Lockheed Martin TRUST Program Overview:

A Path to Certified Bonded Aircraft through Bond Process Control

Brietta Oakley
Lockheed Martin

19 July, 2022

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

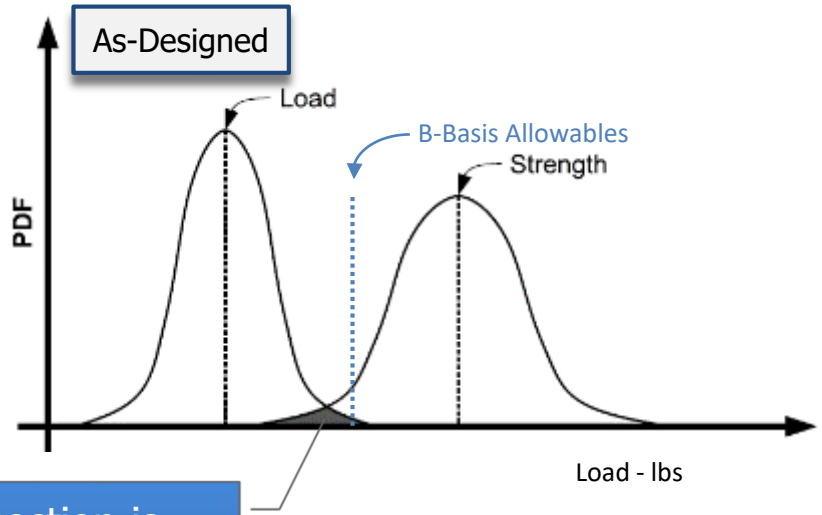
Birth of TRUST: **T**ransition to **R**eliable **U**nitized **St**ructure

Blah Blah Blah…**JSSG Certification of Bonded Structure**…Blah Blah Blah

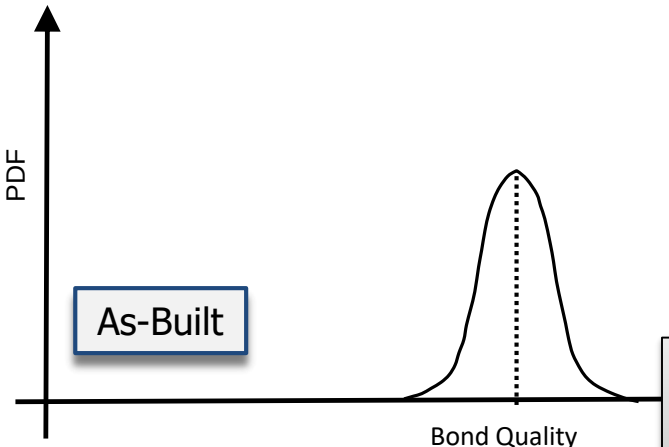
All this talk about Certification assumes you have Process control First!

LM Presenting to NAVAIR at Pax River

TRUST Framework Quantifies Manufacturing Process Reliability, Assuring Engineering Integrity



Intersection is Structural Failure



Traditional Calculation:

Strength ~ $F_{(G, E, T, M)}$

G: Geometry
E: Environment
T: Mfg Tolerances
M: Material Properties

TRUST Enables:

Strength ~ $F_{(G, E, T, M \& P)}$

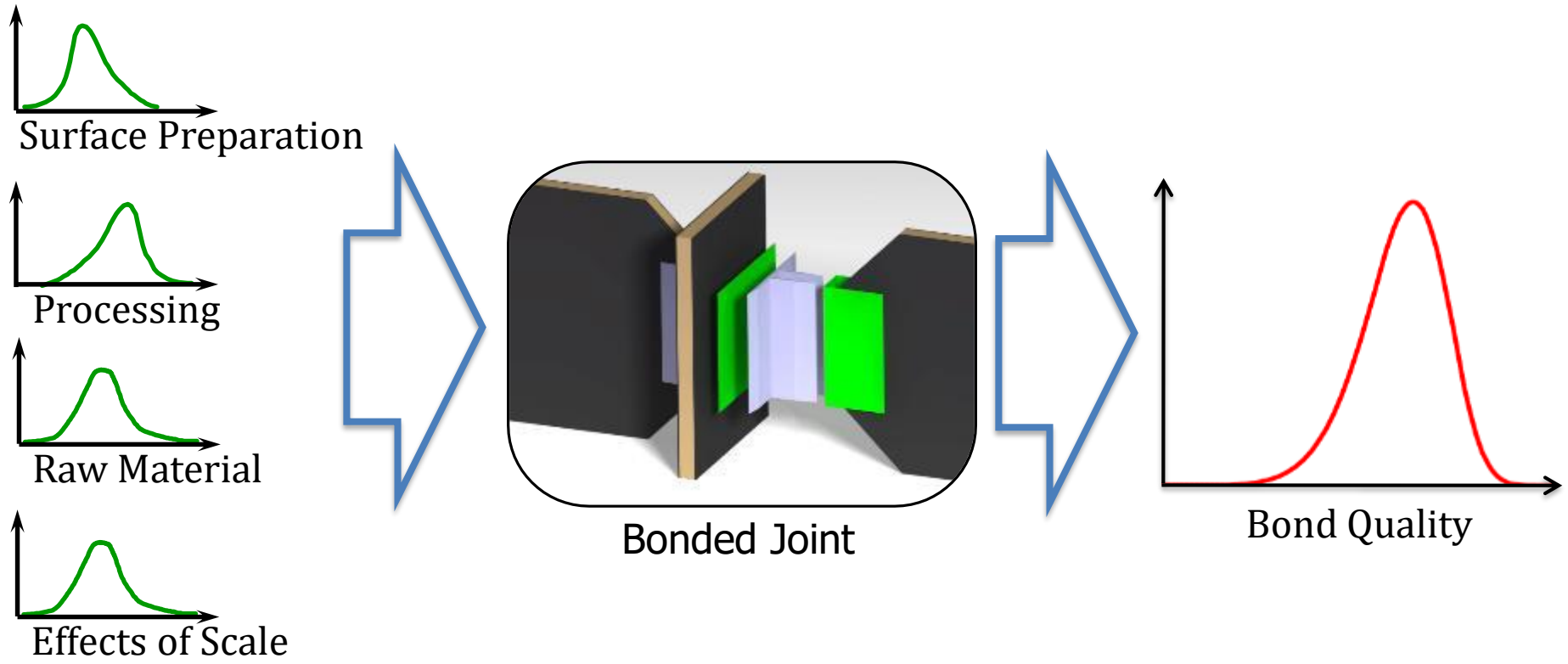
P: Process Control

Process Reliability Protects the Product
(As-Built ≥ As-Designed)

Skunk Works

Quantifying Bond Quality

TRUST Objective: Create a model to predict bond quality



Reduce and quantify process uncertainty
Prevent the rogue weak bond

Skunk Works

Three Phases of TRUST

Phase I: Make A Model

Prove the Ability to *Quantify* Bond Reliability

Phase II: Develop a Framework

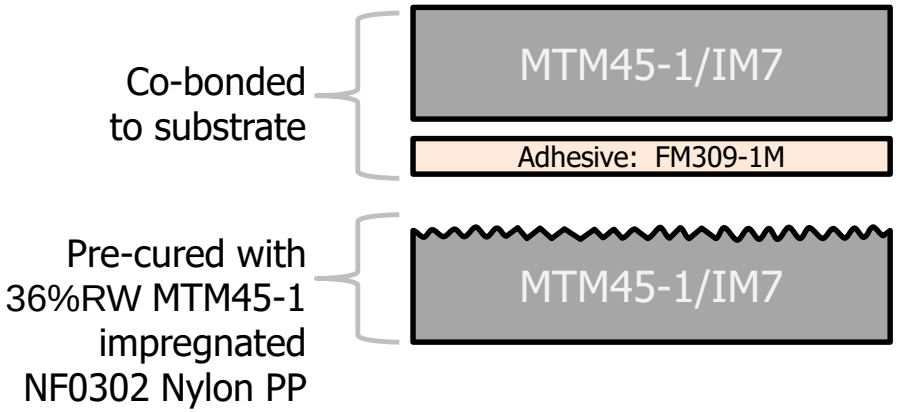
Develop and Mature a Framework to *Predict* Bond Quality

Phase III: Exercise the Framework

Deliver A Template For Reliable Bonded Structure

Skunk Works

TRUST Materials System

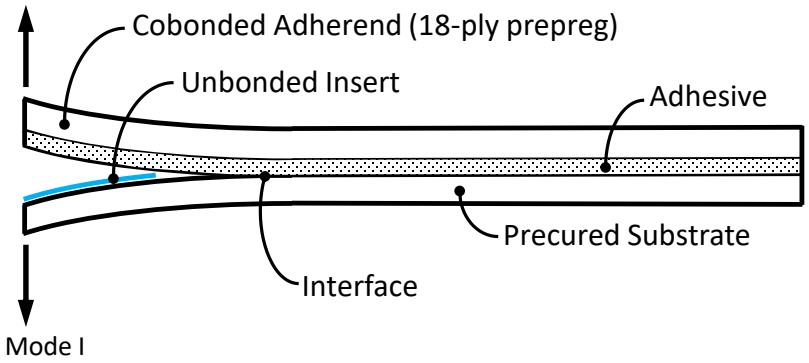


Disclaimer: The TRUST effort was executed on one material system, and the specific conclusions reached may only be applied to that system, however the TRUST approach may be applied to other material systems.

TRUST Coupon: Double Cantilever Beam (DCB)

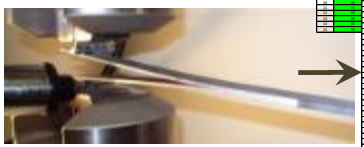
- Why DCB?
  - Common test to quantify fracture toughness of bonded structure
  - Mode I "opening mode" fracture very sensitive to bond process
  - Elucidates all relevant failure modes associated with bond quality
- DCB Specimen
  - Pre-cured adherend co-bonded to a green adherend
  - Non-stick insert used to form initial crack

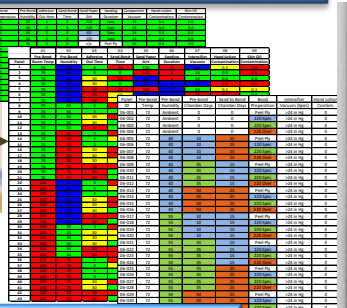
TRUST DCB Coupon

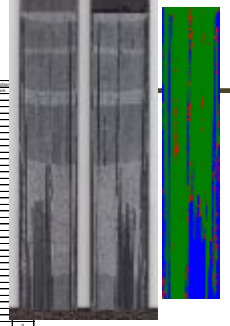


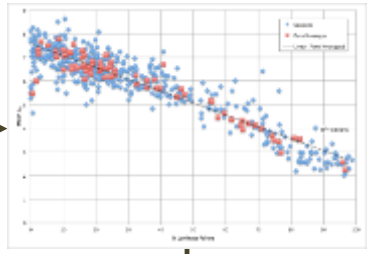
TRUST Phase I: Bond Process Driven by Data

DCB to DOE & Regression Analysis



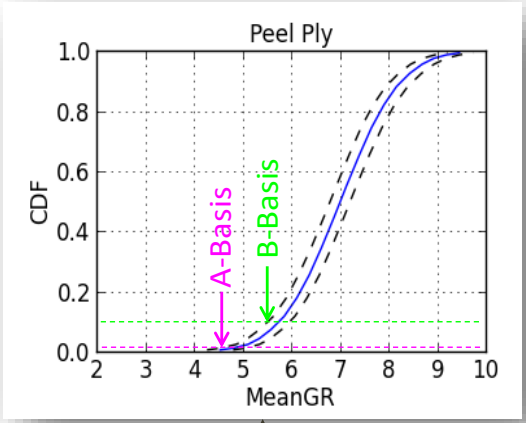




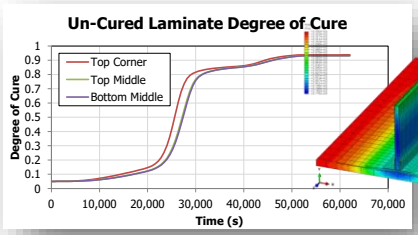


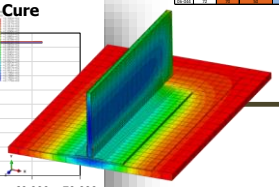
$$f = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_9 x_9 + \beta_{10} x_{10} + \beta_{11} x_{11} + \beta_{12} x_{12} + \beta_{13} x_1^2 + \beta_{14} x_2^2 + \beta_{15} x_3^2 + \beta_{16} x_4^2 + \beta_{17} x_5^2 + \beta_{18} x_6^2 + \beta_{19} x_7^2 + \beta_{20} x_8^2 + \beta_{21} x_9^2 + \beta_{22} x_{11}^2 + \beta_{23} x_{12}^2 + \beta_{24} x_1 x_2 + \beta_{25} x_1 x_3 + \beta_{26} x_2 x_3 + \beta_{27} x_5 x_6 + \beta_{28} x_8 x_9 + \beta_{29} x_8 x_{10} + \beta_{30} x_9 x_{10} + \beta_{31} x_{11} x_{12} + e$$

Linear Regression Model



COMPRO Cure Cycle Modeling

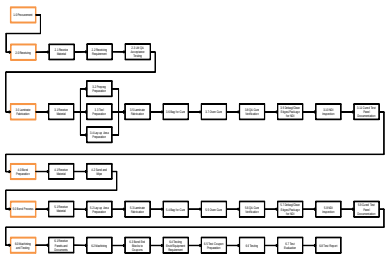


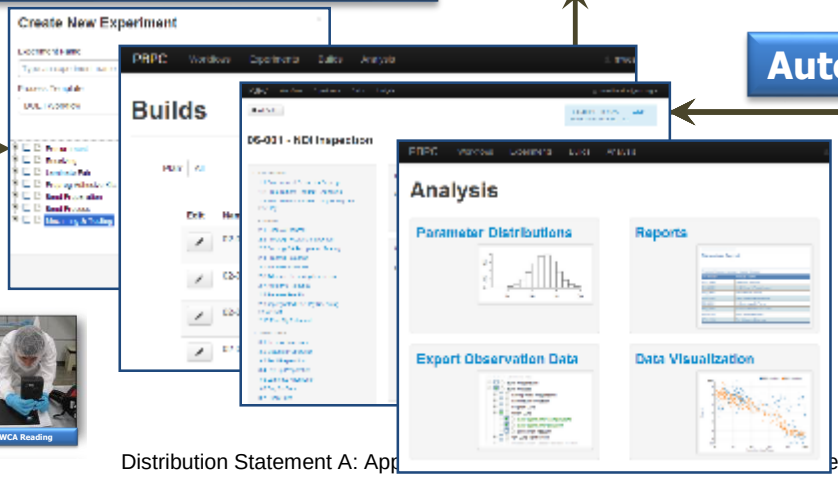


Informatics DB & App Server

NESSUS

Process Map to Electronic Work Instructions





Automated Device Data Capture

Skunk Works

Three Phases of TRUST

Phase I: Make A Model

Prove the Ability to *Quantify* Bond Reliability

Phase II: Develop a Framework

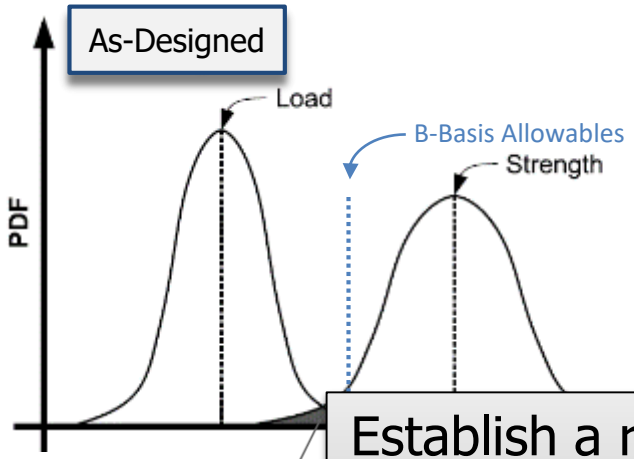
Develop and Mature a Framework to *Predict* Bond Quality

Phase III: Exercise the Framework

Deliver A Template For Reliable Bonded Structure

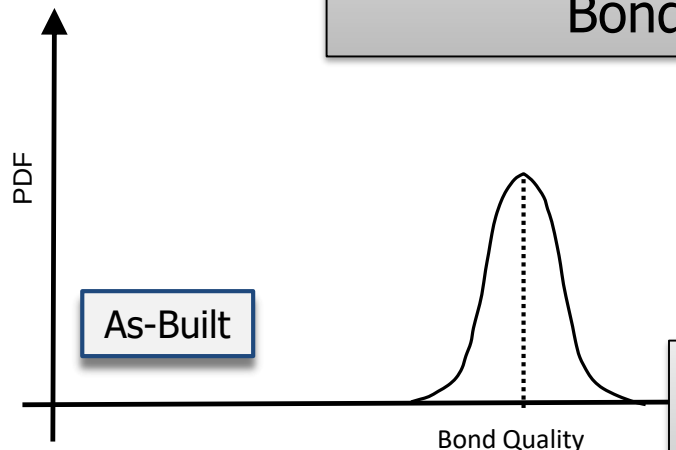
Skunk Works

TRUST Framework Quantifies Manufacturing Process Reliability, Assuring Engineering Integrity



Intersection is Structural Failure

Establish a relationship between bond process and bond quality… but how do we define Bond Quality?



Process Reliability Protects the Product
(As-Built ≥ As-Designed)

Traditional Calculation:

Strength ~ $F_{(G, E, T, M)}$

G: Geometry
E: Environment
T: Mfg Tolerances
M: Material Properties

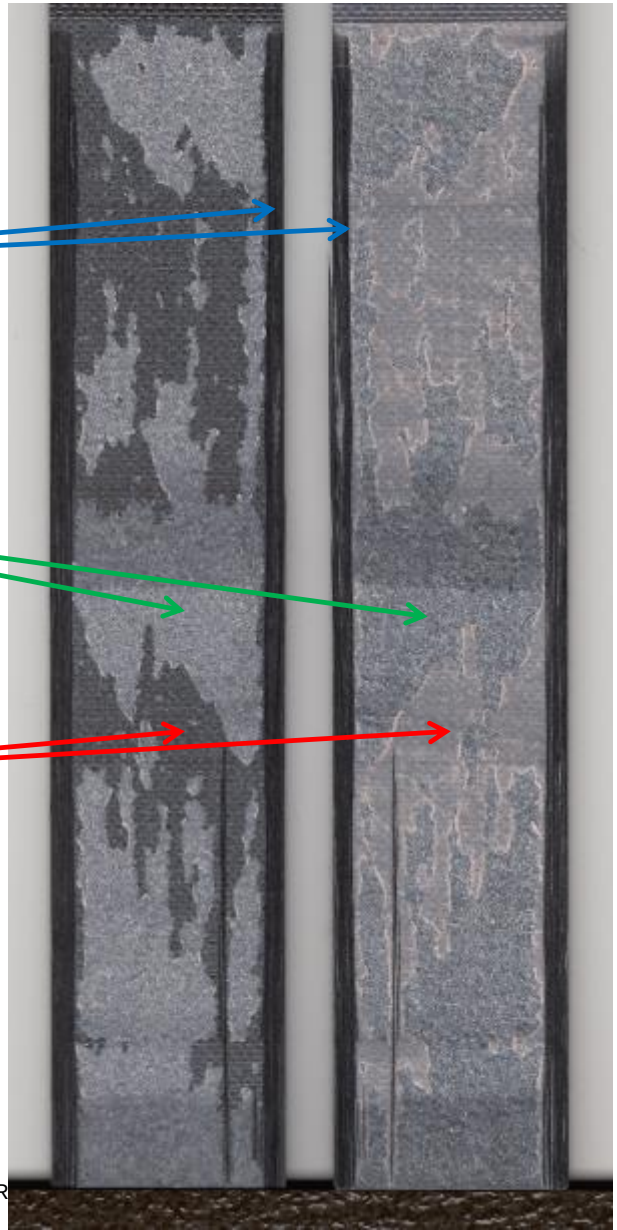
…bles:

Strength ~ $F_{(G, E, T, M \& P)}$

P: Process Control

Bond Quality is a Function of Strength and Failure Mode!

Image Analysis Quantifies the three failure modes present in each coupon.



Laminate Failure

Calculated G_L = 2.7 psi-in

X_L is Percent of Coupon Surface

Cohesive Failure

Calculated G_C = 8.5 psi-in

X_C is Percent Of Coupon Surface

Interfacial Failure

Calculated G_I = 3.7 psi-in

X_I is Percent of Coupon Surface

$$x_L + x_C + x_I = 100\%$$

Why do we need a Quality Metric?

- Individually, none of the direct outputs from DCB tests (G, %IF, %LF, %CF) are sufficient to determine good bonds from bad
- A model of G could tell you good bonds are bad
  - Coupons with laminate failure are weaker than those with cohesive failure
- A model of %IF could tell you bad bonds are good
  - A coupon with low interfacial failure could have weak cohesive failure
- We need a way to combine these outputs into a single metric that captures these complexities

- What is a good bond?
  - High fracture toughness and low interfacial failure
- What is a bad bond?
  - High interfacial failure
  - Low fracture toughness with high cohesive failure

- Two basic questions
  - Given the failure modes, was the bond as tough as expected?
  - Regardless of toughness, was there too much interfacial failure?

Skunk Works

Parallel Deep Dives into Process Details

- Temperature and Humidity Exposure

	Panel No.	% Relative Humidity	Prep to Bond Time (days)	Adhesive Out Time (days)
Nylon Peel Ply, Peel & Stick (NP&S)	12-018	Ambient	0	0
	12-019	40	0	35
	12-020	40	0	50
	12-021	40	15	0
	12-022	40	15	35
	12-023	40	15	50
	12-024	40	25	0
	12-025	40	25	35
	12-026	40	25	50
	12-027	70	0	35
	12-028	70	0	50
	12-029	70	15	0
	12-030	70	15	35
	12-031	70	15	50
	12-032	70	25	0
	12-033	70	25	35
	12-034	70	25	50

Parallel Deep Dives into Process Details

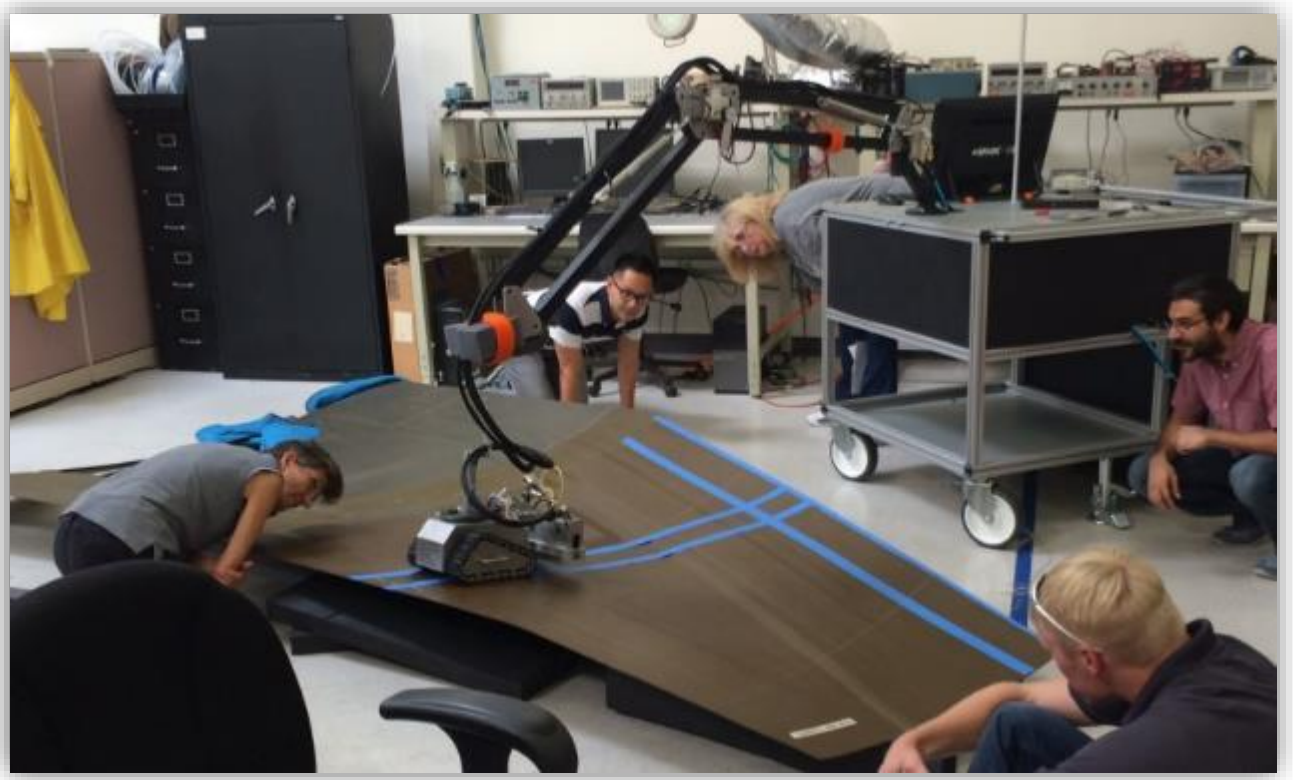
- Temperature and Humidity Exposure
- Contamination Investigation

CHEMICAL CLASS	Triglyceride	Fatty acid	Long Chain Esters	Alcohol	Surfactant/ Emulsifier	Non-polar Hydrocarbon	Water Soluble Polymer	Silicone/ Fluorocarbon
Archetype Compound	Glyceryl trioleate	Octanoic acid	Glycerol monostearate	Glycerol	Sodium tallowate	Mineral oil	Polyvinyl-pyrrolidone	Dimethyl siloxane
Why We Care	Food	Food, Cosmetics	Cosmetics	Food, Cosmetics	Cutting fluid, lubricants	Lubricants, cosmetics	Cosmetics	Mold release, FEP

Skunk Works

Parallel Deep Dives into Process Details

- Temperature and Humidity Exposure
- Contamination Investigation
- Plasma Automation



Skunk Works

Three Phases of TRUST

Phase I: Make A Model

Prove the Ability to *Quantify* Bond Reliability

Phase II: Develop a Framework

Develop and Mature a Framework to *Predict* Bond Quality

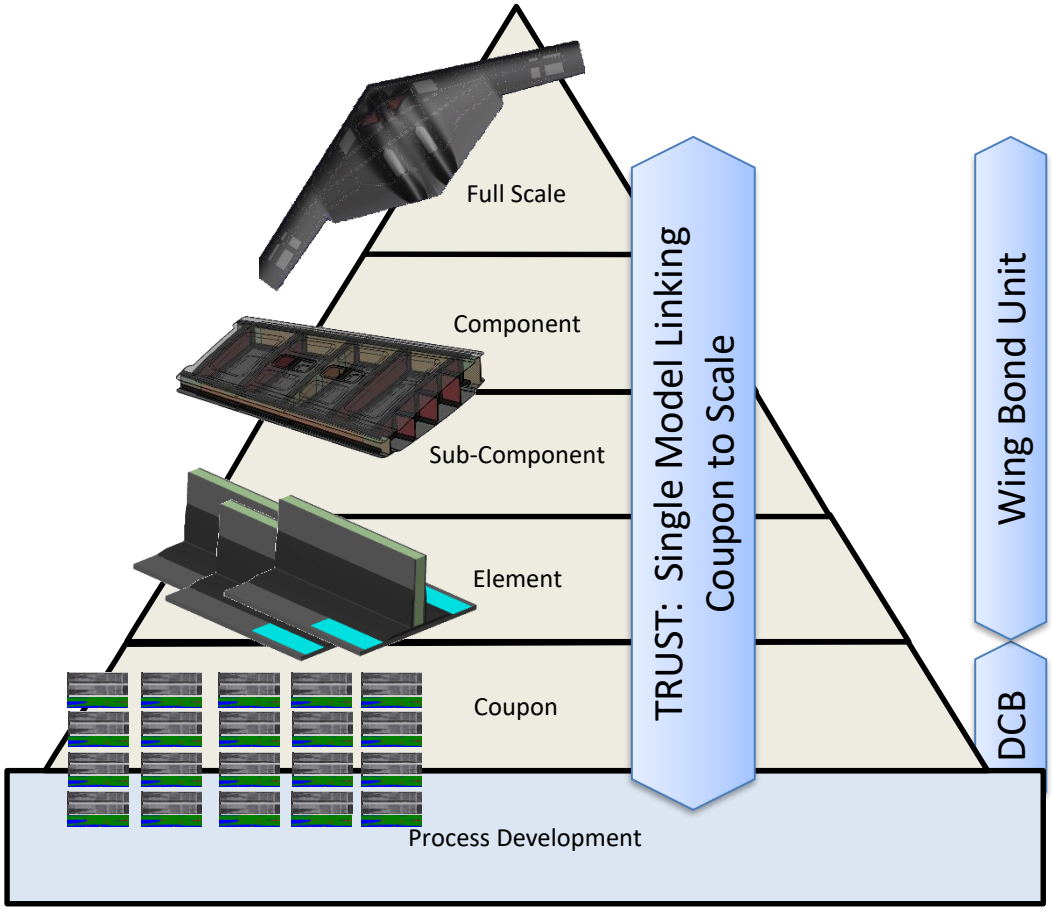
Phase III: Exercise the Framework

***Deliver* A Template For Reliable Bonded Structure**

Skunk Works

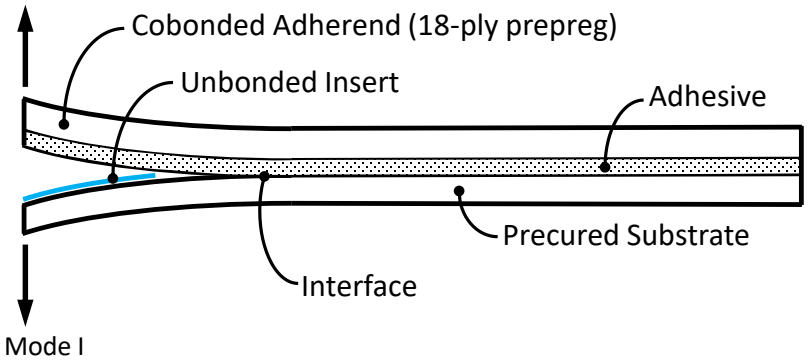
Single Model for Coupon to Article

- Phase III goal: $Q_{DCB} \sim Q_{Wing\ Bond\ Unit}$
  - Build on Phase II Model incorporating effects of scale

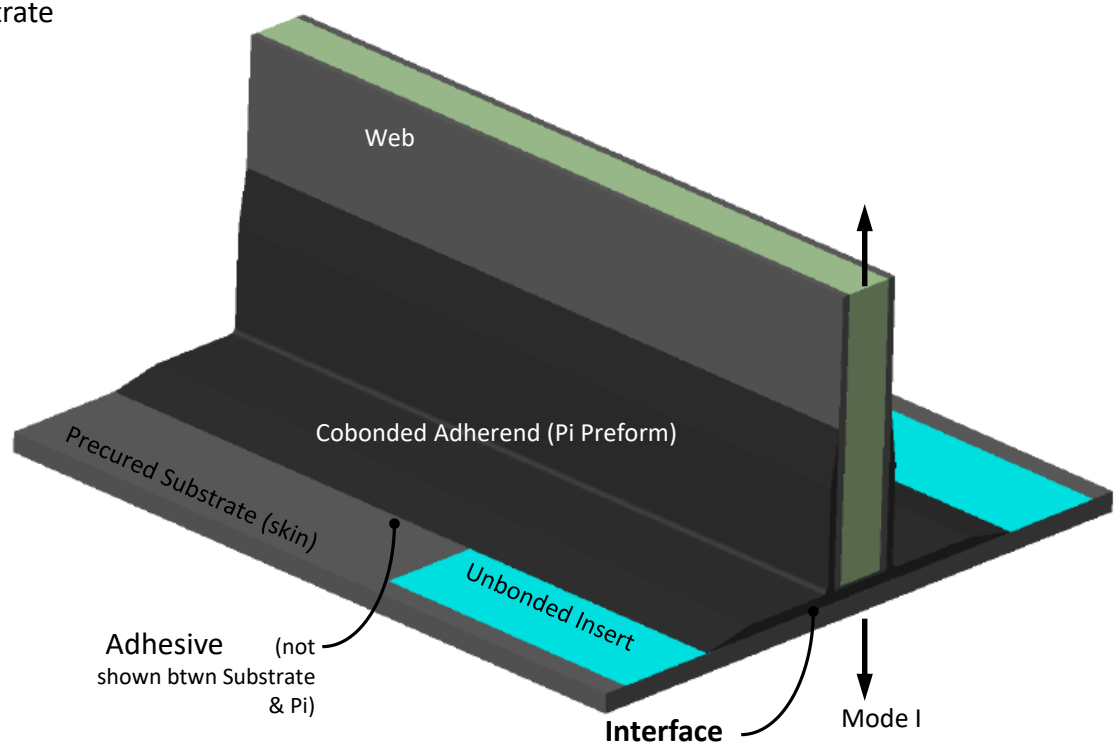


Scale Up: Build Pi Sticks, Excise and Test Pi-CB

TRUST DCB Coupon

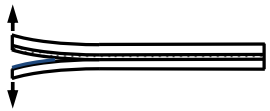


TRUST Pi-CB Coupon

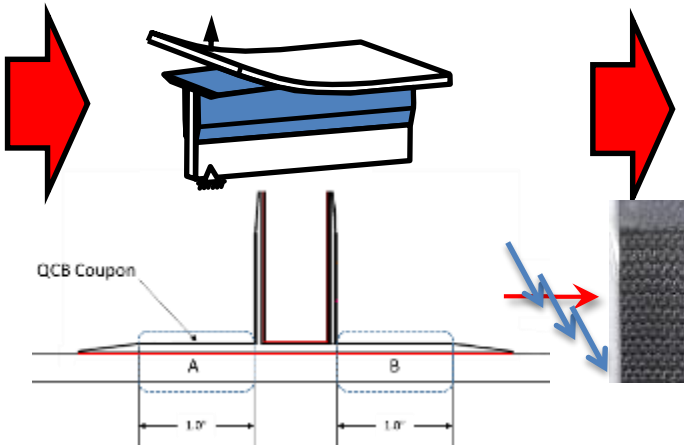


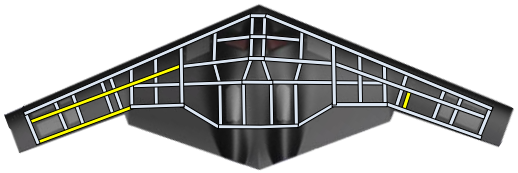
TRUST Phase III Link from Coupon to Scale

Pi-CB and QCB are not the link from DCB to Wing Bond Unit



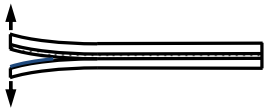
DCB Coupons





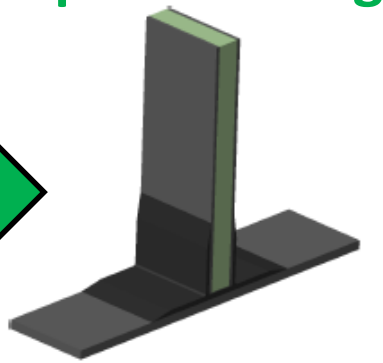
Asymmetry Inducing Failure Modes Not Indicative of DCB Observations

TRUST Phase III: DCB protects Engineering Data, Wing Bond Unit



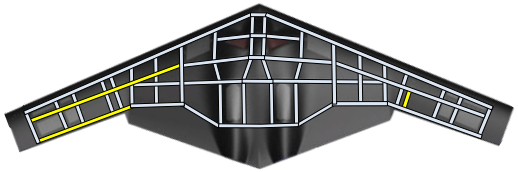
DCB Coupons

Protects

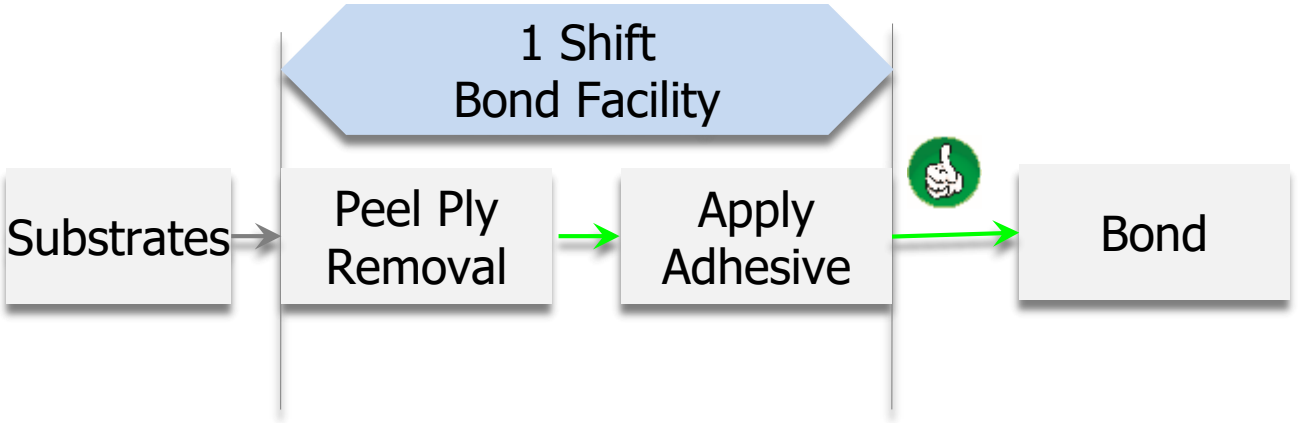


Engineering Data

Protects



Current State of TRUST Bond Prep



Control It, Peel It, Stick It, Bond It

Pre-Bond Inspection Devices Evaluated

BTG Labs Surface Analyst: Water Contact Angle

- Identifies an out-of-spec surface condition
- Sensitive to uppermost ~0.001µm of surface

X-ray Fluorescence Spectroscopy

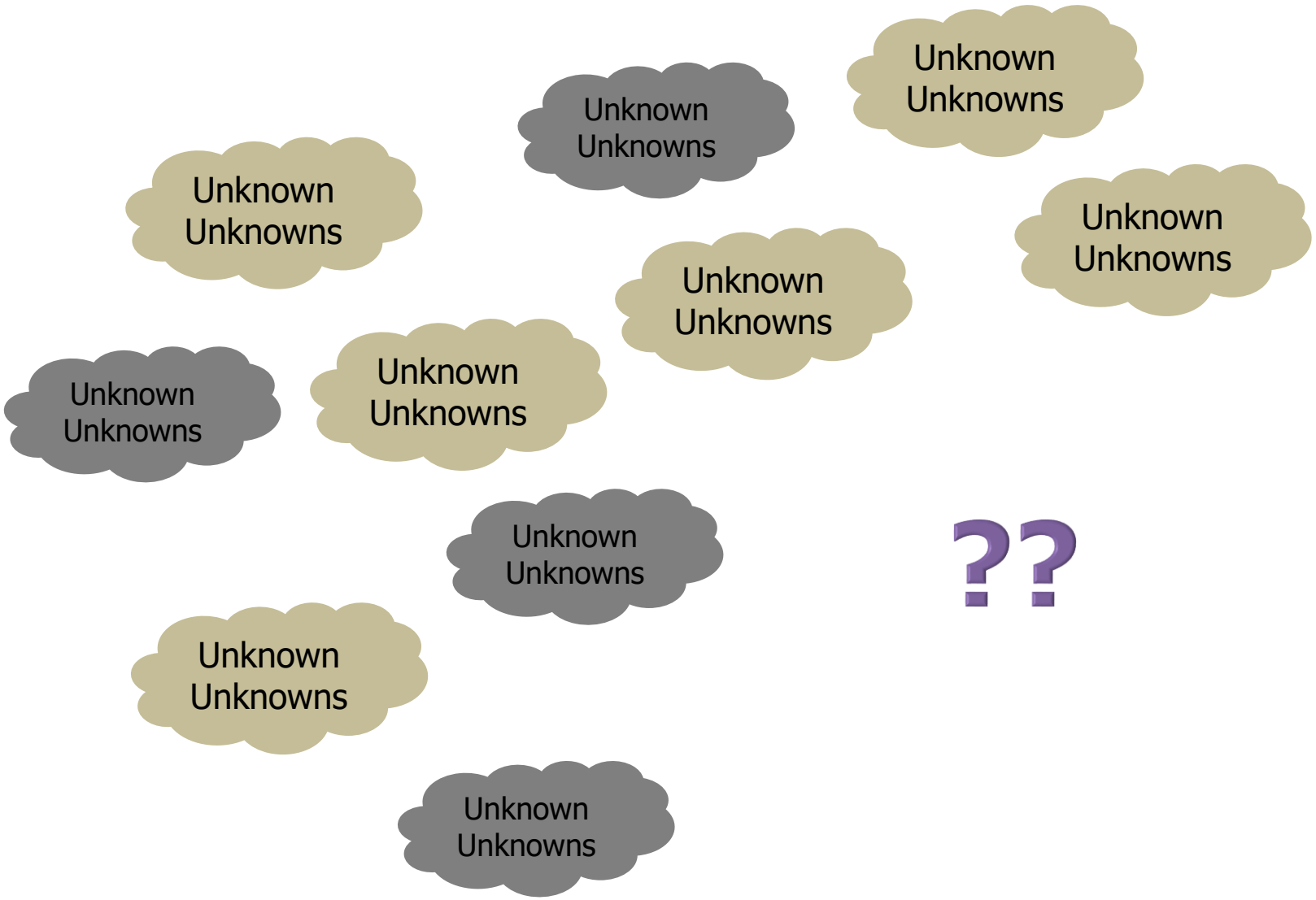
- Quantifies the elemental composition of solids, liquids, powders and soils.
- X-rays generated by the x-ray tube bombard the sample
- Photon wavelength identifies element; signal intensity identifies amount

Skunk Works

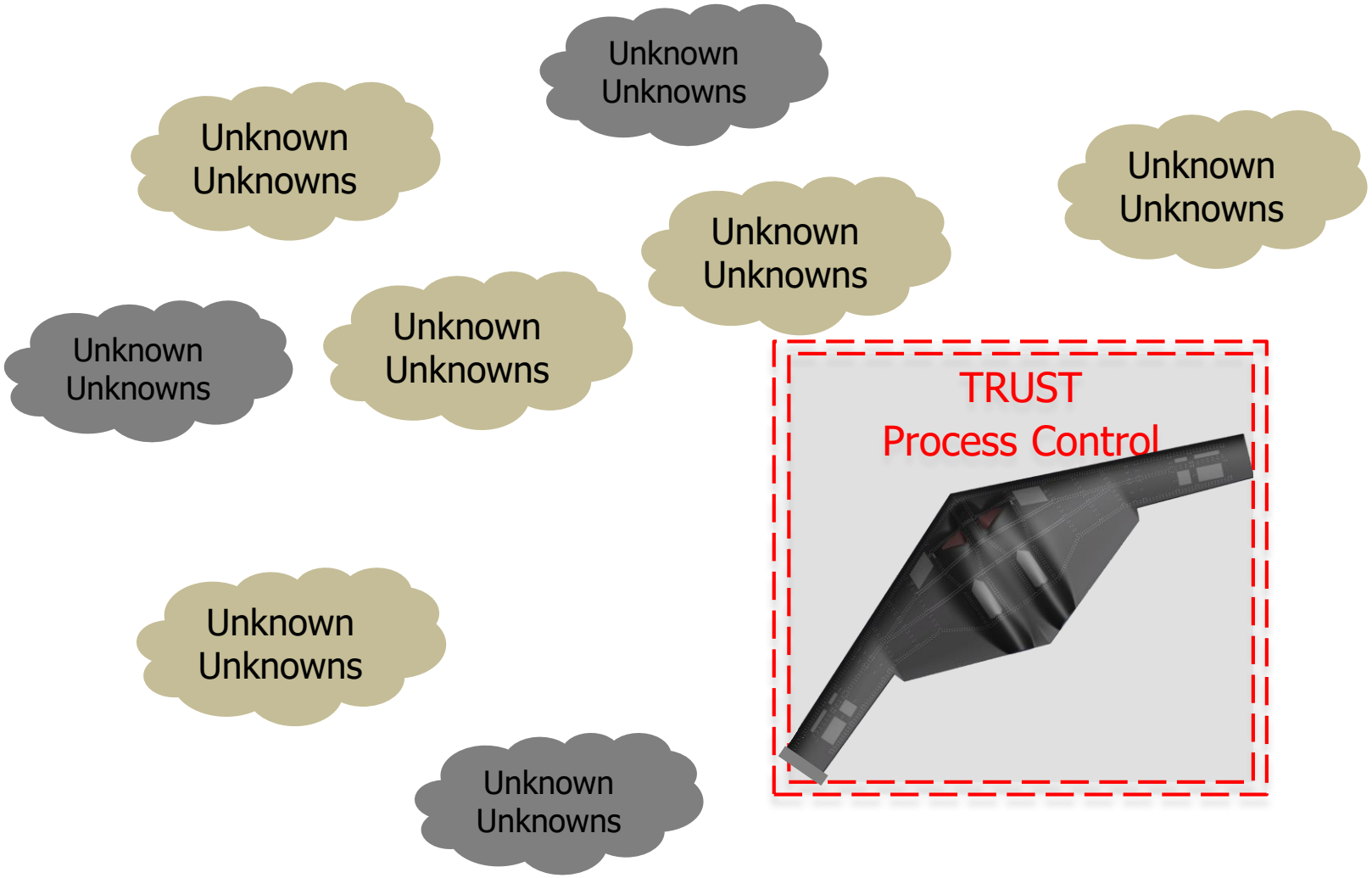
Develop Handheld Plasma

Intelligent Handheld Plasma Tool
IHPT

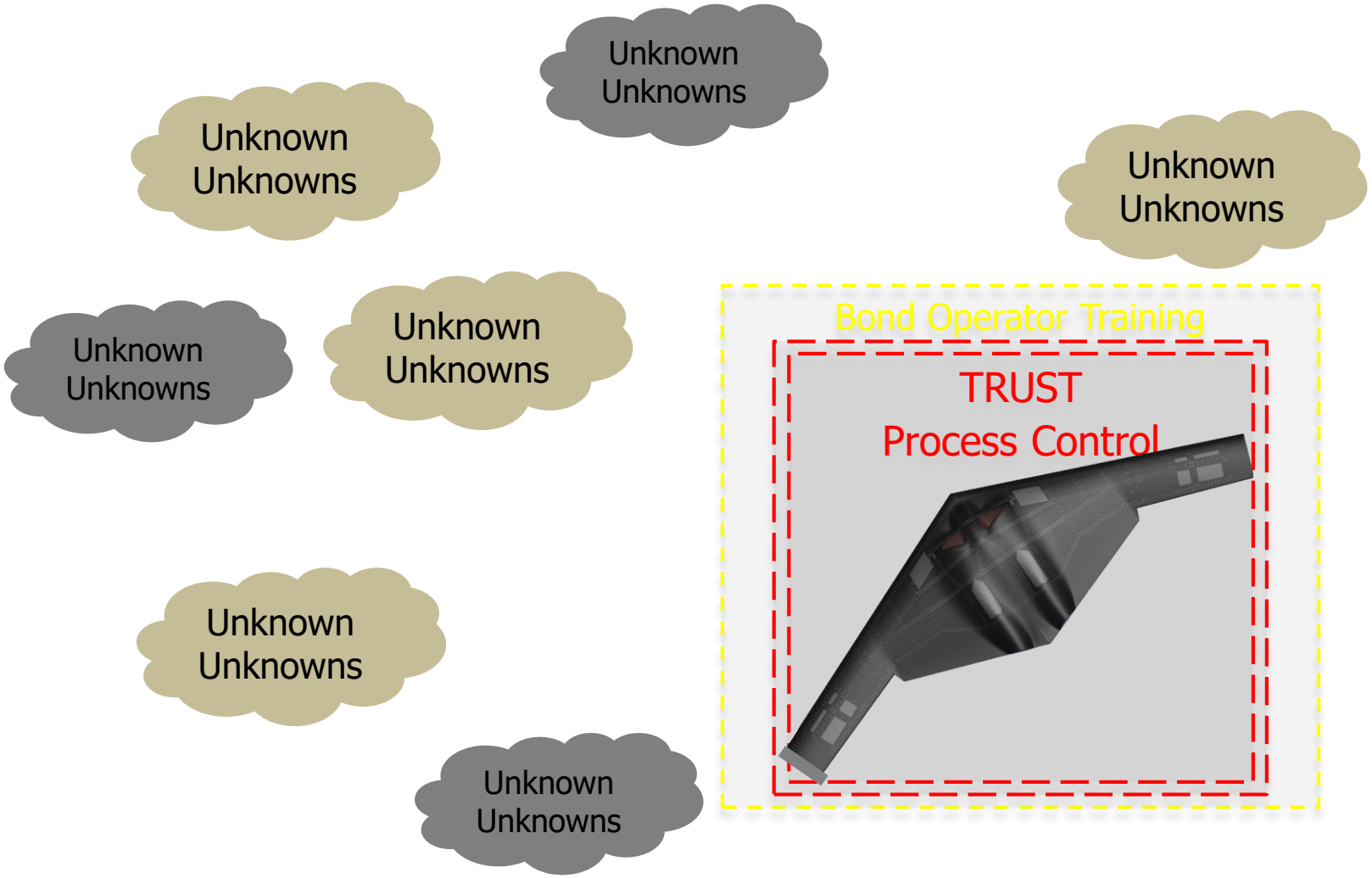
Original Bonding State of Knowledge



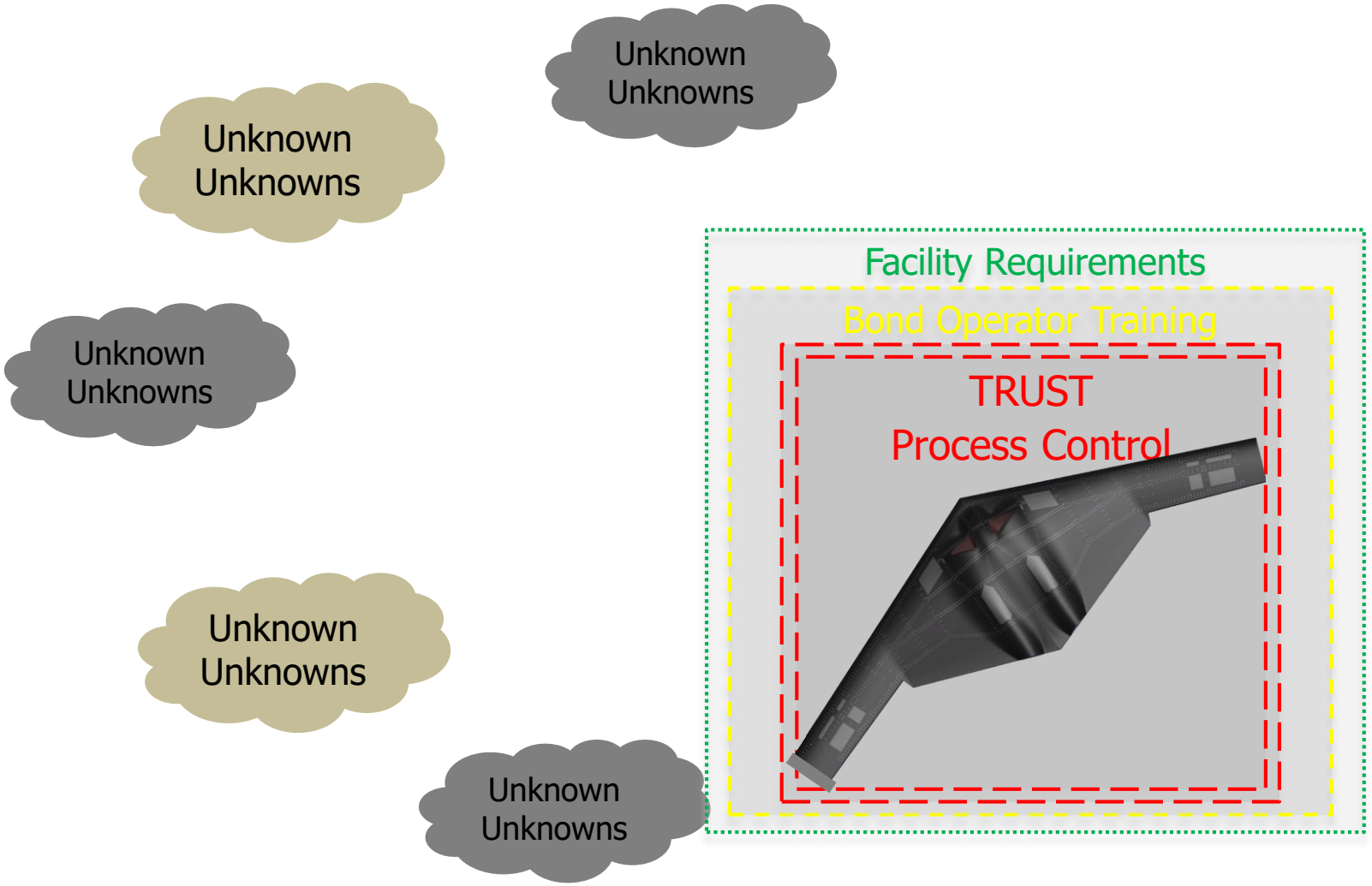
TRUST Protects "As Designed" & Informs Framework Addressing Unknown Unknowns



TRUST Protects "As Designed" & Informs Framework Addressing Unknown Unknowns



TRUST Protects "As Designed" & Informs Framework Addressing Unknown Unknowns

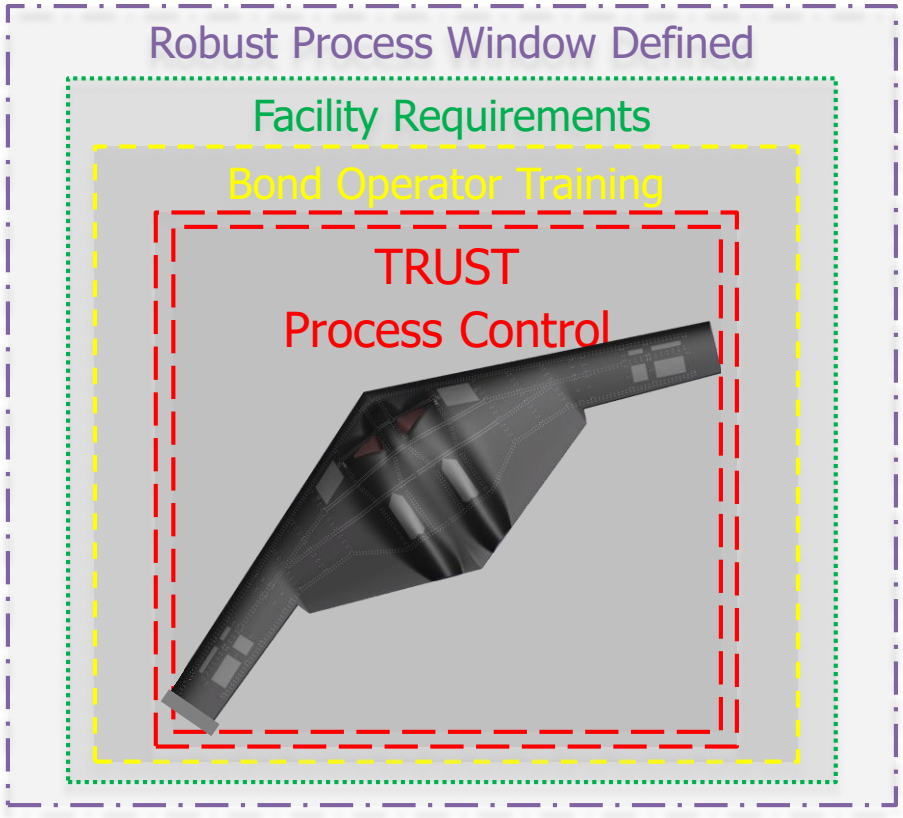


TRUST Protects "As Designed" & Informs Framework Addressing Unknown Unknowns

Unknown Unknowns

Unknown Unknowns

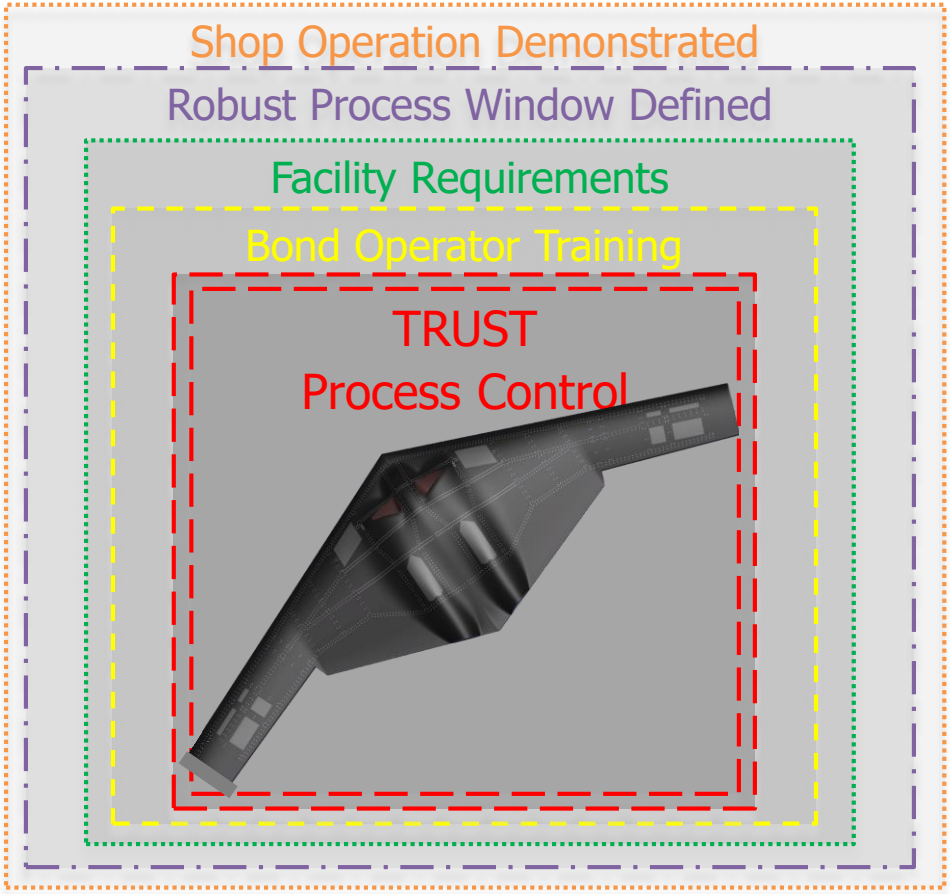
Unknown Unknowns



Skunk Works

TRUST Has Limited the Unk-Unk's

Unknown
Unknowns



Skunk Works

Acknowledgements

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA) and Air Force Research Lab (AFRL-RXM).

Lockheed Martin also wants to recognize our team members who made this happen: BTG Labs, Convergent, Solvay, Southwest Research Inst., and Surfx.