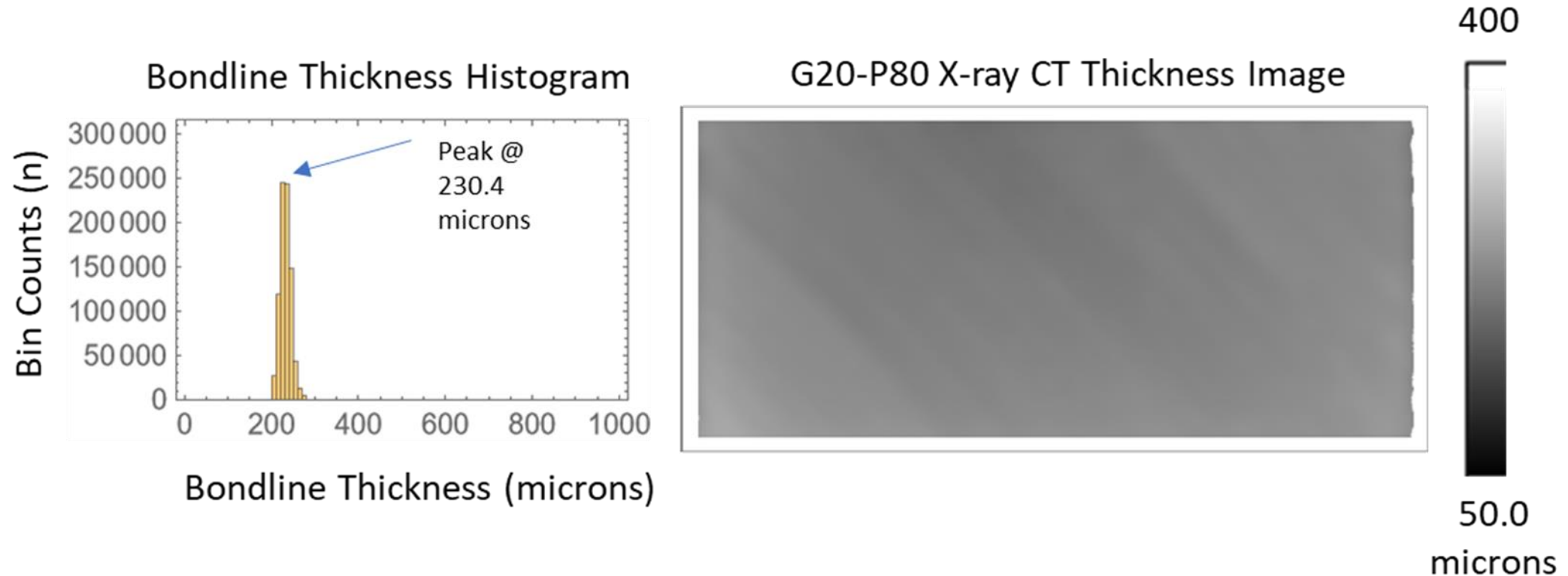
G100-P0 Segmented X-ray CT  
Image, Porosity 2.51%



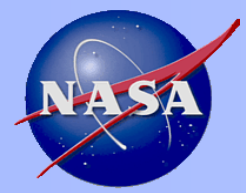


# X-ray CT for Bondline Effective Thickness

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- X-ray CT segmentation differentiates between the adherend, porosity, and adhesive for effective bondline thickness measurement.



# Comparison of X-ray CT to Thermal NDE for Estimation of Bondline Thickness

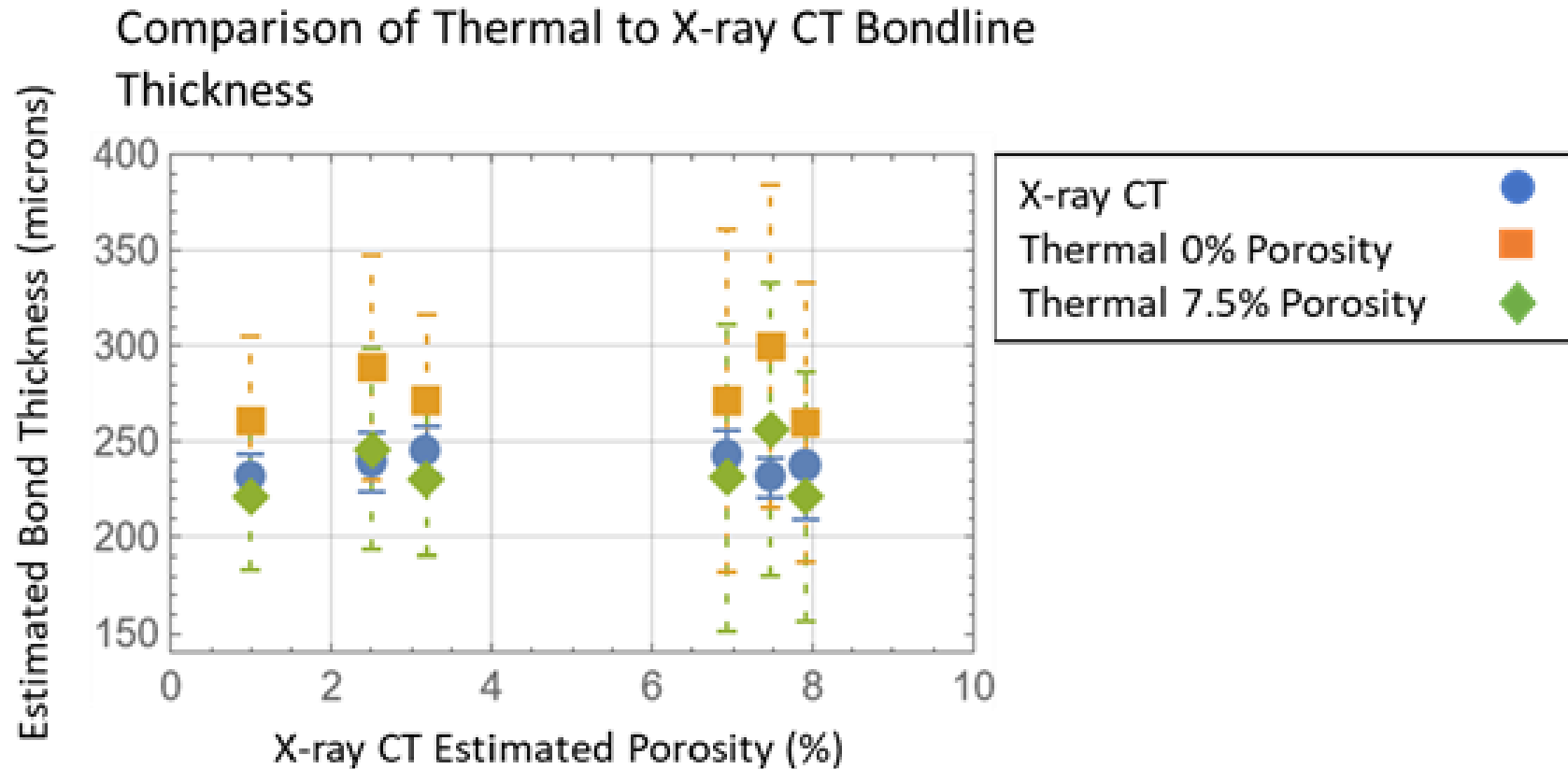
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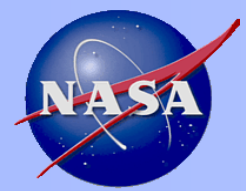
| Sample  | X-ray CT Thickness Mode 1 Histogram Value (microns) | X-ray CT Thickness Mean and Standard Deviation (microns) | X-ray CT Volume Porosity (percent) | Thermal Thickness Mode 1 Histogram Value (microns) 0% Porosity | Thermal Thickness Mean and Standard Deviation (microns) 0% Porosity | Thermal Thickness Mode 1 Histogram Value (microns) 7.5% Porosity | Thermal Thickness Mean and Standard Deviation (microns) 7.5% Porosity |
|---------|-----------------------------------------------------|----------------------------------------------------------|------------------------------------|----------------------------------------------------------------|---------------------------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------------|
| G100-P0 | 246.7                                               | 239.5 +/-15.6                                            | 2.51                               | 265.4                                                          | 288.8+/-58.6                                                        | 213.4                                                            | 246.0+/-52.6                                                          |
| G70-P30 | 240.0                                               | 231.5 +/-10.5                                            | 7.48                               | 273.3                                                          | 299.7 +/-84.4                                                       | 215.8                                                            | 256.6 +/-76.7                                                         |
| G50-P50 | 239.2                                               | 237.4 +/-28.4                                            | 7.91                               | 251.2                                                          | 260.2 +/-72.5                                                       | 210.2                                                            | 221.5 +/-64.9                                                         |
| G30-P70 | 244.1                                               | 242.8 +/-13.1                                            | 6.93                               | 191.3                                                          | 271.4 +/-89.4                                                       | 151.5                                                            | 231.6 +/-80.1                                                         |
| G25-P75 | 241.6                                               | 245.5 +/-12.2                                            | 3.18                               | 241.8                                                          | 271.6 +/-44.7                                                       | 208.7                                                            | 230.4 +/-39.5                                                         |
| G20-P80 | 230.4                                               | 231.5 +/-14.1                                            | 1.00                               | 234.9                                                          | 261.0 +/-43.5                                                       | 194.5                                                            | 221.3+/-38.3                                                          |



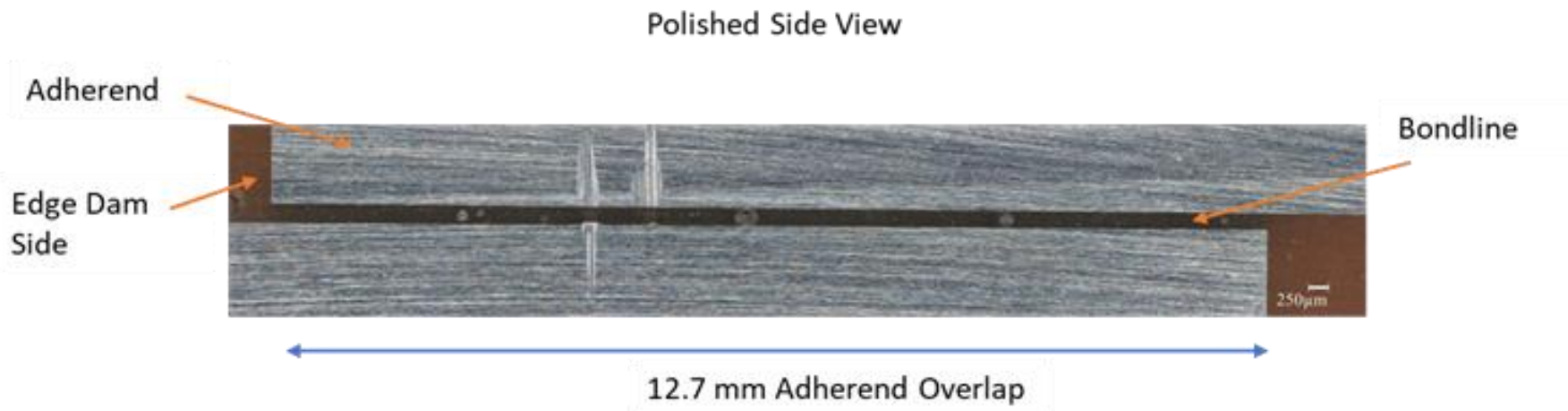
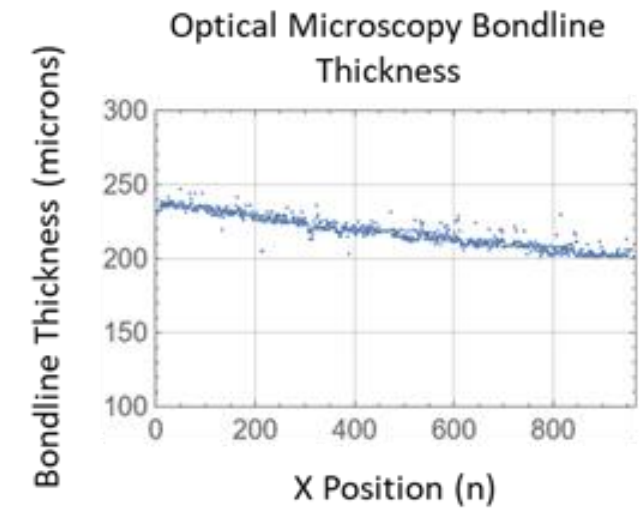
# Comparison of X-ray CT to Thermal for Estimation of Bondline Thickness vs X-ray CT Porosity

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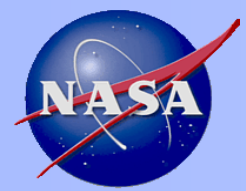




# Optical Microscopy Bondline Porosity Assessment



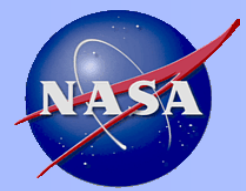
- Optical microscopy performed on all six samples and revealed similar increasing bondline thickness



# Conclusions

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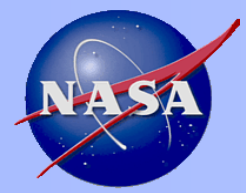
- A thermal inspection methodology is presented that can measure effective bondline thickness in bonded metal adherends
- The thermal measurements for bondline thickness is affected by porosity in the bondline
- A wide distribution of thermally measured bondline thickness can be a possible indicator of porosity in the bondline.
- Small variations in the thermally measured bondline thickness were detected for thickness values varying from approximately 200 to 240 microns
- Spatially mapping the X-ray CT measurements to correct for porosity would be an ideal next step



# Acknowledgements

*Nondestructive Evaluation Sciences Branch*

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- NASA Transformational Tools and Technologies Project and the Transformative Aeronautics Concepts Program for support of this work
- Additionally, thanks to Richard Desnoyers, Sandra Robertson and Derek Winfield of National Research Council for single lap joint sample fabrication



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# Any Questions?