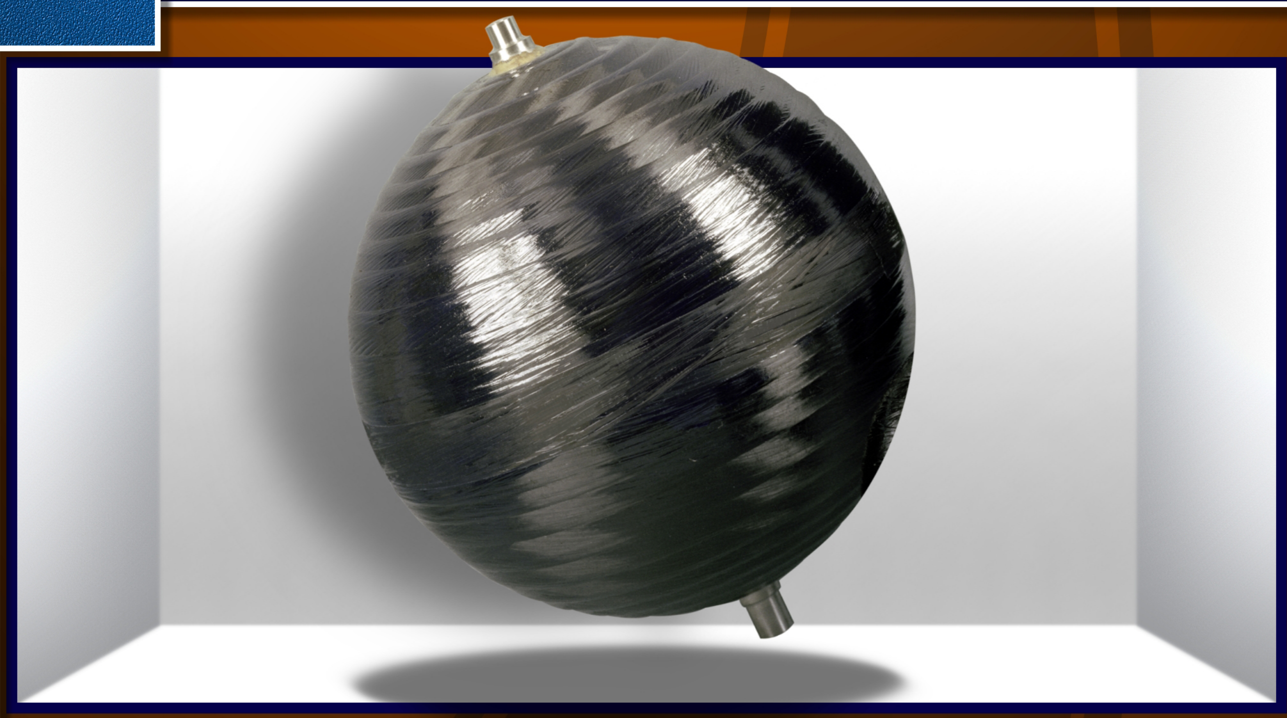
WSTF-RD-1198-001-13

Composite Conference

2012 Proceedings

Day 2



August 13-16, 2012, Las Cruces, NM

Composite Conference 2012

Wednesday, August 15, 2012

7:30 – 8:00 a.m.	Continental Breakfast and Exhibition
8:00 – 8:30 a.m.	***Keynote Introductions – Kezirian Presentation on COPV Safety: Developing Flight Rationale for the Space Shuttle Program***
8:30 – 10:30 a.m.	**Session 3: Statistical Modeling** (Stress Rupture, Reliability and Variability) *M. Kezirian, Boeing Chair* *B. Webb, E&S Chair*
8:30 – 8:50 a.m.	**Development of Automated Acoustic Emission Analysis Software for Self Monitoring "Smart COPVs"** *C. Nichols, J. Waller, R. Saulsberry, K. Johnson, D. Weathers, and J. Tylka*
8:50 - 9:10 a.m.	**Determination of Composite Strength Allowables with Reduced Testing for Composite Overwrapped Pressure Vessels** *F. Abdi, G. Abumeri, and S. Keshavanarayana*
9:10 - 10:00 a.m.	**Providing Pressurized Gasses to the International Space Station (ISS): Developing a Composite Overwrapped Pressure Vessel (COPV) for the Safe Transport of Oxygen and Nitrogen** *M. Kezirian, and S. Phoenix*
10:00 – 12:00 (noon)	**Session 4: Materials and Processes** (Materials, Durability, Manufacturing, Weight, and Part Cost) *J. Waller, NASA/WSTF Chair* *S. Forth, NASA/JSC Chair*
10:00-10:20 a.m.	**High Energy Testing** *H. Beeson, NASA/WSTF*
10:20-10:40 a.m.	**Transforming Composite Pressurized Vessels (CPV) to Unibody Composite Pressurized Structures (UCPS) with expanded capabilities for Spacecraft** *M. Rufer, R. Conger*
10:40-11:00 a.m.	**Thermal and High Energy Particle Enclosure for Electronic Components in Spacecraft and Robotic Platforms** *M. Nevarez, K. Anderson*
11:00-11:20 a.m.	**Developments in Composite Cylinders for Hydrogen Storage** *N. Newhouse, K. Simmons, J. Makinson*
11:40-12:00 a.m.	**A New Methodology for Damage Tolerant Composites Applied to COPVs** *G. Wood, P. Schneider, M. Braley M. Fancher, C. Philips, C. Snyder*
12:00 – 1:00 p.m.	***Lunch***

1:00-3:00 p.m.	**Session 5: Non-Destructive Evaluation** (Health Monitoring) *Regor Saulsberry, NASA/WSTF Chair* *L. Richards, NASA/LARC Chair*
1:00-1:30 p.m.	**Voluntary Consensus Standards for Nondestructive Testing of Composite Overwrapped Pressure Vessels Used In Aerospace Applications** *J. Waller, R. Saulsberry*
1:30-2:00 p.m.	**Smart Composite Overwrapped Pressure Vessels** *C. Banks, E. Madaras, C. Nichols, L. Richards, D. Roth, R. Russell, R. Saulsberry, and J. Waller*
2:00-2:30 p.m.	**Development of Novel Acoustic Emission Procedures for Prediction of Rupture in Carbon-Epoxy Composite Overwrapped Pressure Vessels and Related Composite Materials** *J. Waller, C. Nichols, R. Saulsberry, A. Abraham, E. Andrade, J. Tylka, D. Wentzel, D. Weathers, and K. Johnson*
2:30-3:00 p.m.	**Nondestructive Residual Stress Analysis in Pipes and Pressure Vessels** *J. Jackson*
3:00 – 3:30 p.m.	Break
3:30 – 5:00 p.m.	**Session 6: Non-Destructive Evaluation** (Manufacturing Verification and Damage Detection) *R. Saulsberry, NASA/WSTF Chair* *L. Richards, NASA/LARC Chair*
3:00 – 3:30 p.m.	**Part A. Application of Modal Acoustic Emission (MAE) for Assessing Structural Damage in Composite Overwrapped Pressure Vessel** *M. Toughiry*
4:00 – 4:20 p.m.	**Elements of Composite Pressure Vessel Visual Inspection** *T. Yoder, N. Greene*
4:20 – 4:40 p.m.	**Quantitative Shearography Inspection of CPV and COPV** *J. Newman, President LTI*
4:40 – 5:00 p.m.	**Continued Development of Meandering Winding Magnetometer (MWM®) Eddy Current Sensors for the Health Monitoring, Modeling and Damage Detection of Composite Overwrapped Pressure Vessels (COPVs)** *R. Russell, R. Wincheski, D. Jablonski, A. Washabaugh, Y. Sheiretov, C. Martin and N. Goldfin*
5:00 – 5:20 p.m.	*Identify NDE needs* *Develop research plan* *Construct roadmap*

Development of Automated Acoustic Emission Analysis Software for Self Monitoring "Smart COPVs"

August 2012

NASA Glenn Research Center: Donald Roth; NASA JSC White Sands Test Facility: Charles Nichols, Regor Saulsberry, Josh Simmons, Doug Weathers, Jon Tylka, Jess Waller, & Ralph Lucero

Introduction

Virtually all NASA spacecraft use composite overwrapped pressure vessels (COPVs) for weight savings over metal pressure vessels. However, these composite structures are more susceptible to damage than metal PVs, are difficult to inspect, have large burst pressure variability, and are susceptible to stress rupture when maintained at pressure.

To address these issues, NASA's Nondestructive Evaluation Working Group (NNWG) is supporting the development of an automated, lightweight COPV structural health monitoring (SHM) module. A hands-off demonstration of the unit is planned in FY15.

This program is solely focused on NASA and federal applications. If proven effective and reliable, a wide variety of government and commercial applications could benefit from this technology, notably including compressed gas and hydrogen fueled vehicles.

NASA's Technology Transfer Policy

NASA does not compete with private industry, but does transfer technology to the private sector and state and local governments by actively seeking licensees. Technology transfer promotes commercial activity, encourages economic growth, and stimulates innovation in business and commerce.

More than 1,600 such technology transfer successes have been documented in NASA's *Spinoff Magazine* over the years, which include commercial applications in health and medicine, transportation, public safety, consumer goods, agriculture, environmental resources, computer technology, manufacturing, and energy conversion and use.

The National Aeronautics and Space Act of 1958 and a series of subsequent laws identify the transfer of Federally-owned or originated technology as a national priority and an important mission of each Federal Agency.

Source: http://www.nasa.gov/open/plan/technology-transfer.html

Impact to the International Space Station

COPV Rupture Effect on ISS

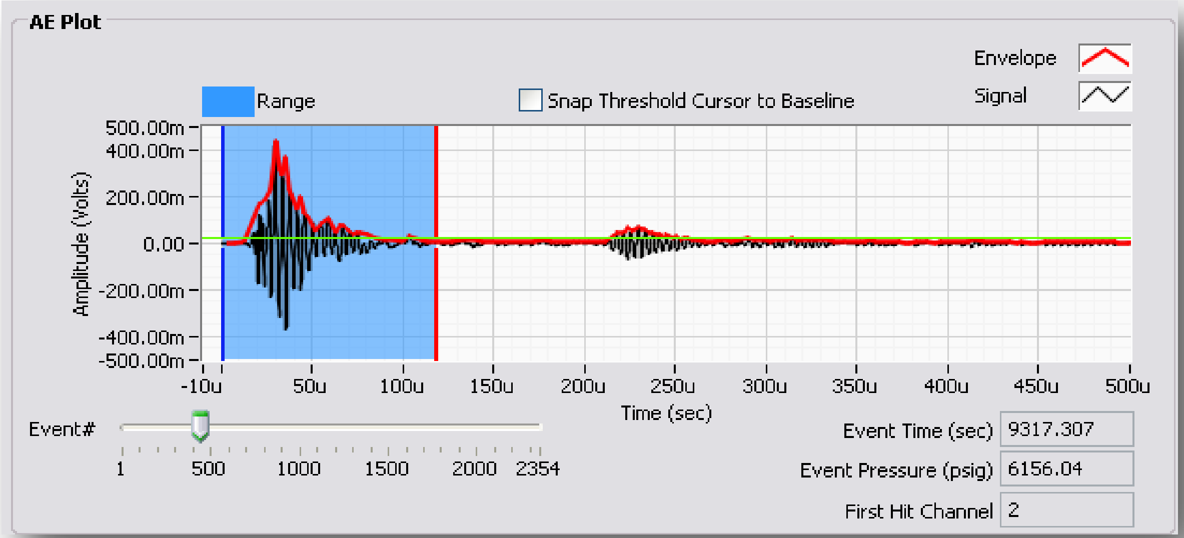
Effect on ISS Systems and Crew

COPV System	ISS Systems Destroyed	Hull Breech	Astronaut Fatality	TNT Equiv. (lbm)
HPGT	Airlock	Very High	Very High	8.9
NTA	ATA, PMA	High	High	3.9
PCU	PCU Enclosure	Low	Low	0.6
SAFER	SAFER Unit	High	Very High (EVA), High (Hull)	0.15
SPACEDRUMS (GBA)	GBA Housing	High	High (EVA)	0.12
AMS CO2	AMS	Low	Low	0.4
AMS Xenon	AMS	Low	Low	0.6
VCAM	VCAM Unit	Very Low	Very Low	0.01
VGA	VGA Unit	Very Low	Very Low	0.01
GBU-Ar GBU-He GBU-CO2	CGSE (COPV Storage Compartment)	Low	Low (Hull)	0.06 0.06 0.2

Objective

Various monitoring techniques are targeted by NNWG, however this presentation will focus on acoustic emission (AE) SHM and the development of an Acoustic Emission Analysis Applet (AEAA).

AE is a term used to describe waves produced when a material undergoes stress as the result of an external force. This event is the result of a small surface displacement produced by stress waves generated when the energy in a material, or on its surface, is rapidly released. If the amplitude crosses a predetermined threshold, the wave signal is recorded.



NNWG

AE Software

As new analysis methods emerge, software must keep pace. In industry, analysts are often buried under several GB of data that must be reduced and reported in a timely manner. SHM is an application that requires sophisticated software to perform many of the duties typically associated with an experienced analyst in real time to mitigate structural failures.

Commercially available AE software packages contain many important and useful features including filters, source location triangulation, and trend tracking. Integrating custom evaluation code into these platforms is often an inefficient and slow process, thus slowing research and development.

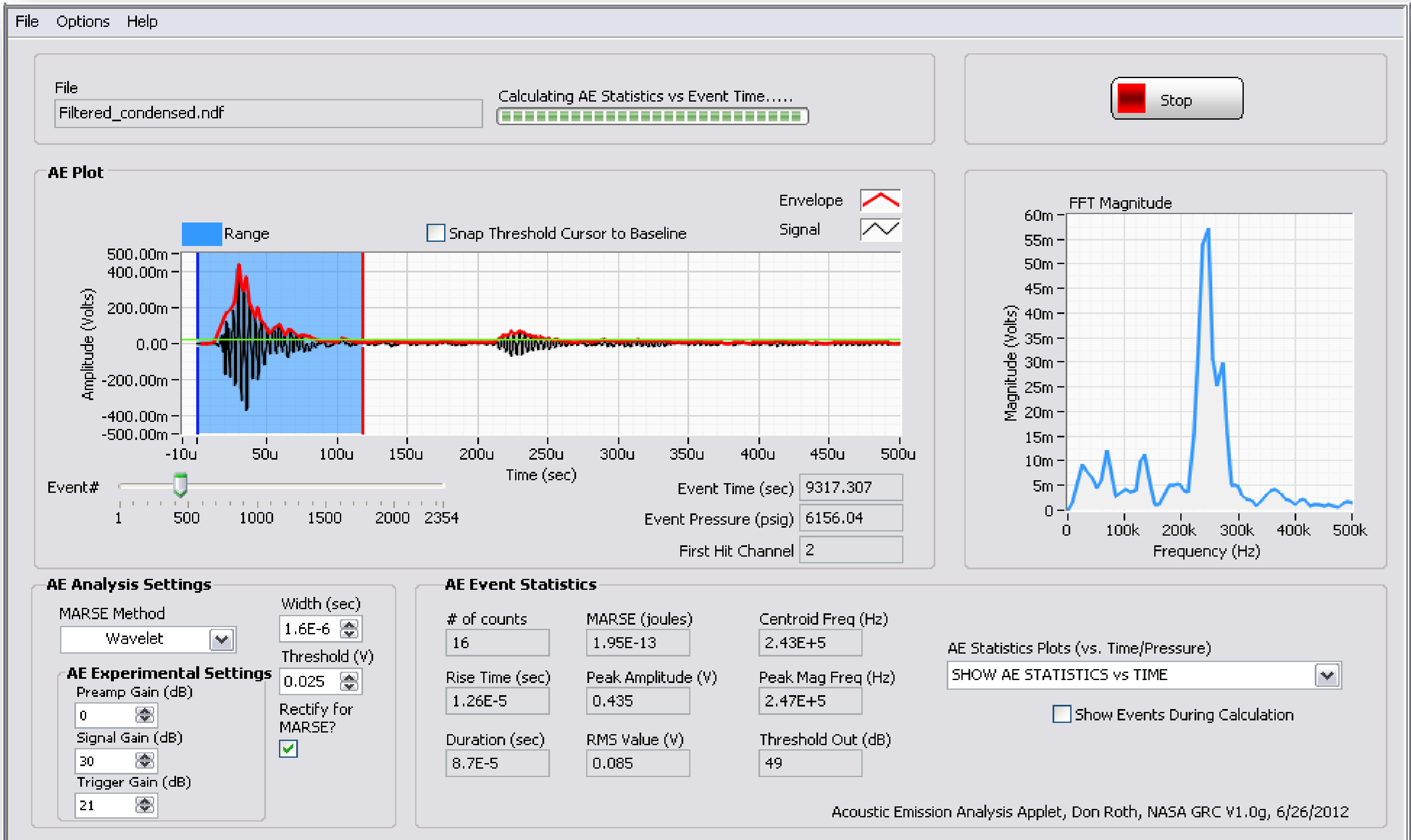
This is why the NNWG has chosen to develop software initially as an easily customizable analysis tool to test emerging methods and alarms on data files generated using commercial software. As the project matures, a decision will be made to augment commercial software with down selected code and methods or produce a NASA-funded AE system.

Progress

The software presented in the following slides is currently serving as a post-processing analysis tool supporting the development and testing of alarm criteria.

Future work will transition the software from a post-processing to an in-situ and automated structural health monitoring system.

AEAA Interface, Developmental



Nomenclature, ordered logically

acoustic emission (AE) – Elastic waves generated by the rapid release of energy from sources within a material as a response to external stimuli. This response is the growth or creation of flaw sites at a physical origin or source.

break points – Time and pressure values associated to significant transition points in a structure's pressure history. Break points are used to define time boundaries for data analysis.

breakage ratio – The ratio of the number of events in a time window with frequencies associated with fiber breakage and significant damage divided by the total events.

counts – The number of times the AE signal crosses the detection threshold.

duration – The time interval between the first and last crossing of the amplitude threshold.

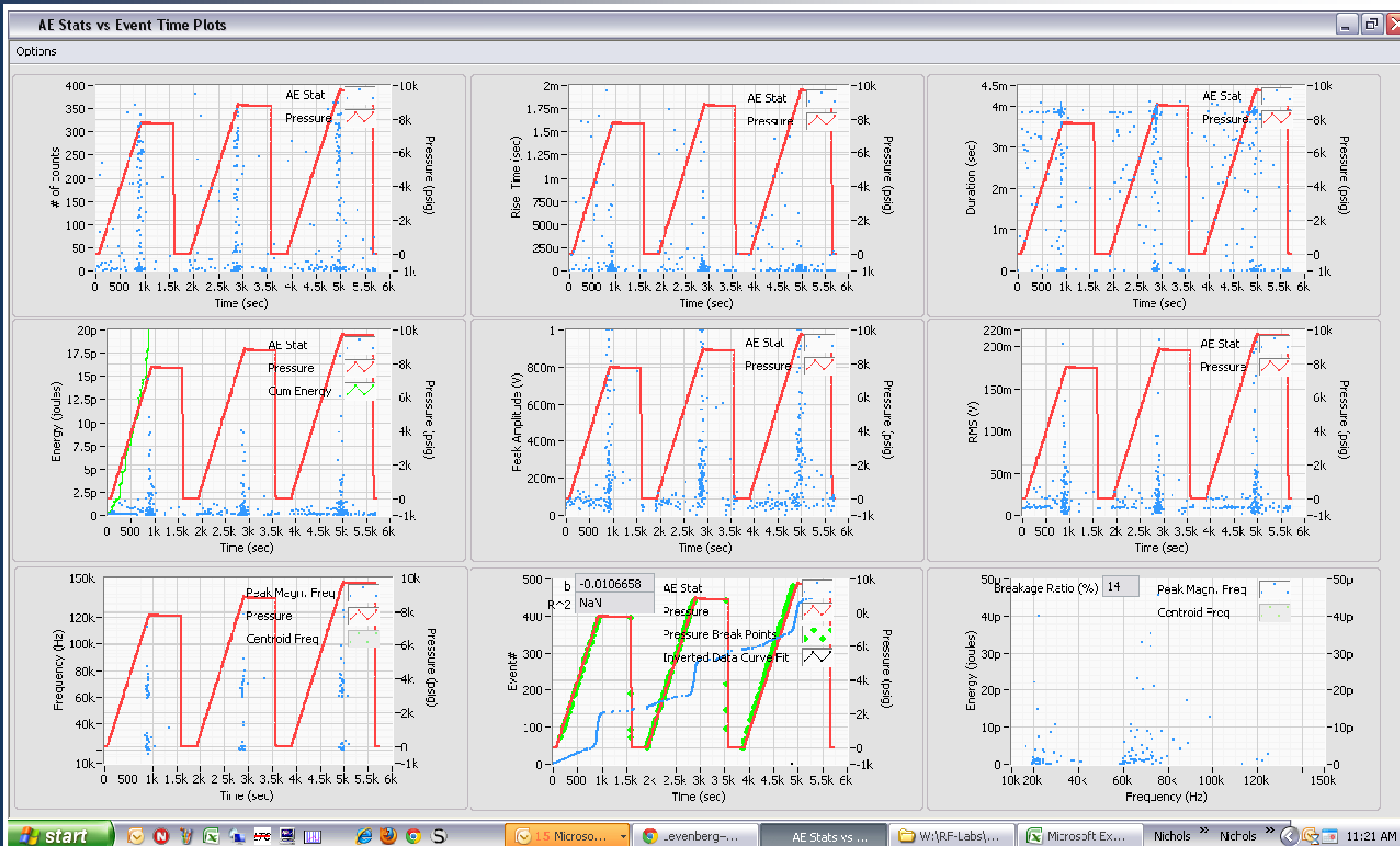
event – The detection and measurement of an AE signal on a channel. A event or hit is registered when an acoustic emission arrives at a sensor with enough energy to exceed an amplitude-based detection threshold.

felicity ratio (FR) – A ratio of the pressure at onset of significant AE to the previous maximum pressure a test article (TA) has experienced. Significance may be interpreted in a number of different ways depending on the structure tested and the desired results.

rise time – The time interval from an AE signal's first threshold crossing to its peak.

stability rate (B) – The exponential growth or decay rate associated to event accumulation.

AEAA Statistics, Developmental



Features

- Software handles unlimited size data sets (amount of RAM is a non-issue)
- Analyzes multi-channel AE data and plots against time and parametric values
- Condenses data across multiple channels and produces statistics for the first arrival channel (threshold crossing method)
- Integrates parametric data from WSTF DAQ and vendor AE systems
- Records gain, threshold settings, and processed data statistics as a text file for simple porting to Excel, MatLab, and other software
- Decibel mode displays statistics in absolute, dBAE units corrected for gain
  Assumes a reference voltage of 1 µv
- Multiple MARSE energy evaluation methods and increment widths with or without rectification
- Corrects energy level for gains and provides an estimate in Joules
  Assumes a nominal total line impedance of 10 kΩ
- Ability to adjust evaluation window to focus on direct waves
- Allows users to configure voltage threshold for analyses
- Converts AE files into LabView NDF format

Advanced Features

State-of-the-art Filtering: versatile digital filtering, wavelet de-noising, and wavelet decomposition / reconstruction

Structural Health Monitoring Methods (Developmental)

- ASME Section X & NB10-0601 methods
  - Structural stability limits
  - Background energy oscillation limits
- NASA-JSC WSTF analysis criteria
  - Felicity-ratio based burst pressure estimation and value limits
  - Fiber breakage ratio over time limits

System Requirements

- PC running Windows XP or 7, 32 or 64-bit
- Recommended: 2 GB RAM

Path Forward

Additional Software Features

- Add user configurable alarms to each AE statistic
- Add sub setting of frequency data (partial power analysis) to calculate energy within different frequency ranges
- Add .ini (configuration) file with AE Analysis and AE Experimental Settings, and ability to save and load this file
- Add the ability to import simplified wave data from more AE manufacturers
- Produce 3D surface plots of AE stats vs. event time and pressure

Integration Efforts

- Down select between NASA hardware and AE vendors for SHM implementation
- Add data collection and periodic remote data backup features as necessary
- Evaluate SHM system efficacy on COPV level tests
- Demonstrate system to NNWG members in FY15

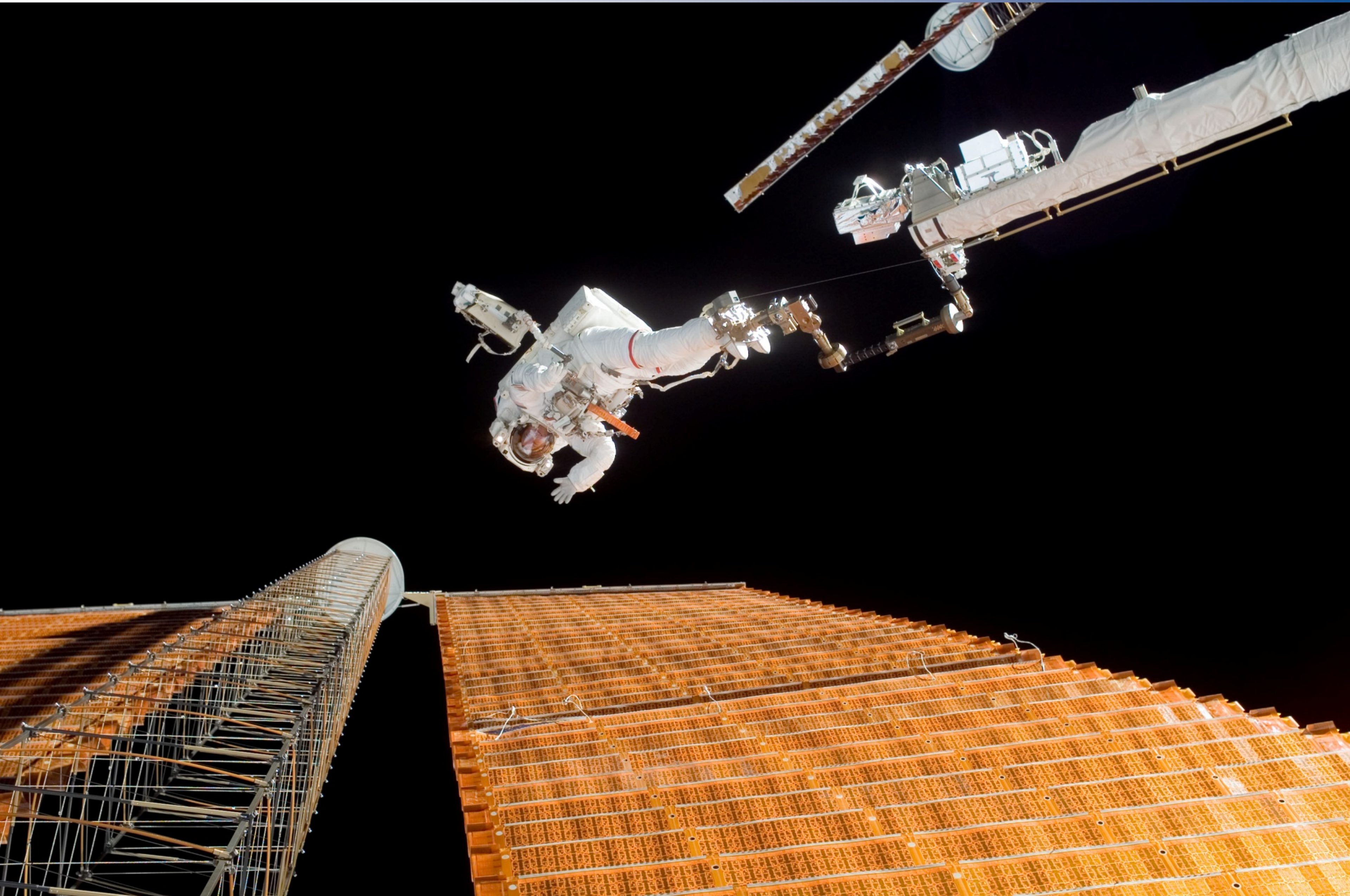
Summary

The methods evaluated show promise and the technological maturity is evolving to the point where the system can be installed and used with little training.

Similar to a check engine light or smoke alarm, once installed the system is ultimately expected to alert ISS crew members to critical alerts, but will have little impact to missions otherwise.

Diagnostic information could then be transmitted to experienced technicians on the ground to determine whether the COPV has been impacted, is structurally unsound, or can be used to complete the mission.

Q & A



Contact Information

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Determination of Composite Strength Allowables with Reduced Testing for Composite Overwrapped Pressure Vessels

NASA Composite Conference 2012:

The Future of Composite Vessels and structures

New Mexico State University, Las Cruises New Mexico

August 13-17, 2012

F. Abdi (PhD), G. Abumeri, M. Garg

AlphaSTAR Corp., Long Beach, CA, USA
http: www.alphastarcorp.com

Outline

- **Compliance with Certification Requirements**
- **Material Characterization**
- **Material Qualification**
  - **Determination of Allowables with Reduced Testing**

- **Lamina/Laminate Level Validation of A- and B- Basis**
  - **Carbon Composite (3 classes)**
    - **IM7/MTM45 (Sealed Envelope Prediction)**
    - **Environments: CTD, RTD, ETD and ETW**
    - **AS4/MTM45-1**
  - **Glass Composite**
    - **MTM45-1/6781 S2-Glass**
  - **Notched and Un-notched specimens**

- **Conclusion and Lessons Learned**

A- And B-Basis Allowables Definitions

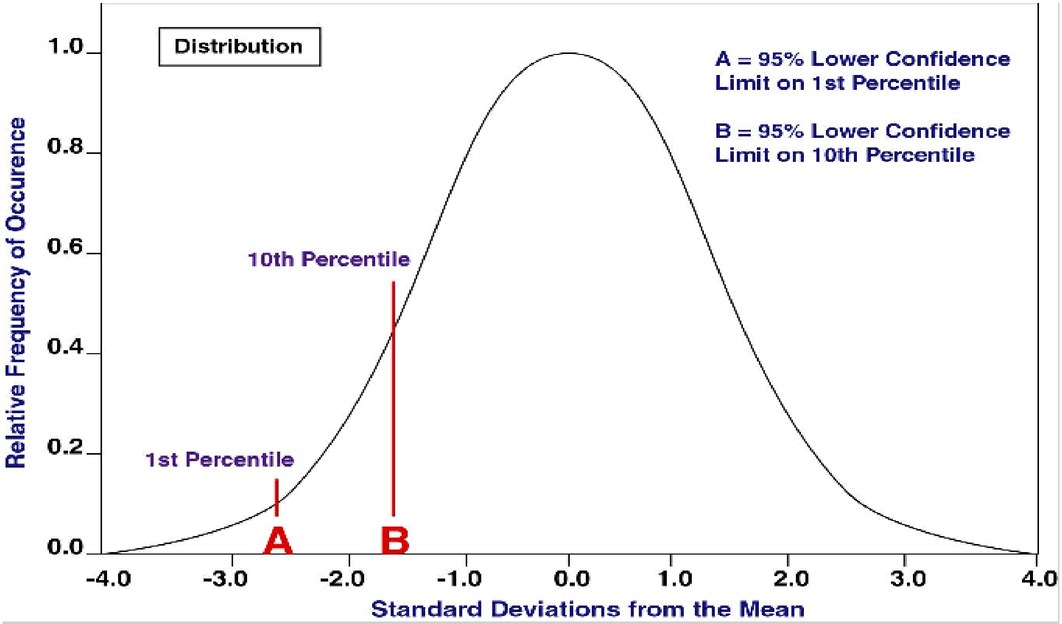
Design values are chosen to minimize the probability of structural failure due to material variability and manufacturing defects.

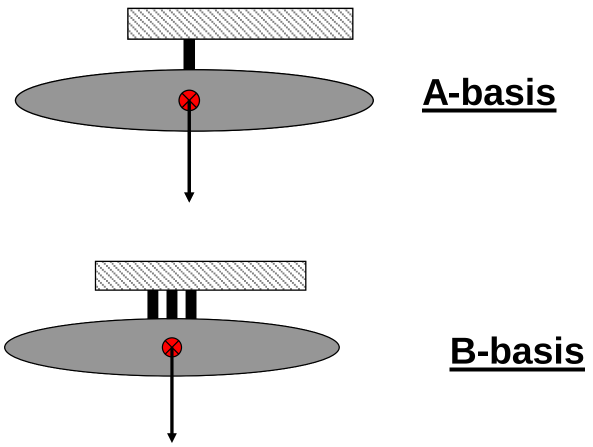
A-Basis or T99

- **At least 99% of the population of material values is expected to equal or exceed this tolerance bound with 95% confidence**
- **Single point catastrophic failure with no-load redistribution**

B-Basis or T90

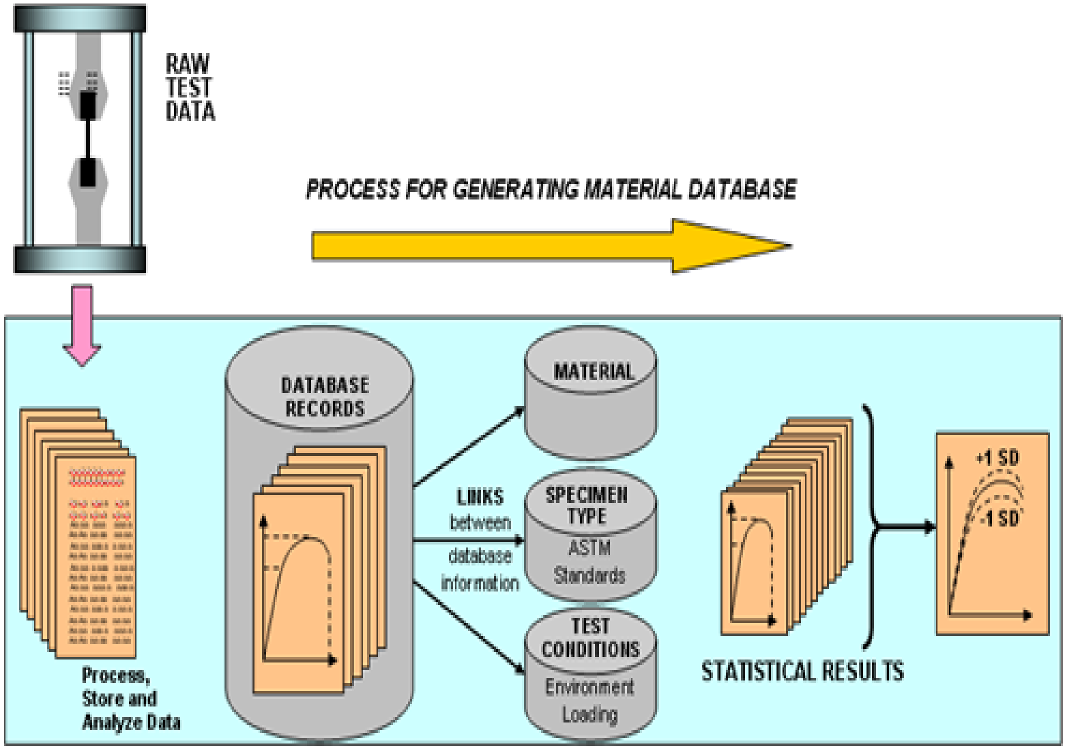
- **At least 90% of the population of material values is expected to equal or exceed this tolerance bound with 95% confidence**
- **Redundant load path with load redistribution**



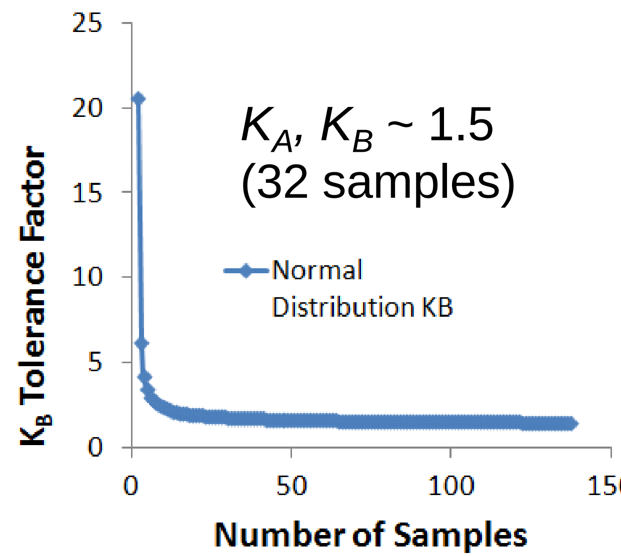


Generating Database of Material Properties is Costly

Many properties need to be determined from a variety of physical tests



One-sided B-basis tolerance limit factors, k_B, *for normal* distribution



Mathematical Model for Allowables relates standard deviation with mean value:

$$A - Basis\ value = \bar{x} - (K_A) \cdot s$$
$$B - Basis\ value = \bar{x} - (K_B) \cdot s$$

K Factor varies with number of samples

Ref: Department Of Defense Handbook Polymer Matrix Composites Volume 1. ***Guidelines For Characterization Of Structural Materials****, MIL-HDBK-17-1E, Volume 1 of 3, 23 JANUARY 1997*

CMH17 A-B Basis Robust & Reduced Sampling Test

A-Basis

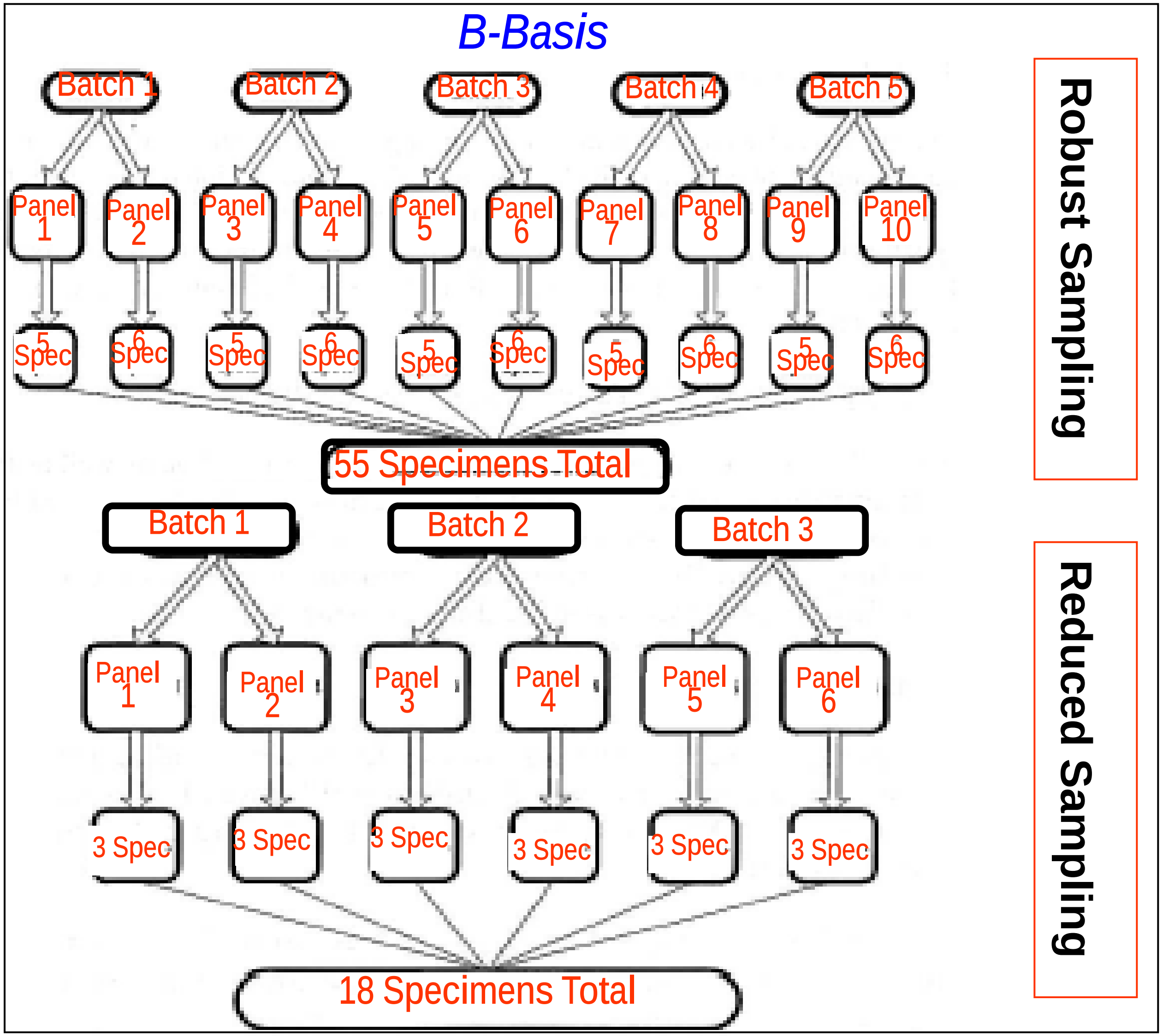
Category	# of Batches	# of Specimens
A-basis – Robust Sampling	10	75
A-basis – Reduced Sampling	5	55

Standard Practice:

- STAT 17/AGATE
- Modified CV Method
  - 8% inplane COV
  - 12 % out-of-plane
- All Requires Testing

Must follow requirements for:

- Panel Manufacturing
- Independent Cure process,
- Environment
- etc.



Ref: Final Report: *Material Qualification and Equivalency for Polymer Matrix Composite Material Systems* DOT/FAA/AR-03/19, September 2003, Office of Aviation Research, Washington, D.C. 20591

Allowables are Obtained From Many Tests

ASTM Test Methods

Common properties for determination of allowables for:

Lamina Level:

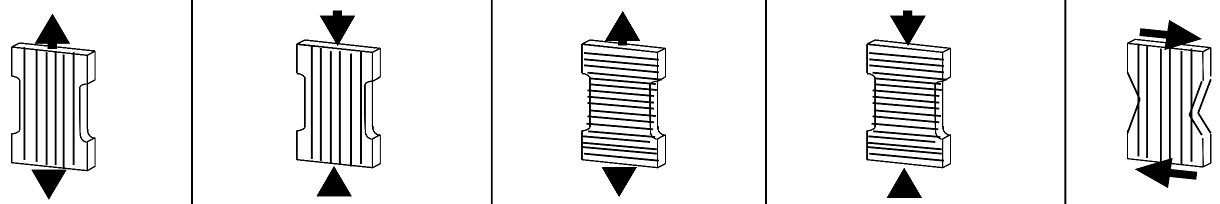
- Tension Strength & Modulus: *Warp and Fill*
- Compression Strength & Modulus: *Warp and Fill*
- Short Beam Strength
- Interlaminar Tension Strength
- In-Plane Shear Strength (0.2% offset, 5% strain) & Modulus
- **Laminate Level**
- Open-Hole & Filled-Hole Tension Strength
- Open-Hole & Filled-Hole Compression Strength
- Compression after Impact Strength
- Pin Bearing Strength
- Unnotched Tension Strength and Modulus
- Unnotched Compression Strength and Modulus
- Interlaminar Shear Strength

- **Environments**: cold temperature dry (CTD), room temperature dry (RTD), elevated temperature dry (ETD), and elevated temperature wet (ETW) conditions

Characterization Calibration

Calibration of Constituent Properties "Root Cause Problem"

Test Type				
3 coupons	3 coupons	3 coupons	3 coupons	3 coupons
Longitudinal Tension	Longitudinal Compression	Transverse Tension	Transverse Compression	Shear
ASTM D638, D3039	ASTM D695, D3410	ASTM D638, D3039	ASTM D695, D3410	ASTM D3518



Additional Tests Verification

ASTM Coupon Test Data Lamina or Laminate

(1) Longitudinal Tension

(2) Longitudinal Compression

(3) Transverse Tension

(4) Transverse Compression

(5) Shear

<u>Start</u>
Manufacturer fiber and matrix stiffness and strength

GENOA MCA

Difference Analysis vs. Test

Not Acceptable

Adjust fiber and matrix properties

Sensitivity Data

Acceptable

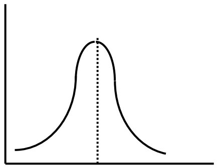
Fiber and matrix constituent properties

Qualification: Reproduce Lamina Level Testing*

Consider variability in 32 fiber/matrix properties and 6 manufacturing variables

INPUT

Fiber and Matrix Uncertainty Data



- **Fiber and matrix properties**
- **Assumed or manufacturer provided coefficients of variation**
- **Variability in Manufacturing**

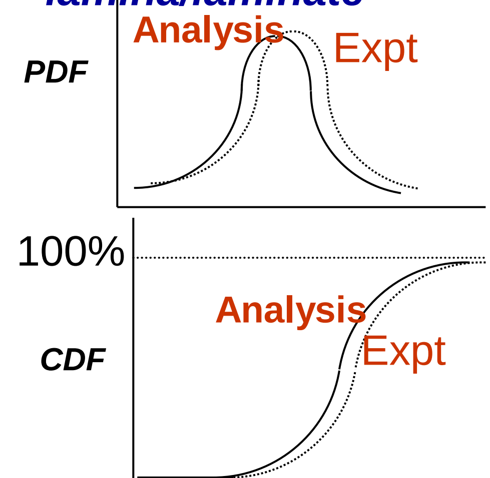
Identify Root cause for Composite Failure; Determine Scatter in Failure Stress

OUTPUT

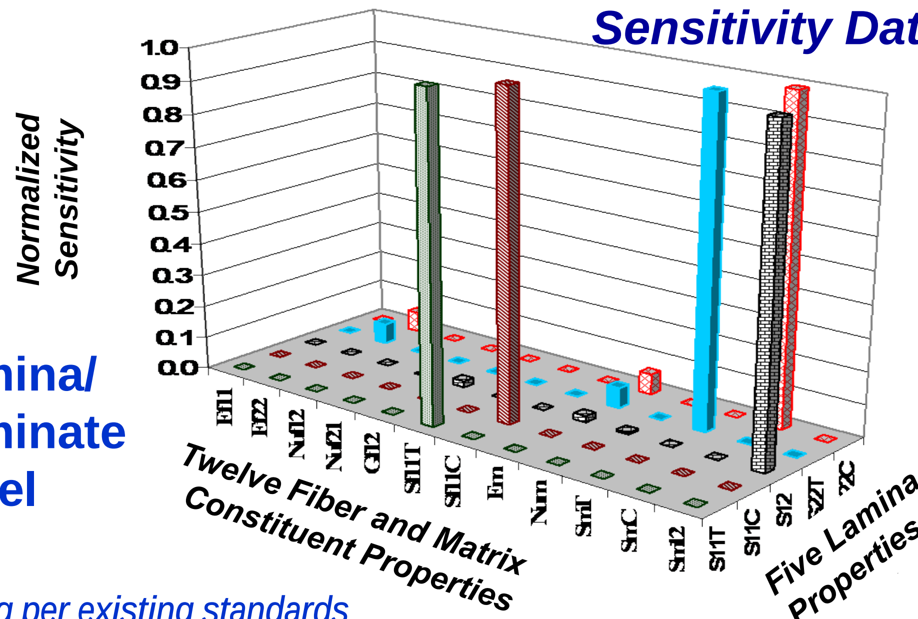
Sensitivity Data

SUPPLEMENTARY OUTPUT

Probability and cumulative density functions for lamina/laminate



Lamina/ Laminate Level



**Testing per existing standards*

Ref: G. Abumeri, M. Garg, M. Taleghani, "A Computational Approach for Predicting A- and B-Basis Allowables for Polymer Composites". SAMPE 2008, Memphis Tennessee, September, 2008.

Flow Chart for Generation of A & B values with Reduced Testing

Combines multi-scale multi-physics progressive failure analysis & advanced probabilistic

- Lamina level data are used to predict laminate & higher order tests from micro-scale
- Fewer laminate level tests are needed;
- Rely on simulation to virtually generate tests
- Determine Right # of tests

Characterization of Material with Lamina Level Testing

Lamina Level Testing (per FAA/CMH17 Guidelines)

- LT, LC, TT, TC, TT & IPS
- Environments: CTD, RTD, ETW1, & ETW2
- Minimum 18 specimens (3 batches)

Material Characterization

- Reverse engineer In-Situ fiber & matrix properties from lamina level testing;
- Repeat for each environment;

Multi-Scale PFA Simulation

Sensitivity Analysis

- Determine influence of material and fabrication random variables on lamina strength;

Calibration of Uncertainties

- Reverse Engineering of uncertainties:
  - Fiber & matrix properties parameters;
  - Fabrication variables;

Reproduce Lamina Level Test Scatter

- Determine with calibrated COVs scatter observed in lamina level testing;
- Compare CDF/PDF from test and simulation;
- Adjust COVs of manufacturing variables as needed

Determination of Allowables

Virtual Sampling of Notched and Un-Notched Laminates

- Apply uncertainties to select laminates;
- Generate 55 or 75 random samples (with FEA of specimens as applicable);
- Run laminate samples with MS-PFA;
- Retrieve strength & stiffness;

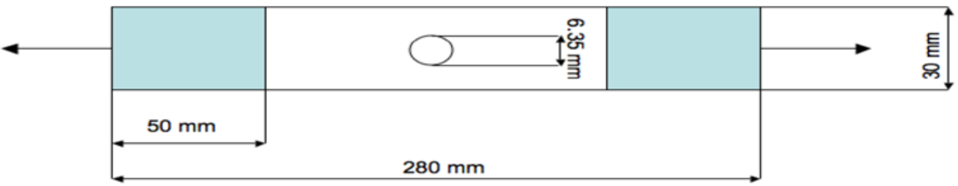
Calculate Allowables

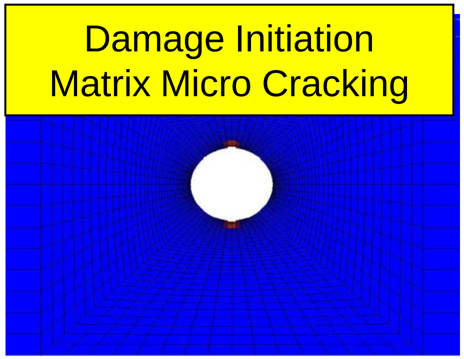
- Run probabilistic analysis to rank sensitivity of random variables & generate strength CDF and PDF;
- Use Bayesian statistics to update CDF & PDF with limited test (if available);
- Obtain A and B-Basis from:
  - 1/100 and 1/10 probabilities off CDF curve from probabilistic analysis or
  - STAT17 using MS-PFA generated samples;

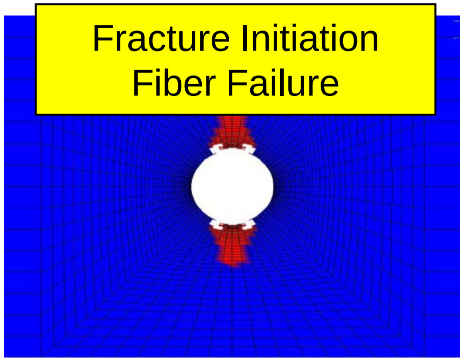
Longitudinal Tension (LT); Longitudinal Compression (LC); Transverse Tension (TT); Transverse Compression (TC); In-plane Shear (IPS)

Example of A-B Allowables Prediction

# of Tests = 30 – Notched Laminate (tension)

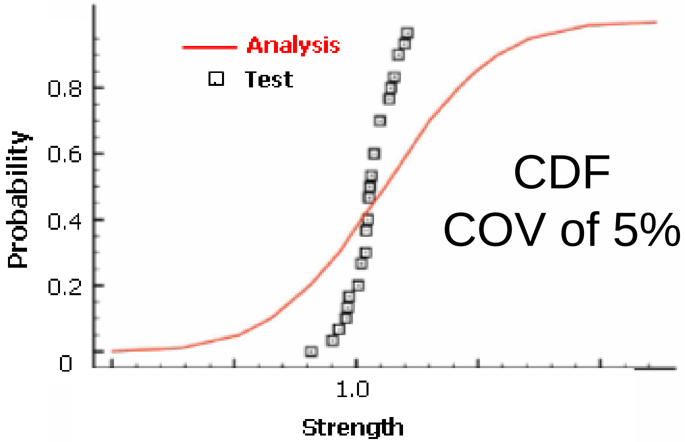


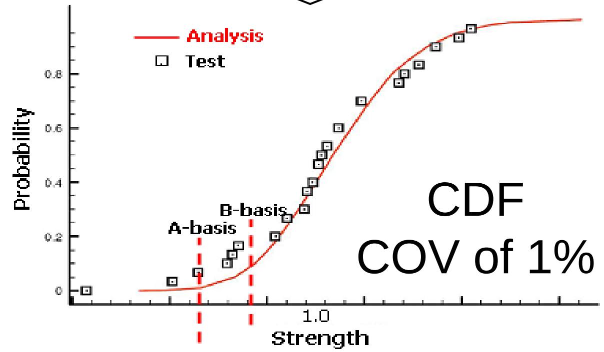




Random Variables Used in Simulation

Property	COV
Fiber longitudinal modulus	5%
Fiber longitudinal tensile strength	5%
Matrix modulus	5%
Matrix tensile strength	5%
Matrix shear strength	5%
Fiber volume fraction	5%
Void volume fraction	5%





Prediction vs. Test

Normalized	Test	Analysis	Error
A-basis	0.92	0.9104	1.04%
B-basis	0.9486	0.959	1.10%

Ref: M. R. Talagani, Z. Gurdal, and F. Abdi, S. Verhoef "Obtaining A-basis and B-basis Allowable Values for Open-Hole Specimens Using Virtual testing" AIAAC-2007-127, 4. Ankara International Aerospace Conference, 10-12 September, 2007 – METU, Ankara.

Why Material Characterization and Qualification?

CHARACTERIZATION

- **Identify Root Cause Problem**: Composites Damage/Failure Initiates at Fiber/Matrix
  - **Input: Lamina or Laminate ASTM standard Test Data**
- **Several Failure Mechanisms** Cause the Damage to Evolve from (Translaminar to Interlaminar):
  - **Matrix and Fiber → Lamina → Interlaminate → Laminate**
- **Study Different Material and Layup** and Architecture to Meet Design Requirements
  - **Fiber Failure Dominated**
  - **Matrix Failure Dominated (Delamination and Shear)**

QUALIFICATION

- **Introduce Scatter** at Fiber/Matrix or Lamina Level to Study the Effect at Laminate Level
- **Effect of Defects** (Manufacturing Parameters and Anomalies)
  - **Voids, Waviness and Gaps**
- **Rapid Assessment** as it is Independent of Finite Element Analysis

- **Generate (Import/Export) 'As Built' Material Properties** for FEA
  - **Input: model.bdf (NASTRAN), model.inp (ABAQUS), *model.cdb (ANSYS)**
  - **Output: *MAT8 (NASTRAN), *MATERIAL (ABAQUS), *MP (ANSYS)**

Characterization

Failure Process in Composite Thermal Mechanical

Manufacturing Defects

- Matrix Void Shape/Size/Distribution
- Thickness Effect
- Residual Stress
- Fiber Waviness
- Resin Rich

Damage Evolution

Trans Laminar Failure

- Matrix Crack Density
- Matrix Failure (L/T)
  - Tension
  - Compression
  - Shear
- Inter Phase
- Fiber Failure (L/T)
  - Long Compression
  - F/Matrix Delamination
  - Fiber micro Buckling
  - Fiber Compression
  - Shear kink band
- Ply Failure
  - Tension
  - Compression
  - Shear

Interlaminar Failure

- Interlaminar Shear
- Interlaminar Tension
- Relative Rotation
- Edge Delamination

Propagation

- Crack Path
  - 2-d
  - 3-d

Fracture Evolution

Fracture Initiation

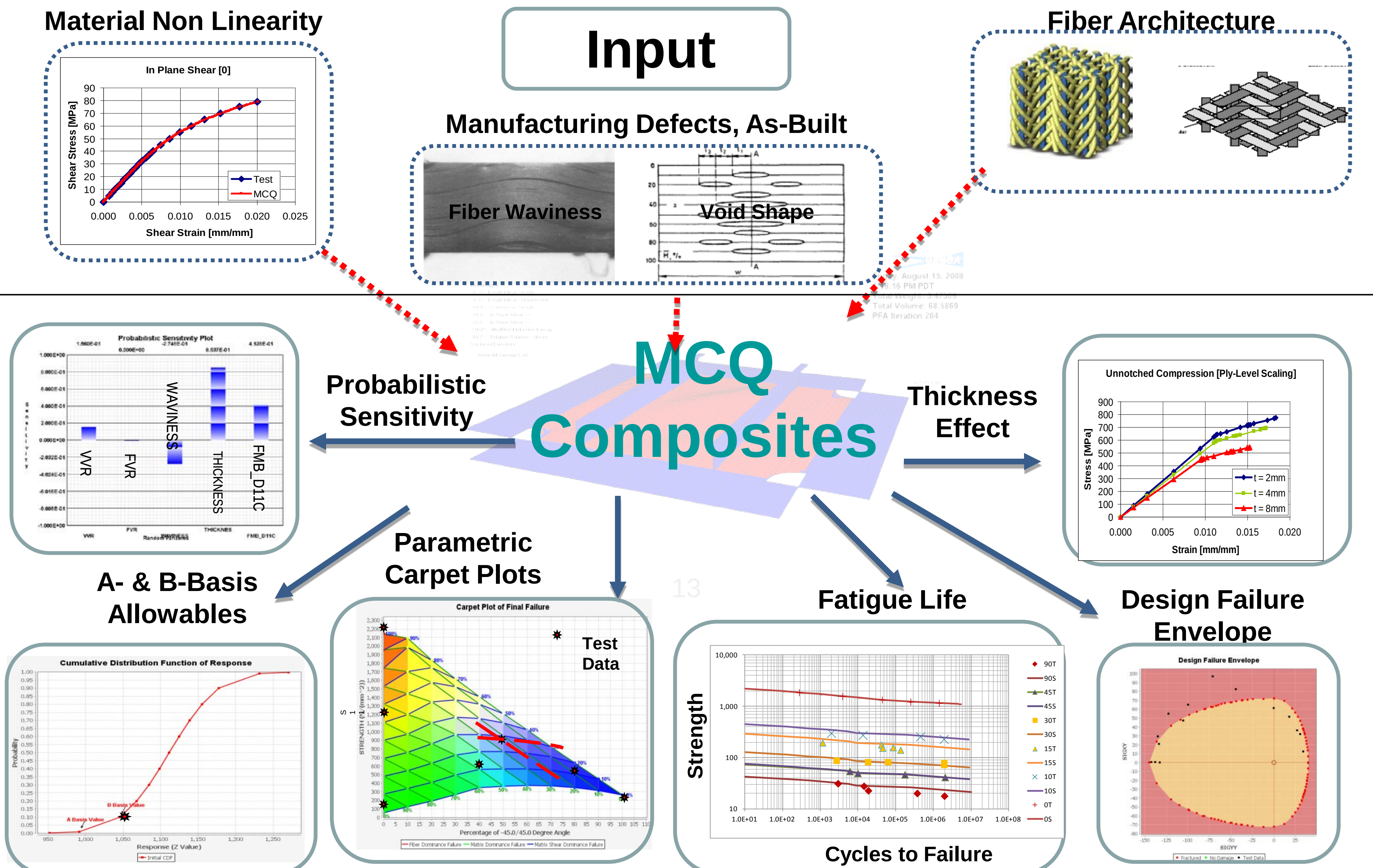
- .005 inch

Fracture Propagation

- Gic
- GIIc
- Mixed Mode

Residual Strength

PMC Material Characterization and Qualification (MCQ)



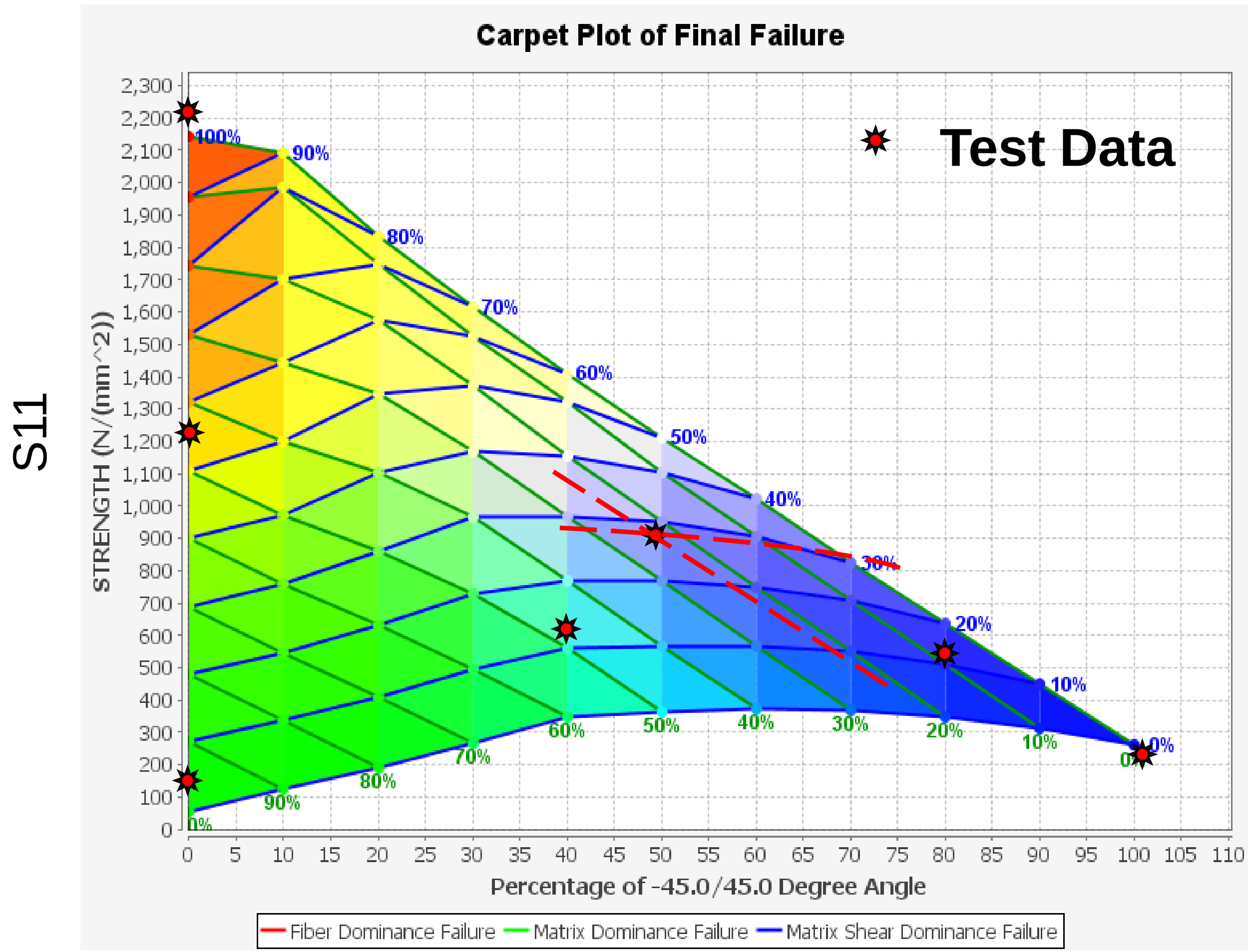
lpha STAR Corporation

Characterization of Carbon Composite IM7/MT45 (Tape)

Parametric Carpet Plot of Longitudinal Failure Stress for Un-Notched Tension

Benefits:

- Provide alternate design options
- Reduce testing by validating fewer laminates and generate other laminates with simulation
- Identify region with dominant failure such matrix cracking, fiber failure, etc. to reduce risk in structural design

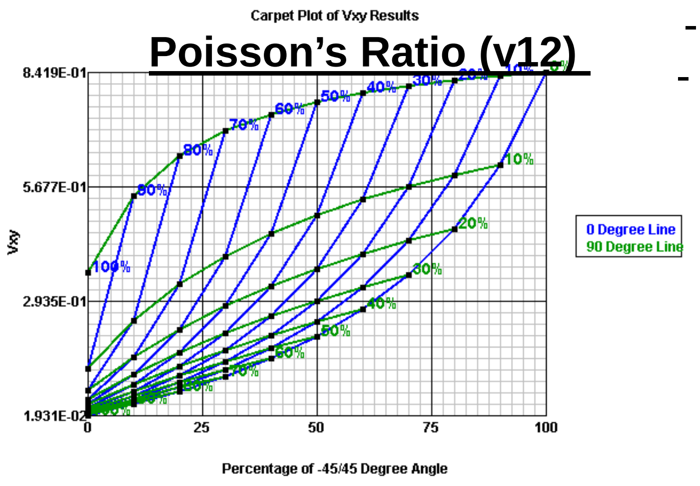


Characterization of Carbon Composite IM7/MT45 (Tape)

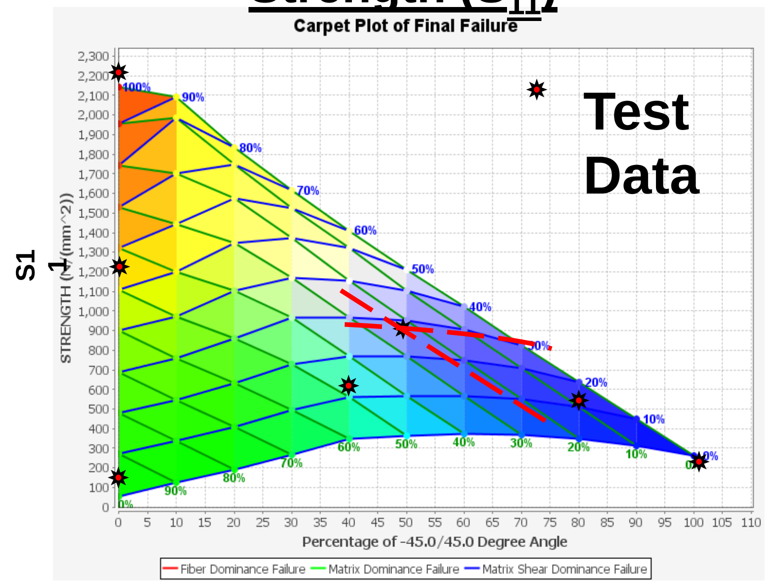
Parametric Carpet Plot of Strength, Stiffness and Poisson's Ratio – Un-Notched Tension

Benefits:
-Design options
- Reduce testing

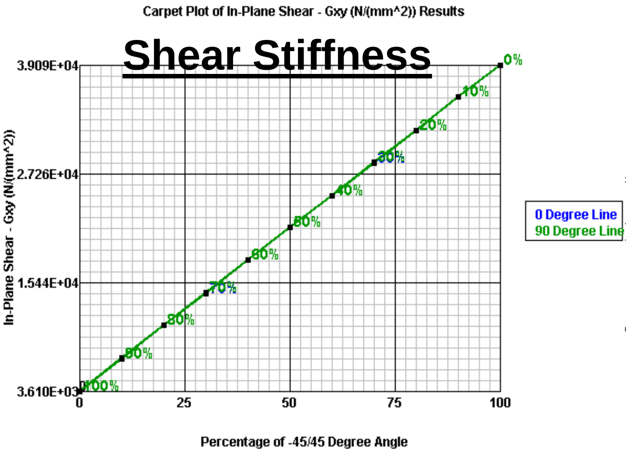
Poisson's Ratio (ν12)



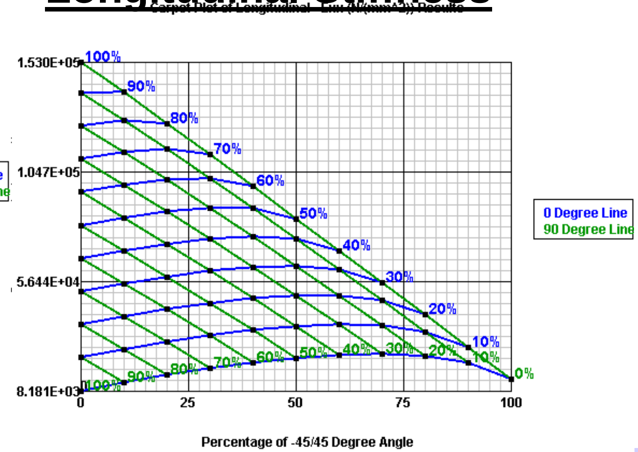
Strength (S_{11})



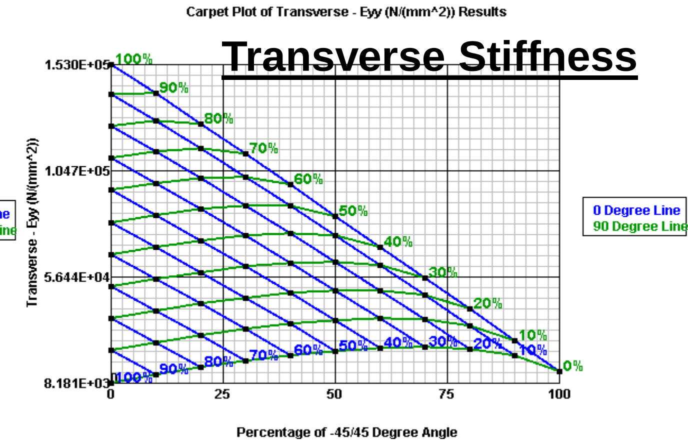
Shear Stiffness



Longitudinal Stiffness

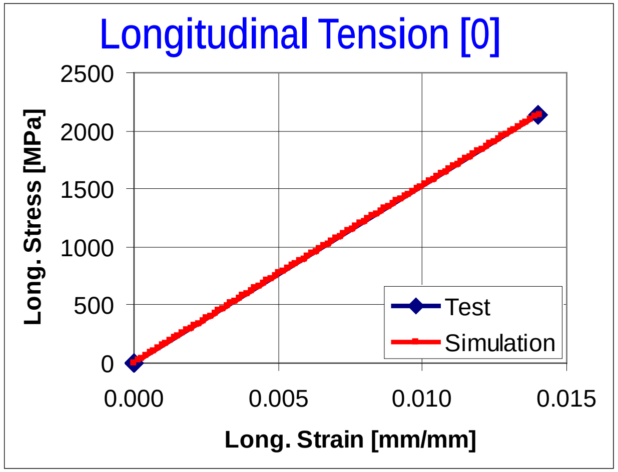


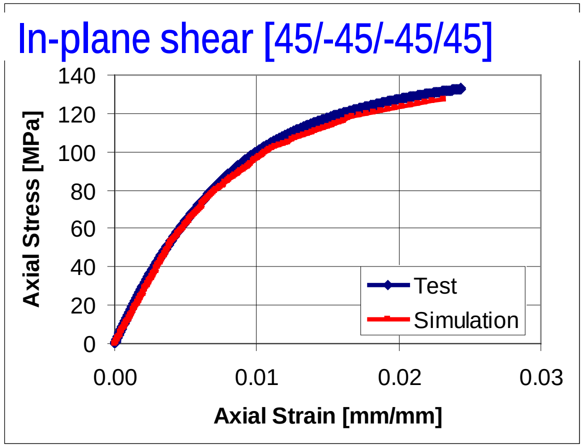
Transverse Stiffness

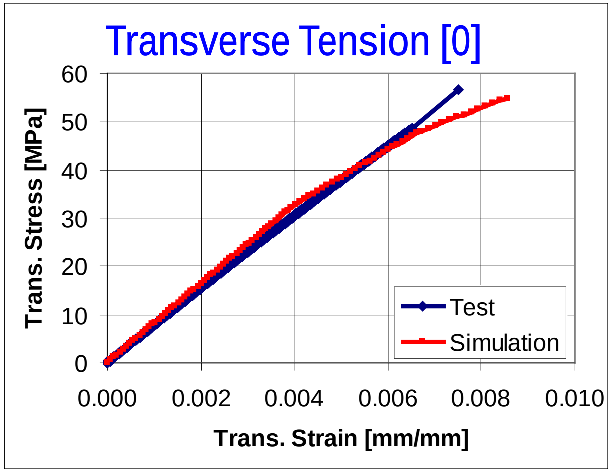


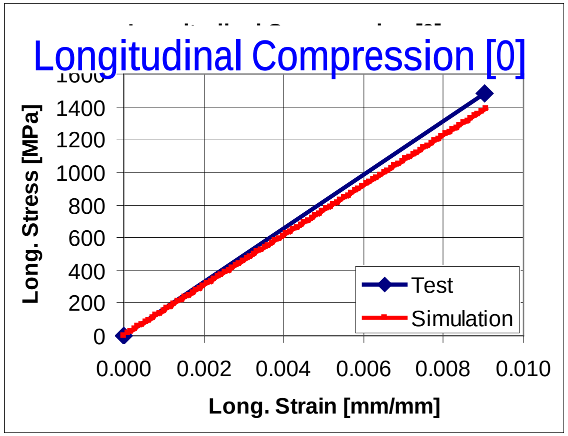
Characterization Validation

Un-notched IM7/MT45 (Tape); Stress-strain from simulation compared to test



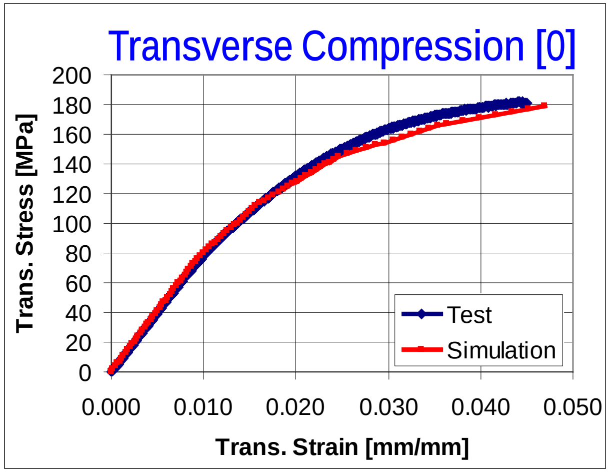






Un-notched Tension Strength From Test and MCQ simulation

Layup [0%/45%/90%]	Test [MPa]	MCQ [MPa]	Error [%]
[50/0/50]	1204.56	1110.00	-7.85
[25/50/25]	901.87	855.00	-5.20
[10/80/10]	504.03	507.90	0.77
[50/40/10]	1377.62	1319.00	-4.26

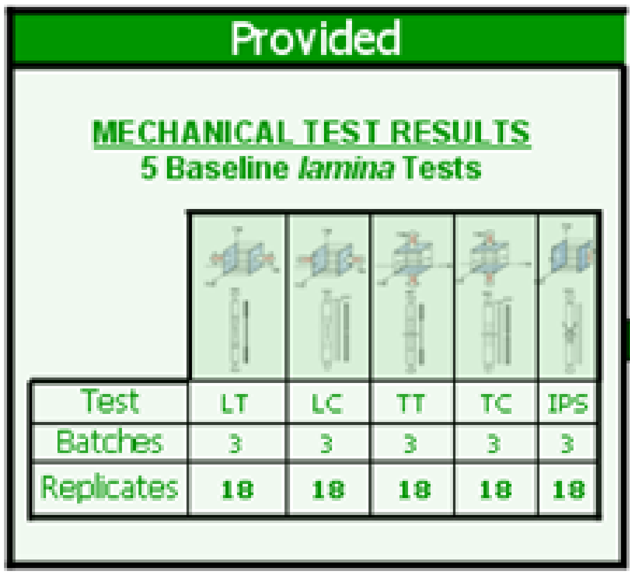


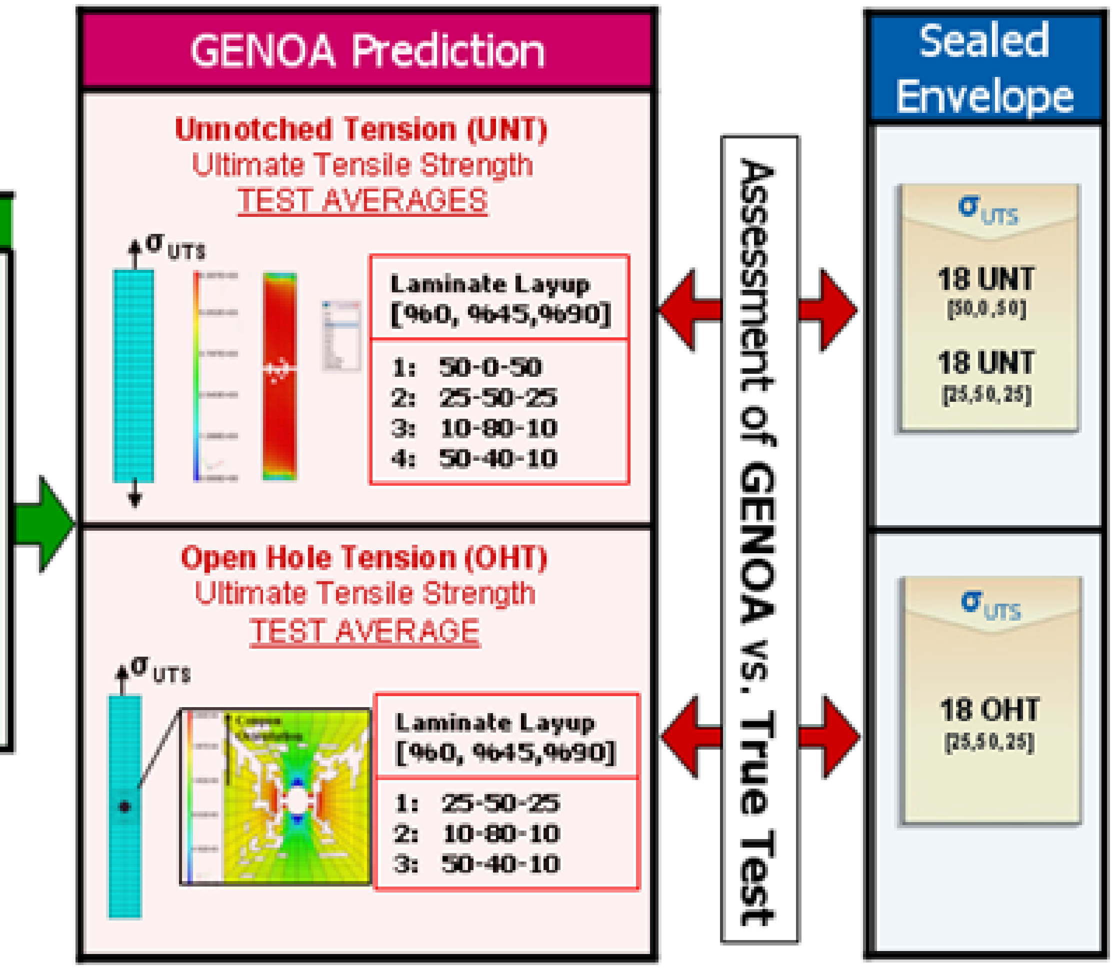
Ref: G. Abumeri, M. Garg, F. Abdi, A. McCloskey and R. Bohner, "*Validation of a Computational Approach for Composite Material Allowables Using Sealed Envelope Predictions for Reduced Testing* ," Sampe Journal, September/October 2009.

Process Used for Mechanical Test Predictions IM7/MTM45-1

1/3 of Test Data is Used to Predict Laminate (notched/Un-notched)

Lamina Level test Data Provided by NGC





Ref: G. Abumeri, M. Garg, F. Abdi, A. McCloskey and R. Bohner, "*Validation of a Computational Approach for Composite Material Allowables Using Sealed Envelope Predictions for Reduced Testing*," *Sampe Journal, September/October 2009.*

Sealed Envelope Predictions for Mean Strength

Validation of Characterization

Coupon Type	Lamina Proportions [%0 -,%45 -%90]	Failure Stress from GENOA Sealed Envelop Prediction (ksi)	Failure Stress Average from True Tests (ksi)	Error	Number of Replicas Tested *
Un-notched Tension - RTD	[50-0-50]	177	174.7	1.31%	19 (3 batches)
	[25-50-25]	134	130.8	2.44%	18 (3 batches)
	[10-80-10]	67	73.1	-8.29%	6 (1 batches)
	[50-40-10]	194	199.8	-2.91%	6 (1 batches)
Open-Hole Tension - RTD	[25-50-25]	72.72	66.8	8.88%	18 (3 batches)
	[10-80-10]	42.86	46.4	-7.65%	6 (1 batches)
	[50-40-10]	99.02	113.4	-12.7%	8 (1 batches)

*** Test results were not available prior to delivering MS-PFA GENOA simulation results**

Ref: *G. Abumeri, M. Garg, F. Abdi, A. McCloskey and R. Bohner, "Validation of a Computational Approach for Composite Material Allowables Using Sealed Envelope Predictions for Reduced Testing ," Sampe Journal, September/October 2009.*

Determine Allowables for IM7/MTM45-1

Sealed Envelope Predictions for B-basis of Un-Notched and Notched Laminates

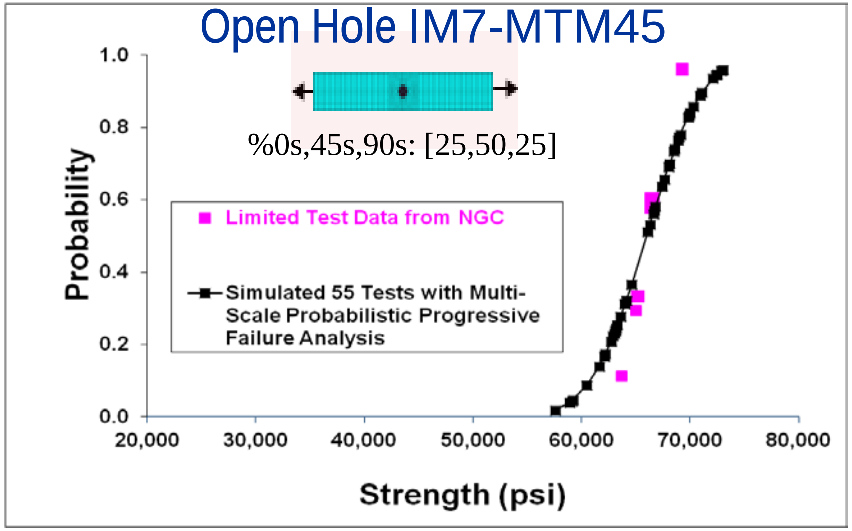
Coupon Type	Lamina Proportions [%0-%45-%90]	Number of Replicas Provided for GENOA Solution	B-Basis Strength GENOA-PFA* Sealed Envelop (ksi)	B-Basis Strength MIL-HDBK 17** (ksi)	Error	B-Basis Strength Modified COV Method**	Error
Un-notched Tension - RTD	[50-0-50]	6 of 19	156.22	158.54	-1.461%	154.13	1.36%
	[25-50-25]	6 of 18	112.98	119.91	-5.77%	116.54	-3.05%
	[10-80-10]	3 of 6	69.09	69.3	-0.30%	68.8	0.42%
	[50,-40-10]	3 of 6	173.41	170	-2.91%	164.44	5.46%
Open-Hole Tension - RTD	[25-50-25]	6 of 18	59.4	62.15	-4.42%	59.5	-0.17%
	[10-80-10]	3 of 6	41.59	41.5	0.23%	38.54	7.93%
	[50-40-10]	3 of 8	98.13	n/a	n/a	97.98	0.15%

*** Data from reduced number of test replicas are used in GENOA to calculate B-basis values; remaining test data were not made available until after the determination of B-basis with GENOA**
****Obtained from References [8,9] with CMH-17**

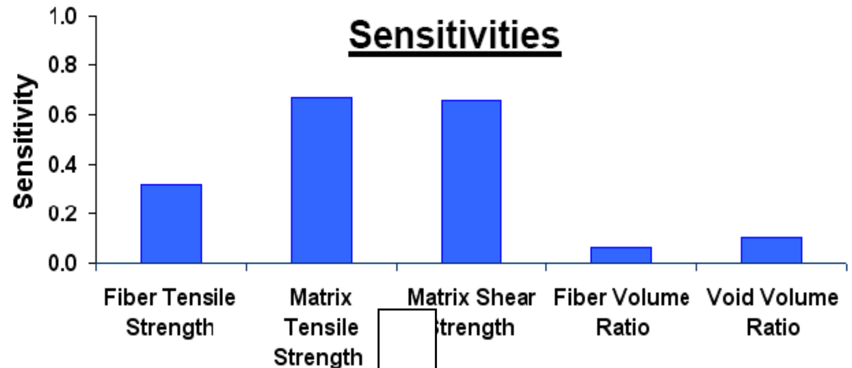
Ref: G. Abumeri, M. Garg, F. Abdi, A. McCloskey and R. Bohner, "*Validation of a Computational Approach for Composite Material Allowables Using Sealed Envelope Predictions for Reduced Testing* ," Sampe Journal, September/October 2009.

B-Basis Strength Prediction (Sealed Envelope]

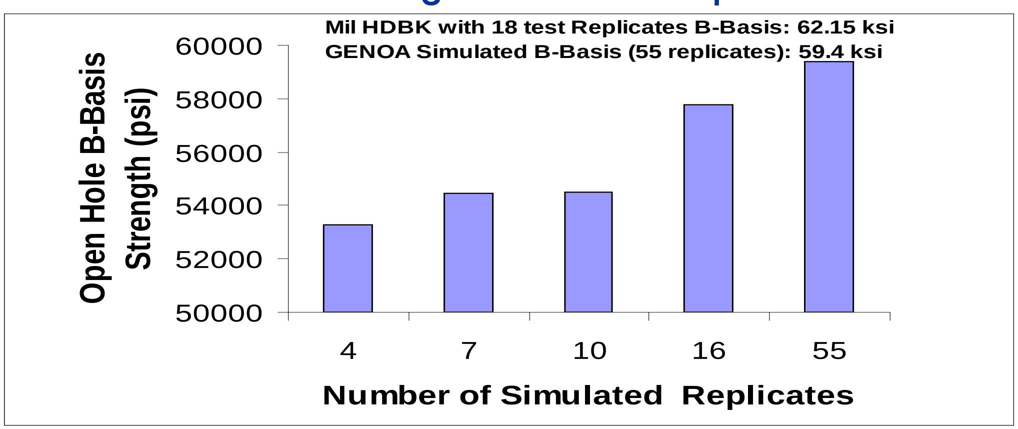
Determine # of Tests, Reduce Testing (Virtual Generation Of Test Replicates)



Sensitivity Identifies Cause of Scatter



Determine Right # of Test Replicates:



Prediction Vs. Test: 66% Replicate Reduction

Data	B-Basis Allowable	%Diff
*Physical Test	62.15 ksi	——
Genoa Simulated Test	59.40 ksi	- 4.4%

Ref: G. Abumeri, M. Garg, F. Abdi, A. McCloskey and R. Bohner, "*Validation of a Computational Approach for Composite Material Allowables Using Sealed Envelope Predictions for Reduced Testing*,", *Sampe Journal, September 2009,In print.*

Determine Allowables for AS4/MTM45-1

Reverse Engineering of Uncertainties from Unidirectional Testing

Test Longitudinal Tension Strength Data

Env	CTD	RTD	ETW	ETW2
Mean	266.77	274.78	257.63	271.16
Stdev	17.56	14.87	11.43	9.57
CV	6.58	5.41	4.44	3.53

Lamina prediction after calibration compared with test

AS4/12k (Tape): FVR=60.65%; VVR=2%

Propety	RTD		
	Test [msi]	Simulation [msi]	Error [%]
E11	17.925	18.79	4.83
E22	1.2	1.15	-4.17
G12	0.53	0.53	0.00
v12	0.02	0.019	-5.00
	[ksi]	[ksi]	[%]
S11T	274.78	271.6	-1.16
S11C	203.65	200.9	-1.35
S22T	6.92	6.84	-1.16
S22C	26.81	25.18	-6.08
S12S	9.36	8.68	-7.26

Fiber and Matrix Properties Random Variables

Material Variables Setup

Type	Name	Property	Mean Value	Coefficient Variation	Standard Deviation	Distribution Type
FIBER	AS4-	E11 (Longitudinal Modulus)	31390000	0.030000	941700.000000	Normal
FIBER	AS4-	S11T (Tensile Strength)	450000	0.055000	24750.000000	Normal
FIBER	AS4-	S11C (Compressive Strength)	312000	0.050000	15600.000000	Normal
MATRIX	MT45	E (Normal Modulus)	349500	0.031000	10834.500000	Normal
MATRIX	MT45	ST (Tensile Strength)	10750	0.175000	1881.250000	Normal
MATRIX	MT45	SC (Compressive Strength)	40000	0.050000	2000.000000	Normal
MATRIX	MT45	SS (Shear Strength)	14000	0.040000	560.000000	Normal

Fabrication Parameters Random Variables

Fabrication Variables Setup

Property	Plies	Mean Value	Coefficient Variation	Standard Deviation	Distribution Type
FVR	1-8	0.6065	0.040000	0.024260	Normal
VVR	1-8	0.02	0.025000	0.000500	Normal

Statistical Uncertainties Remain unchanged for laminate level

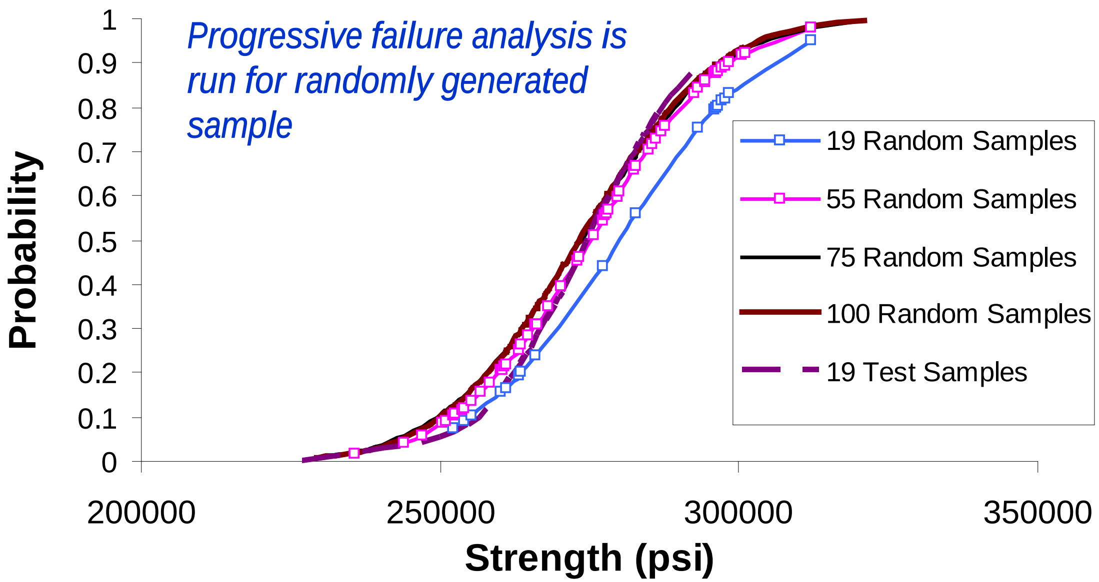
FVR: Fiber volume ratio; VVR: Void volume ratio

Determine Allowables for AS4/MTM45-1

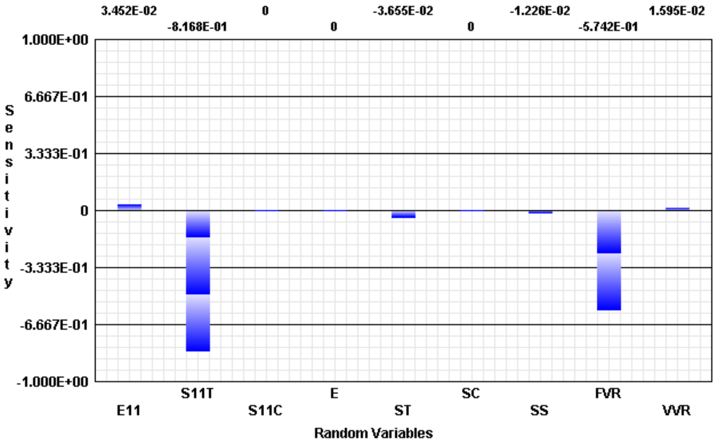
Lamina Longitudinal Tension Allowables Determined with MS-PFA

	# Samples	Mean Strength (ksi)	A-Basis (ksi)	% Diff	B-Basis (ksi)	% Diff
NIAR Test Report	**19**	**274.78**	**234.76**		**256.71**	
MS-PFA	**19**	**279.97**	**230.03**	**-2.01%**	**251.71**	**-1.95%**
MS-PFA	**55**	**275.18**	**224.01**	**-4.58%**	**245.80**	**-4.25%**
MS-PFA	**75**	**273.52**	**222.17**	**-5.36%**	**244.18**	**-4.88%**
MS-PFA	**100**	**273.31**	**224.49**	**-4.37%**	**245.54**	**-4.35%**

CDF: Test compared to simulation



Sensitivity Analysis



Fiber tensile strength;
Fiber volume ratio

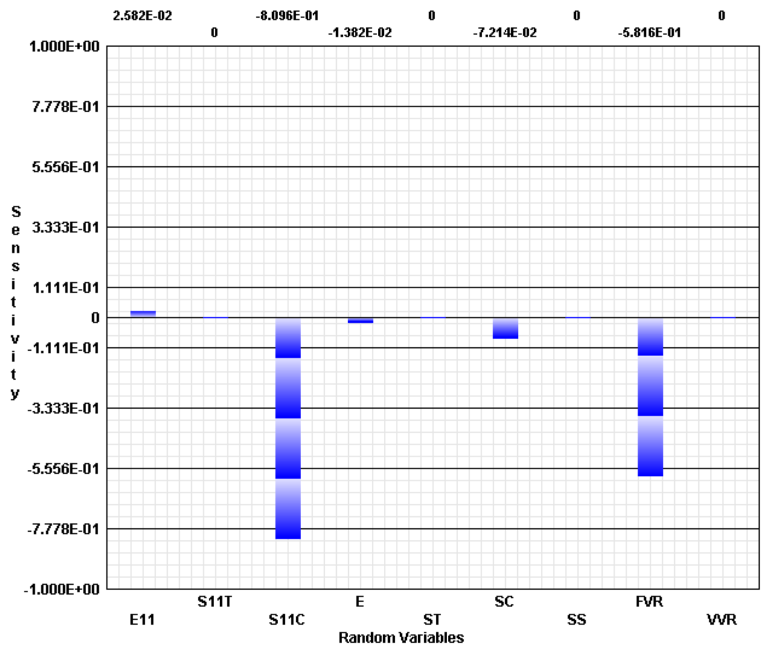
__Test Ref:__ E. Clarckson, "Advanced Composites Group MTM45-1 145 AS4 Unidirectional Tape Qualification Statistical Analysis Report", National Institute for Aviation Research, Wichita State University, 2009.

Determine Allowables for AS4/MTM45-1

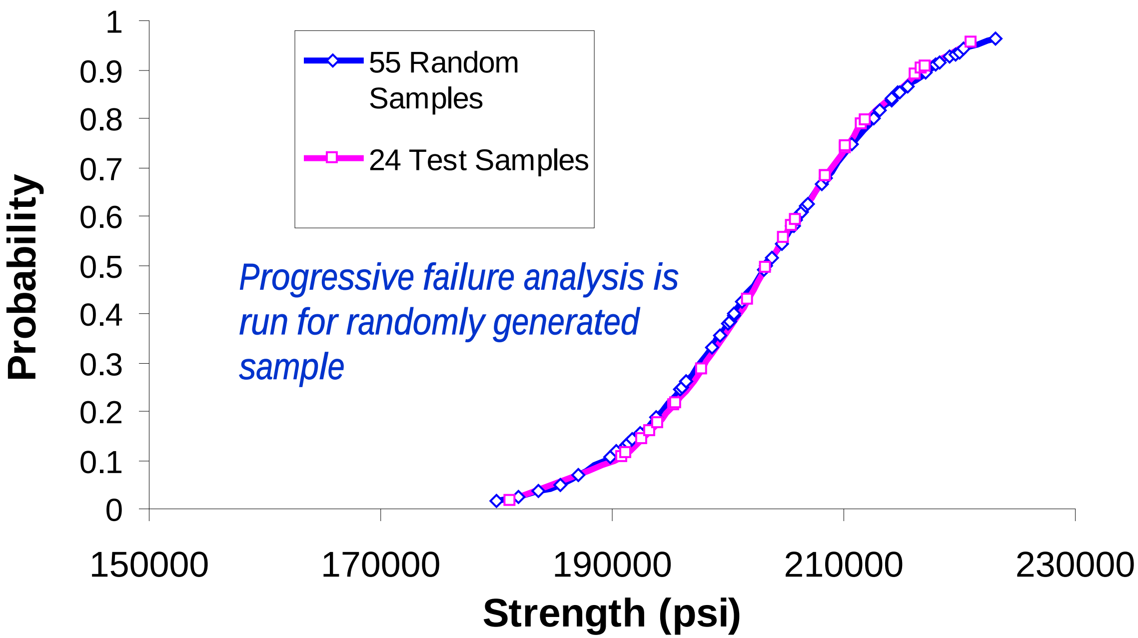
Lamina Longitudinal Compression Allowables Determined with MS-PFA

	# Samples	Mean Strength (ksi)	A-Basis (ksi)	% Diff	B-Basis (ksi)	% Diff
Test Report	**24**	**203.53**	**168.23**		**182.47**	
MS-PFA	**55**	**203.38**	**172.55**	**2.57%**	**185.68**	**1.76%**

Sensitivity Analysis



CDF: Test compared to simulation



Fiber compressive strength; Fiber volume ratio

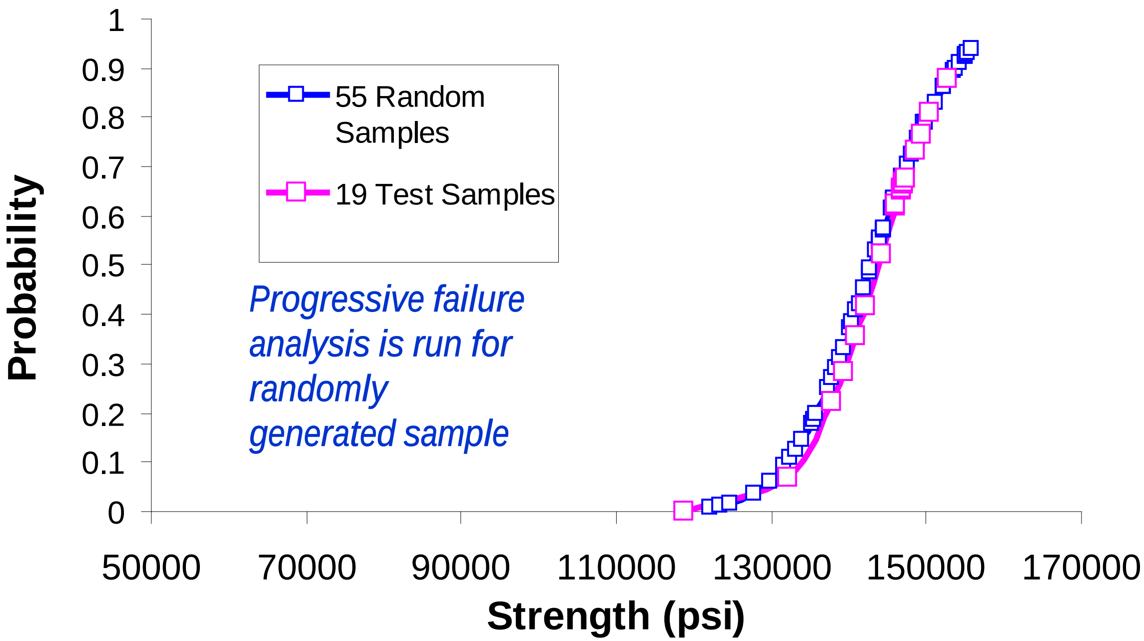
Determine Mixed Laminate Allowables: AS4/MTM45-1

Laminate (0/90)s Un-Notched Tension Allowables Determined with MS-PFA

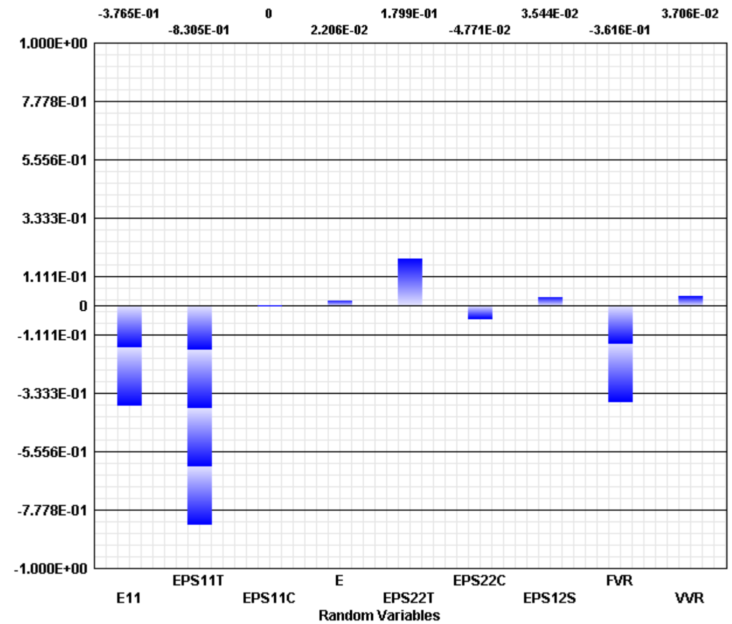
	# Samples	Mean Strength (ksi)	A-Basis (ksi)	% Diff	B-Basis (ksi)	% Diff
NIAR Test Report	**19**	**143.74**	**122.82**		**131.12**	
MS-PFA	**55**	**142.96**	**118.996**	**-3.11%**	**129.20**	**-1.46%**

CDF: Test compared to simulation

(test data are not used to guide prediction, plotted for comparison purpose)



Sensitivity Analysis



Fiber modulus, tensile strain of fiber, and fiber volume ratio

Test Ref: E. Clarckson, "*Advanced Composites Group MTM45-1 145 AS4 Unidirectional Tape Qualification Statistical Analysis Report*", *National Institute for Aviation Research, Wichita State University, 2009.*

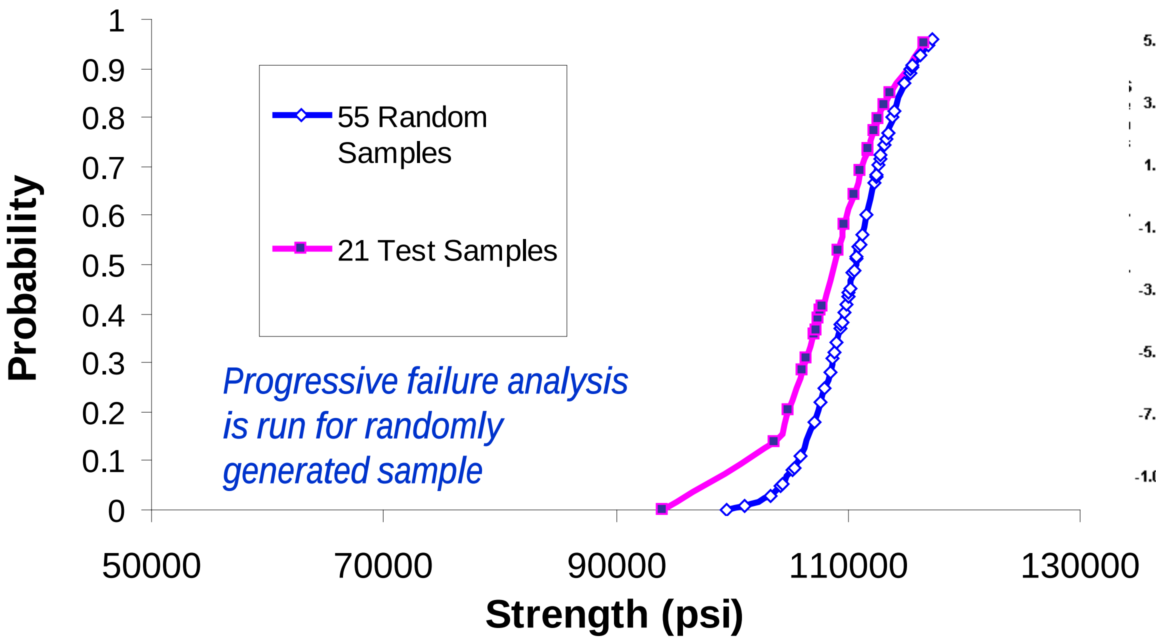
Determine Mixed Laminate Allowables: AS4/MTM45-1

Quasi-Isotropic Laminate Un-Notched Tension Allowables Determined with MS-PFA

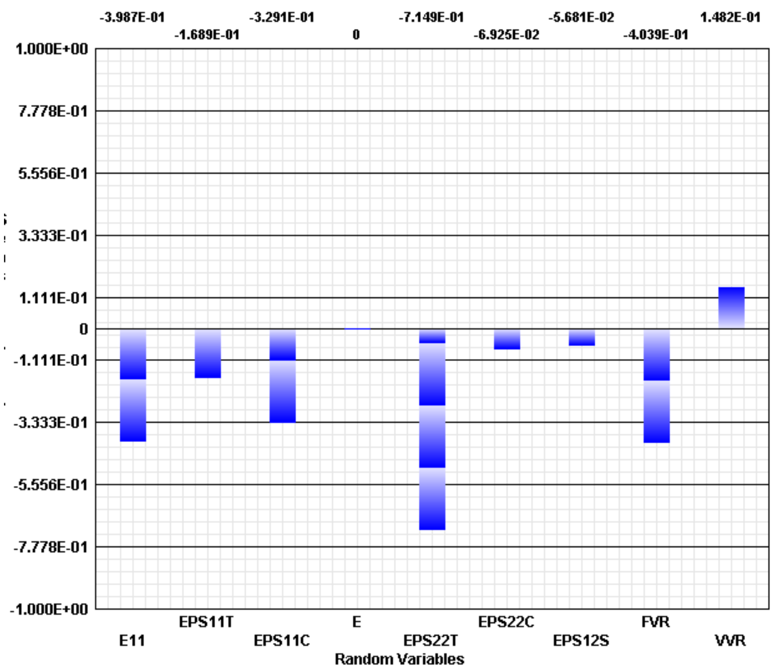
	# Samples	Mean Strength (ksi)	A-Basis (ksi)	% Diff	B-Basis (ksi)	% Diff
NIAR Test Report	21	108.82	93.53		99.89	
MS-PFA	55	110.62	99.80	6.70%	104.41	0.05

CDF: Test compared to simulation

(test data are not used to guide prediction, plotted for comparison purpose)



Sensitivity Analysis



Fiber stiffness, fiber compressive strain, fiber volume ratio, and void

Determine Environmental A & B (Carbon Epoxy Fabric)

Used 33% of Test Data to Generate Allowables, Multiple Environment Conditions

- **One Coupon Test from Each Cure Cycle of Each Batch guides the prediction of allowables**

Full Test Matrix from FAA Report* 18 specimens were tested (Compressive Loading)

		CTD	RTD	ETD	ETW
Batch	Panel	Strength (MPa)	Strength (MPa)	Strength (MPa)	Strength (MPa)
1	**1**	**711.95**	**650.83**	**501.33**	**384.79**
1	1	718.99	702.26	564.57	385.09
1	1	707.75	705.77	474.51	400.52
1	**2**	**767.63**	**699.42**	**543.11**	**438.42**
1	2	709.93	666.63	584.94	414.63
1	2	748.87	717.83	550.93	392.66
2	**3**	**780.56**	**705.75**	**403.34**	**434.27**
2	3	766.35	666.61	573.01	467.43
2	3	705.47	671.79	552.70	447.84
2	**4**	**734.84**	**656.84**	**557.20**	**421.23**
2	4	705.75	720.39	583.92	453.23
2	4	700.85	681.95	633.53	425.88
3	**5**	**773.25**	**646.38**	**524.75**	**428.16**
3	5	786.83	616.12	536.67	414.24
3	5	720.92	647.14	574.36	410.60
3	**6**	**746.63**	**658.58**	**508.45**	**456.43**
3	6	742.08	669.38	580.74	392.83
3	6	696.09	711.95	494.24	413.94

Data Marked in Red Used in Order Reported to Guide the Prediction Process

Ref: "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure". DOT/FAA/AR-03/19, Office of Aviation research, Washington, D.C. 20591, September 2003.

Determine Environmental A & B (Carbon Epoxy Fabric)

Derived Statistics to Generate Allowables

Input for Generation of Allowables

Random Variables Statistics

Random Variables Description	Symbol	COV	Mean Value	Distribution
Fiber Compressive Strength (Mpa)	Sf11C	7%	2069	Normal
Matrix Normal Modulus (Mpa)	Em	7%	3449	Normal
Matrix Compressive Strength (Mpa)	SmC	7%	241	Normal
Fiber Volume Ratio	FVR	7%	0.53	Normal
Void Volume Ratio	VVR	7%	0.02	Normal

COV remains unchanged for different environments

Fiber/Matrix Constituent Properties for Various Different Environments

Properties	Environment CTD	Environment RTD	Environment ETD	Environment ETW
Fiber Normal Modulus (11) (Mpa)	206928	206928	206928	206928
Fiber Normal Modulus (22) (Mpa)	20003	20003	20003	20003
Fiber Compression Strength (11) (Mpa)	*2276*	*2069*	*1483*	*1173*
Matrix Normal Modulus (Mpa)	3449	3449	3449	3449
Matrix Compression Strength (Mpa)	*262*	*241*	*193*	*179*

CTD: Cold Temperature Dry (-54 °C); RTD: Room Temperature Dry; ETD: Elevated Temperature Dry (82 °C); ETW: Elevated Temperature Wet (82 °C with 85% relative humidity)

Determine Environmental A & B with Reduced Testing

Reliable A and B Basis Strength Values Obtained Using 6 out of 18 replicates (66% Reduction as Compared to Standard Practices)

A-Basis Allowable

(Carbon Polymer Fabric Subject to Compressive Loading)

Environment	A-basis Strength (Mpa)	A-basis Strength (Mpa)	Error
	FAA Report (Ref 1)	GENOA Simulation	(wrt Ref 1)
Cold Temperature (-54 °C) Dry CTD	602.51	597.28	-0.87%
Room Temperature Dry RTD	555.60	538.50	-3.18%
Elevated Temperature (82 °C) Dry ETD	443.86	426.44	-4.09%
Elevated Temperature (82 °C) Wet ETW	345.43	344.99	-0.13%

B-Basis Allowable

(Carbon Polymer Fabric Subject to Compressive Loading)

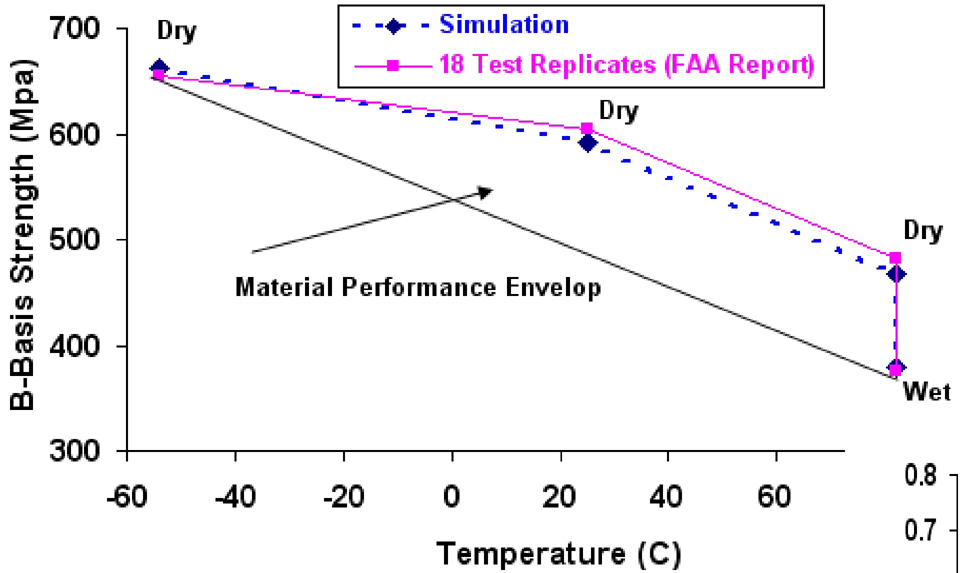
Environment	B-basis Strength (Mpa)	B-basis Strength (Mpa)	Error
	FAA Report (Ref 1)	GENOA Simulation	(wrt Ref 1)
Cold Temperature (-54 °C) Dry CTD	655.13	661.44	0.95%
Room Temperature Dry RTD	604.16	592.71	-1.93%
Elevated Temperature (82 °C) Dry ETD	482.62	468.00	-3.12%
Elevated Temperature (82 °C) Wet ETW	375.64	378.99	0.88%

Ref:

1. *"Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure". DOT/FAA/AR-03/19, Office of Aviation research, Washington, D.C. 20591, September 2003.*
2. *G. Abumeri, F. Abdi, and M. Lee, "Verification of Virtual Generation of A- and B-Basis Allowables of Polymer Composites Subject to Various Environmental Conditions", Presented at SAMPE CHINA 2009 Conference-Tianjin Binhai, Oct. 28-29-30, 2009*

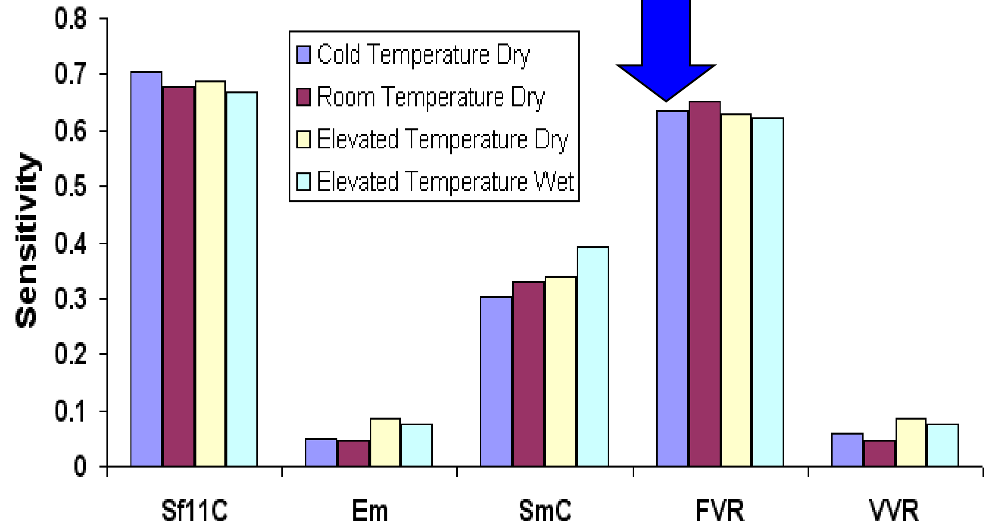
Determine Environmental A & B with Reduced Testing

Material Performance Envelop and Sensitivity of Composite Variables



Material Performance Envelop

Sensitivity to Environment



Random Variables Contributing to Allowables Prediction:

Sf11C: Fiber compressive Strength
Em: Matrix modulus
SmC: Matrix compressive strength
FVR: Fiber volume ratio
VVR: Void volume ratio

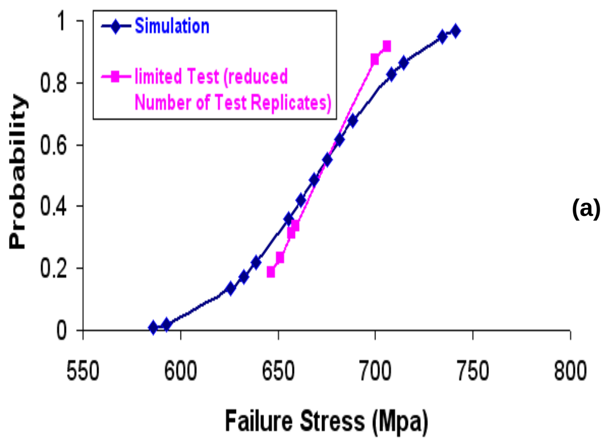
Ref:

1. *"Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure". DOT/FAA/AR-03/19, Office of Aviation research, Washington, D.C. 20591, September 2003.*
2. *G. Abumeri, F. Abdi, and M. Lee, "Verification of Virtual Generation of A- and B-Basis Allowables of Polymer Composites Subject to Various Environmental Conditions", Presented at SAMPE CHINA 2009 Conference-Tianjin Binhai, Oct. 28-29-30, 2009*

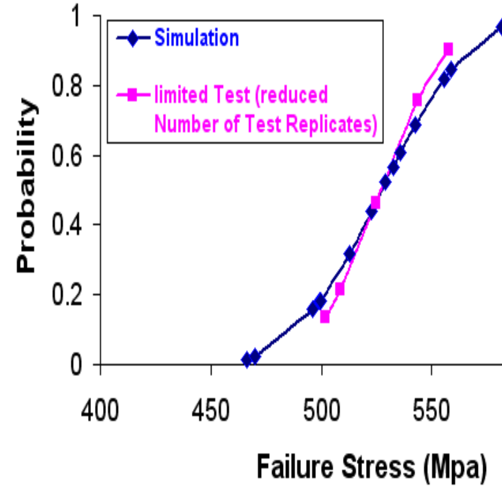
Determine Environmental A & B with Reduced Testing

Fewer Tests Guides the Prediction Process

Room Temperature Dry Condition



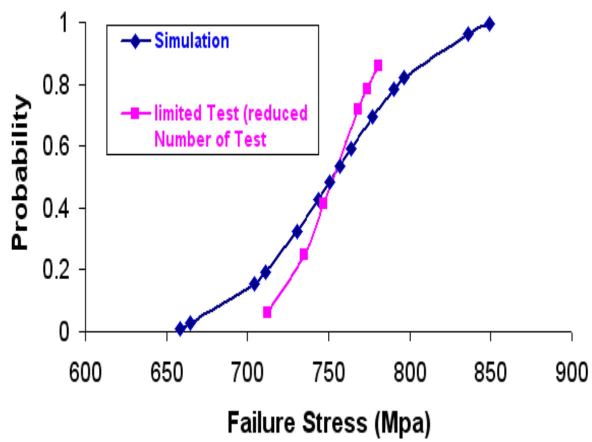
(a)



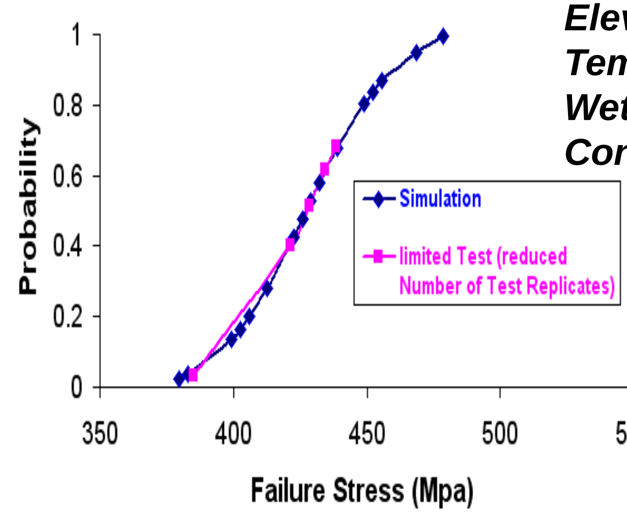
Elevated Temperature Dry Condition

(b)

Cold (-54 C) Temperature Dry Condition



Elevated Temperature Wet Condition



Ref:

1. *"Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure". DOT/FAA/AR-03/19, Office of Aviation research, Washington, D.C. 20591, September 2003.*
2. *G. Abumeri, F. Abdi, and M. Lee, "Verification of Virtual Generation of A- and B-Basis Allowables of Polymer Composites Subject to Various Environmental Conditions", Presented at SAMPE CHINA 2009 Conference-Tianjin Binhai, Oct. 28-29-30, 2009*

Determine Allowables for Glass Composite

Ply Properties for MTM45-1/6781 S2-Glass from test and Simulation

MTM45-1/6781 S2-Glass: FVR=49.0%; VVR=2.0%				
Material		MTM45-1/6781 S2-Glass		
Property	Units	Test	MS-PFA	% Error
E11	[msi]	4.14	4.1	-0.97
E22	[msi]	3.99	3.89	-2.51
E33	[msi]	-	1.92	-
G12	[msi]	0.55	0.6	9.09
G13	[msi]	-	0.49	-
G23	[msi]	-	0.48	-
v12	[-]	0.138	0.149	7.97
v13	[-]	-	0.454	-
v23	[-]	-	0.459	-
S11T	[ksi]	79.92	81.41	1.86
S11C	[ksi]	81.41	82.03	-
S22T	[ksi]	78.92	80.03	1.41
S22C	[ksi]	67.08	69.3	3.31
S33T	[ksi]	-	7.987	-
S33C	[ksi]	-	2.695	-
S12S	[ksi]	9.16	9.405	2.67
S13S	[ksi]	9.79	9.5	-2.96
S23S	[ksi]	-	7.396	-

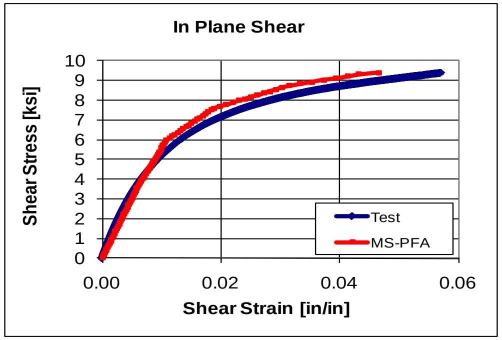
Standard Methods give different Answers

MTM45-1/6781 S2 Glass predicted

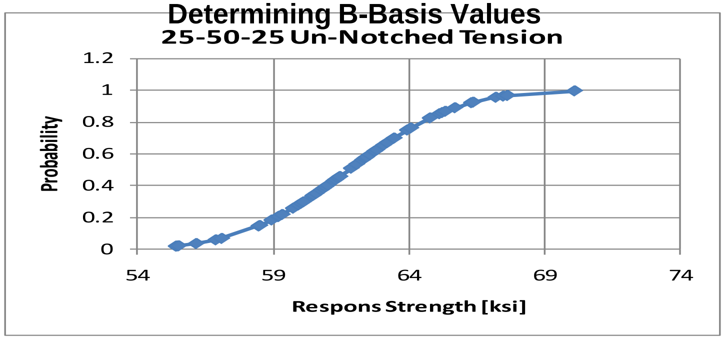
Tension					
Layup [0%/45%/90%]	MS-PFA B-basis [ksi]	CMH-17 B-basis [ksi]	Difference [%]	Mod CV B-basis [ksi]	Difference [%]
[10/80/10]	34.85	-	-	-	-
[25/50/25]	57.12	48.81 **	17.03	55.1	3.67
[40/20/40]	66.34	-	-	-	-
Compression					
Layup [0%/45%/90%]	MS-PFA B-basis [ksi]	CMH-17 B-basis [ksi]	Difference [%]	Mod CV B-basis [ksi]	Difference [%]
[10/80/10]	38.24	-	-	-	-
[25/50/25]	60.86	60.23	1.05	61.71	-1.38
[40/20/40]	67.19	-	-	-	-

****CMH17 Sol was too conservative for 25-50-25, has to use Anova**

Test and Simulation In-Plane Shear



Virtual Samples Generated by MS-PFA for Determining B-Basis Values



Ref: M. Garg, G. Abumeri, J. Housner, F. Abdi , and E. Clarkson, "Prediction Of B-basis Strength Allowables Of S2-glass Composites With Reduced Testing",, SAMPE 2011 Fall Conference.

Conclusion/Lessons Learned

- Offers Test Reduction Methodology
- Predict Test Considering Uncertainties
- Building Block Verification with one set of input

Material Modeling:

- Find Root Cause Problem "Fiber/Matrix"
- Consider Composite architecture 2-D, 3-D
- Consider residual stress during cool down process
- Consider manufacturing anomalies
- Obtain A_B Base Allowables with Reduced Tests
- Obtain the Entire Design Envelope

- Can generate allowables for configurations (layups) not included in test plan
- Scatter in material properties can be reproduced analytically by combining progressive failure with probabilistic analysis
- Increase in temperature and moisture content reduces the allowable values
- Sensitivity analysis can be used to reduce scatter in material behavior

Validation

- 3 Carbon Composite, and 1 Glass Composite

Composite Conference 2012

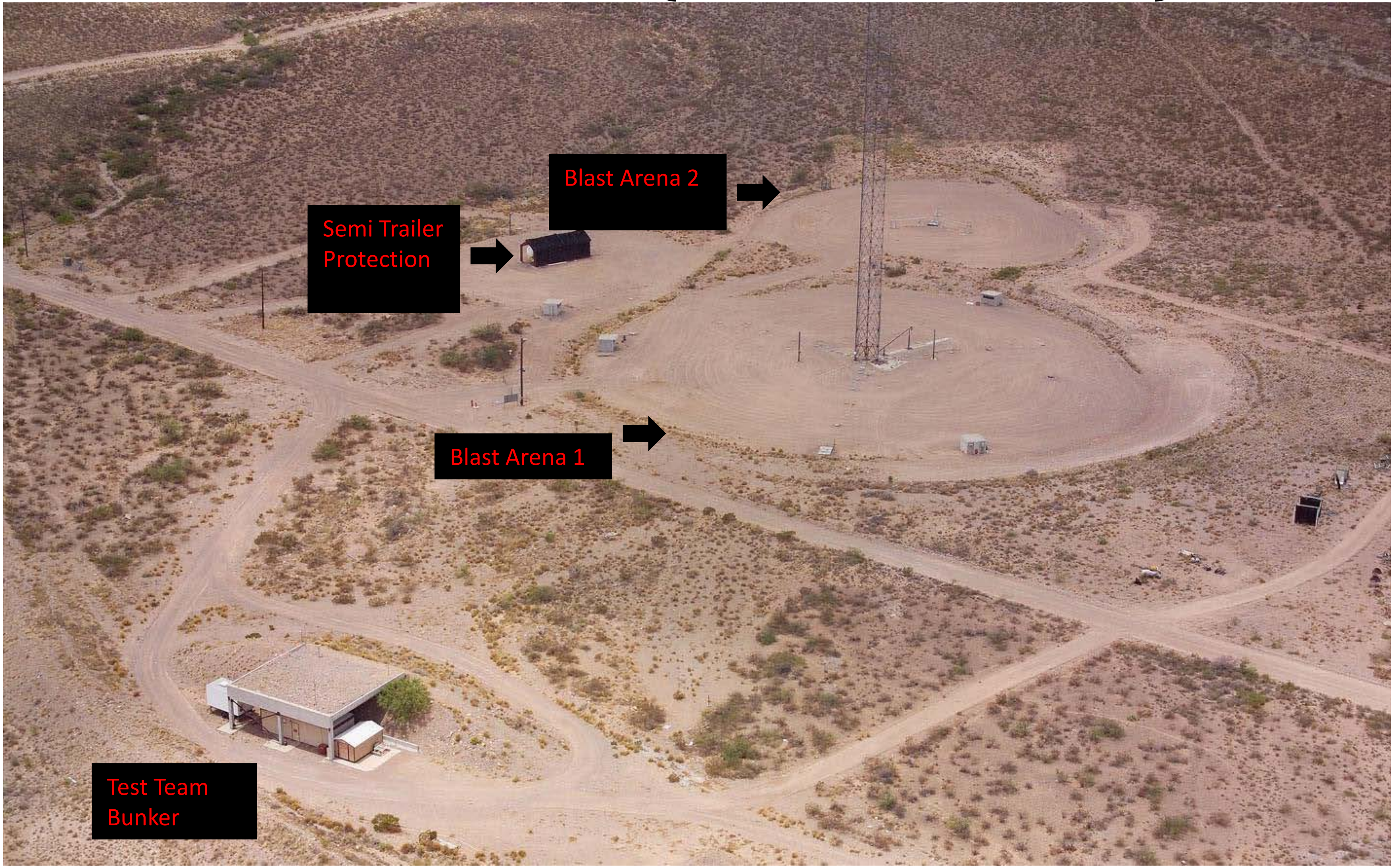
High Energy Testing

Harold Beeson, PhD.
NASA White Sands Test Facility
Laboratories Office Chief

High Energy Testing

- Testing up to 500 lb of TNT
- Pressure and chemical explosions
- Detonation and deflagration
- Blast wave characterization
- Fragment throw distance and velocity

Test Location (WSTF 700 Area)



Arena 2 fragment & Pressure

- **Arena 2:** Measuring overpressure and fragment throw

- **Arena 1:** Hydrogen/Oxygen common bulkhead tank burst measuring overpressure

Arena 1 (tower removed)

Arena 1 (tower removed)

Composite Conference 2012

Transforming Composite Pressurized Vessels (CPV) to Unibody Composite Pressurized Structures (UCPS) with Expanded Capabilities

Markus Rufer
Scorpius Space Launch Company

Relevant History

- 1999 SSLC was incorporated as a spin-off Company of Microcosm Inc.
- 2001 All-Composite linerless tank development
- 2006 INNOVATION IN COMPOSITES ENGINEERING award by the ACMA — Start of **PRESSURMAXX** production
- 2008 Development and patent applications for integrated features
- 2009 Proprietary Sapphire*77 cryogenic resin system completes qual tests
- Scorpius Space Launch Company is a qualified vendor to the nation's foremost aerospace and defense contractors and has received the maximum vendor performance rating awarded by NASA. Our tank products use award winning, patented technology for superior performance. We operate as a commercial company.

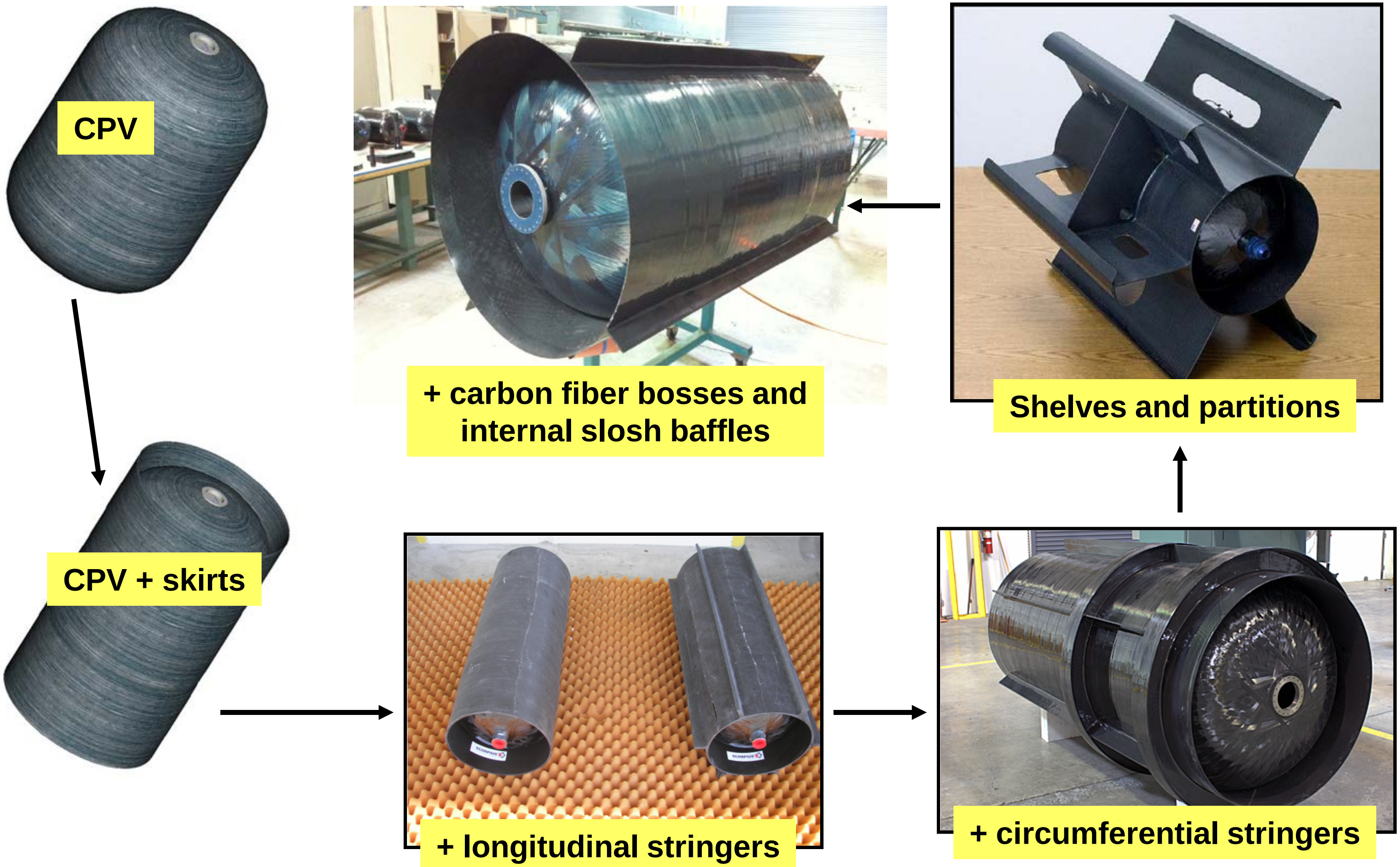
All-Composite Pressure Vessel Technology Development Background

Local transport of a 200 cu. ft. 500 psi LOX tank

Tanks produced from 0.5 cu. ft. to 200 cu. ft. volume for Fuels / Propellants, Gases / Pressurants, Cryogens, up to 5,000 psi MEOP

Prize winning Armadillo Lunar Lander Ghe tanks, 2,300 psi MEOP

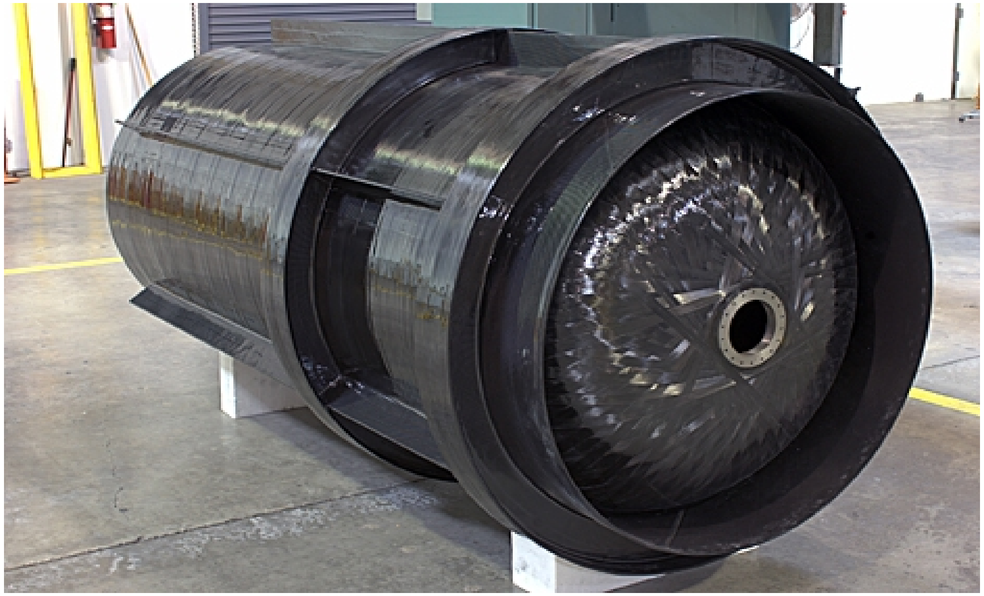
CPV to UCPS Transformation



Unibody Composite Pressurized Structure (UCPS) Evolution

Additive manufacturing techniques for integrated features such as circumferential or longitudinal stringers

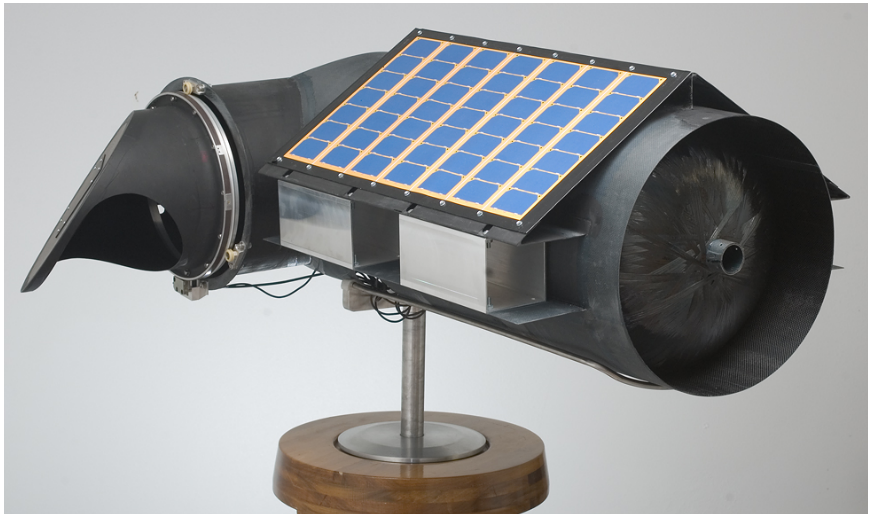
No CTE based separation or de-lamination issues



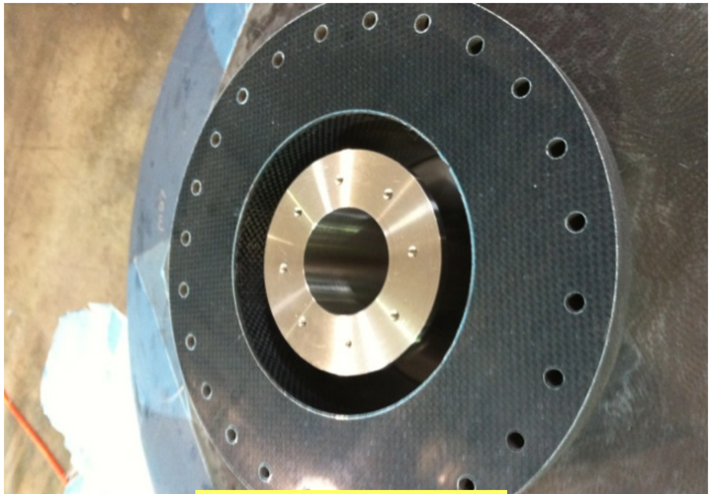
Features are not externally attached but built from "inside out"

Variations / Applications

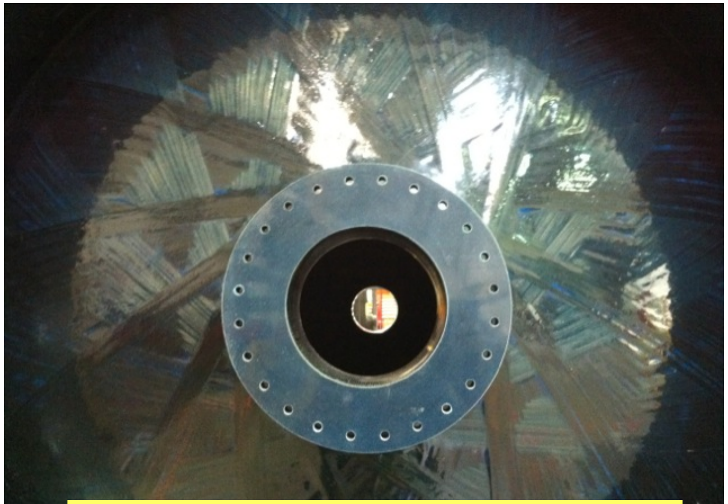
Embedded health monitoring system



Interplanetary Satellite "Hummingbird"

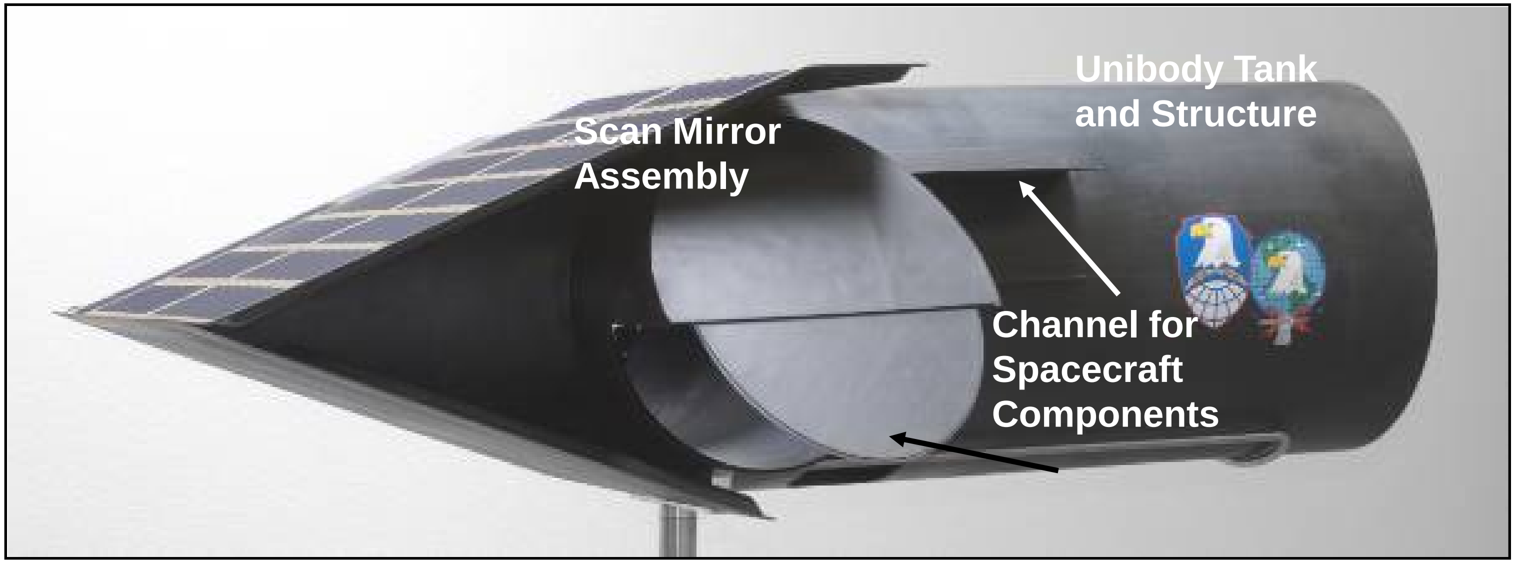


Integrated PMD

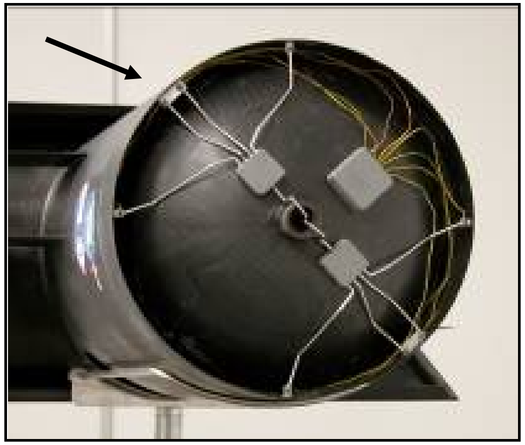


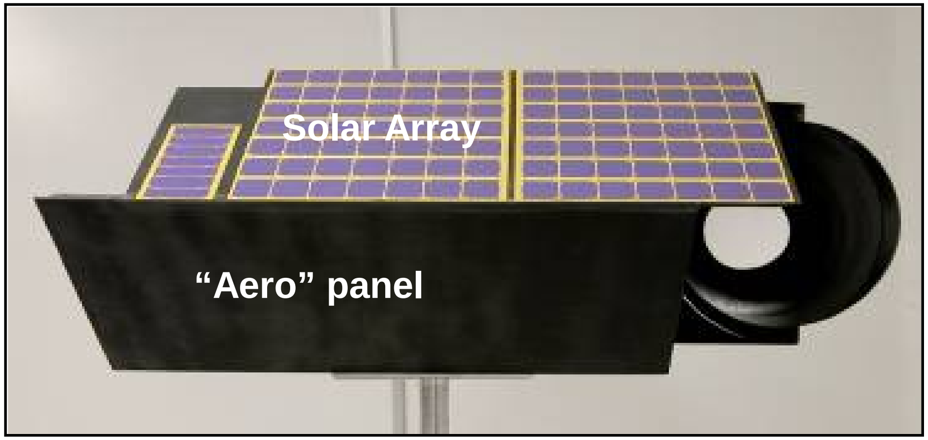
Carbon fiber "boiler type" flange

UCPS Applied to Spacecraft Design



Propulsion
System

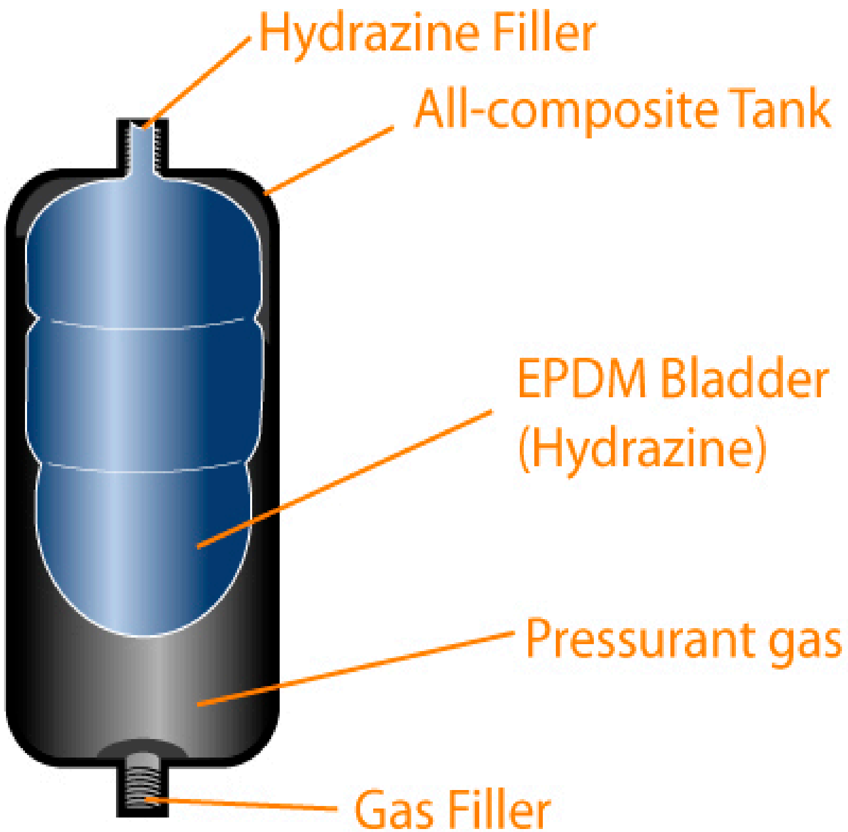




PED Tank Technology

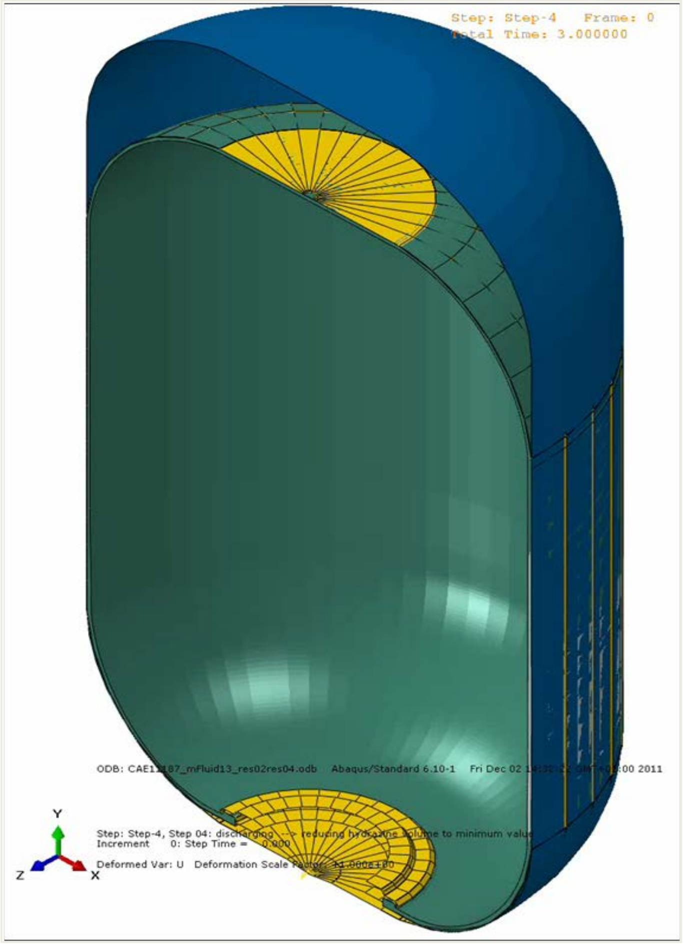
Positive Expulsion Device

- Tank uses the linerless all-composite PRESSURMAXX unibody technology, already successfully demonstrated in various applications
- Bladder tank without standpipe design for use in blow-down or external accumulator mode
- This technology does not require propellant management devices (PMD). Simple and reliable



PED tank development effort is funded under SBIR PH II "Unibody Composite Pressurized Structure (UCPS) for In-Space Propulsion" (NASA Glenn).

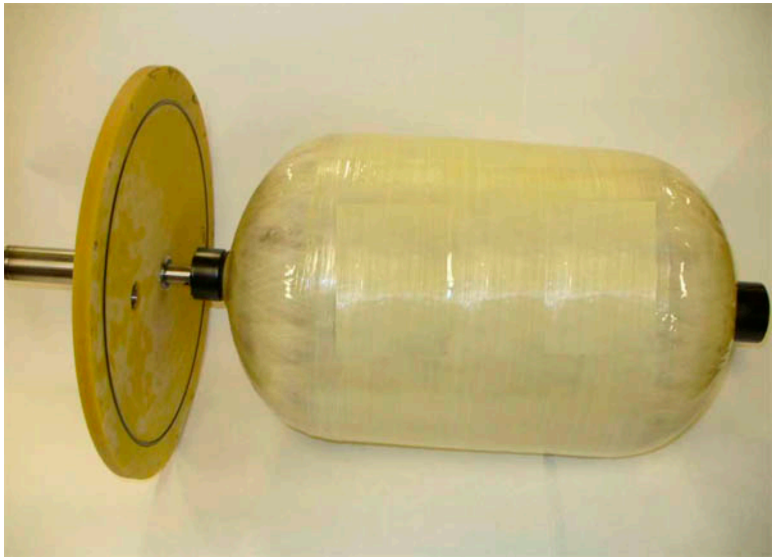
Bladder Folding Motion FEM



Both, Tank and Bladder, are Hydrazine (N2H4) and HAN compatible

LN Dewar for HTS Transformer Coils

(Superconducting coils for the power grid—SmartGrid 2020)



- LN Dewar system tested at Oakridge National Labs, TN. Long term vacuum and out-gassing tests
  - (see "Vacuum Studies of a Prototype Composite Coil Dewar for HTSC Transformers"
    S. W. Schwenterly, Y. Zhang, E. F. Pleva,
    and M. Rufer)

Production

- Over 50 UCPS products delivered since 2006
- Ramped up to one tank/week output
- 100% on-time delivery record
- Production lead time average 12 weeks

Mandrels ready for baking

Mandrels treated for layup

A tank ship-set of four

Tests Conducted

- Chemical—compatibilities include petroleum-based fuels, e.g. Kerosene, as well as alcohol based fuels, e.g. Ethanol. Cryogens such as liquid oxygen and nitrogen, and various gases, e.g. methane, helium, oxygen, nitrogen, as well as propellants such as turpentine, hydrazine, HAN / green propellant e.g. M-315
- Pressure—pressurant tanks operating at 5,000psi (10,000psi burst rating) are in use, 50 fill and rapid discharge cycles performed
- Temperature—25 temperature cycles and rapid chill-down testing has been conducted from 175 deg F to -321 deg F
- Load / Impact / Vibration—Falcon 9 launch profile of unibody composite pressurized structure spacecraft has been tested (ITT)
- Radiology—NASA WSTF shearography, pressure and leak tests have been conducted. (Detailed session on that this Friday)

Tests Conducted (cont'd)

- **NASA White Sands Test Facility**
- Two Microcosm Composite Pressure Structures (CPS) for green propellant service constructed to support green propellant Lander concepts
- WSTF tasked to develop a test plan with JSC-EP and JSC-ES to develop acceptance and qualification data
- Tasks Completed on S/N 1010 and 1011
  - WSTF designed and built shipping crates for CPS
  - WSTF performed visual inspection with certification trained inspectors per ANSI/AIAA S-081A, AFSPCMAN 91-710 and KNPR 8715.3 and provided report to JSC
  - Laser Shearography completed at WSTF by WSTF, LTI and JSC
  - Instrumented Proof Test (S/N 1010)
  - Instrumented Pneumatic leak check (S/N 1010)
- Stepwise plan to evaluate designs for spacecraft propellant and structural load capability
  - LOx, LCH4 and potentially LH2
- WSTF Visual Inspection at Microcosm Laser Sherography NDE at WSTF
- 860 Remote test cell for Instrumented Proof and Pneumatic Leak Test WSTF Vacuum Permeation Test Chamber
- WSTF 700 High Energy Test Area
- WSTF 700 CPV Burst Test

Current Applications

- Launch vehicle, (Jet-A, Kerosene, Turpentine)
- Launch vehicle oxidizer, LOX
- Launch vehicle pressurization, GHe and NO
- Lunar lander pressurization, RCS and landing dampening with gas expulsion
- LN Dewars for HTS transformer coils (superconducters) for the electrical power grid
- Automotive, liquid air motors

What's Next?

- Long term permeation testing with high pressure GHe
- Liquid hydrogen testing
- Liquid Helium testing
- Better LOX compatibility testing (standards!)
- Complete the work on CPV standards (Type V vessels)
- Space environment simulated tests (outgassing)
- Get this technology into space!

SAPPHIRE 77 SERIES CRYOGENIC TANKS

10" Diameter All-Composite Cryogenic Tank

Tank Diameter (in)	Length (in)	Operating Pressure (psi)	Boss Material	Wall Thickness (in)	Weight* (lbs)	Volume (ft^3)	Volume (in^3)	Safety Factor (-)	PV/W* (10^6 in)
10	16	250	Carbon Fiber	0.08	3.1	0.70	1,210	2.0	0.20
10	16	500	Carbon Fiber	0.09	3.4	0.70	1,210	2.0	0.36
10	16	1500	Carbon Fiber	0.14	5.5	0.70	1,210	2.0	0.66
10	16	3000	Carbon Fiber	0.16	6.1	0.70	1,210	2.0	1.20
10	24	250	Carbon Fiber	0.08	4.3	1.00	1,728	2.0	0.20
10	24	500	Carbon Fiber	0.09	4.7	1.00	1,728	2.0	0.37
10	24	1500	Carbon Fiber	0.14	7.7	1.00	1,728	2.0	0.67
10	24	3000	Carbon Fiber	0.16	8.5	1.00	1,728	2.0	1.2

25" Diameter All-Composite Cryogenic Tank

Tank Diameter (in)	Length (in)	Operating Pressure (psi)	Boss Material	Wall Thickness (in)	Weight (lbs)	Volume (ft^3)	Volume (in^3)	Safety Factor (-)	PV/W (10^6 in)
25	59	250	Carbon Fiber	0.08	25	14.3	24,757	2.0	0.49
25	59	500	Carbon Fiber	0.12	36	14.3	24,757	2.0	0.68
25	59	3000	Carbon Fiber	0.29	91	14.3	24,757	2.0	1.6

42" Diameter All-Composite Cryogenic Tank

Tank Diameter (in)	Length (in)	Operating Pressure (psi)	Boss Material	Wall Thickness (in)	Weight (lbs)	Volume (ft^3)	Volume (in^3)	Safety Factor (-)	PV/W (10^6 in)
42	136	250	Carbon Fiber	0.08	96	97.5	168,480	2.0	0.9
42	136	500	Carbon Fiber	0.13	160	97.5	168,480	2.0	1.1
42	136	3000	Carbon Fiber	0.45	540	97.5	168,480	2.0	1.9

53" Diameter All-Composite Cryogenic Tank

Tank Diameter (in)	Length (in)	Operating Pressure (psi)	Boss Material	Wall Thickness (in)	Weight (lbs)	Volume (ft^3)	Volume (in^3)	Safety Factor (-)	PV/W (10^6 in)
53	170	250	Carbon Fiber	0.08	150	196	338,688	2.0	1.1
53	170	500	Carbon Fiber	0.17	240	196	338,688	2.0	1.4
53	170	3000	Carbon Fiber	0.55	1050	196	338,688	2.0	1.9

*Estimated values with IM7

Rev. June 2010

Composite Conference 2012

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Thermal and High Energy Particle Enclosure for Electronic Components in Spacecraft and Robotic Platforms

Moises Nevarez

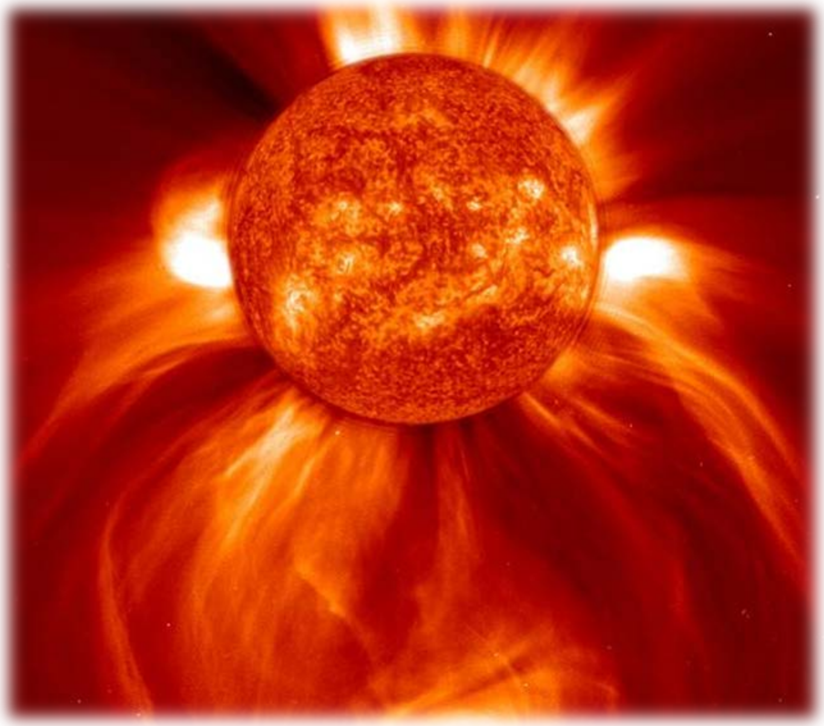
Dr. Kevin Anderson

California State Polytechnic University, Pomona
Mechanical Engineering Department

Project Scope

- Protect critical electronic components in spacecraft and robotic platforms susceptible to damage from high temperatures and harmful radioactive particles
- A "Radiation Absorbing and Thermally Insulating Material" (RATIM) can be used to enclose electronics

RADIATION IN SPACE



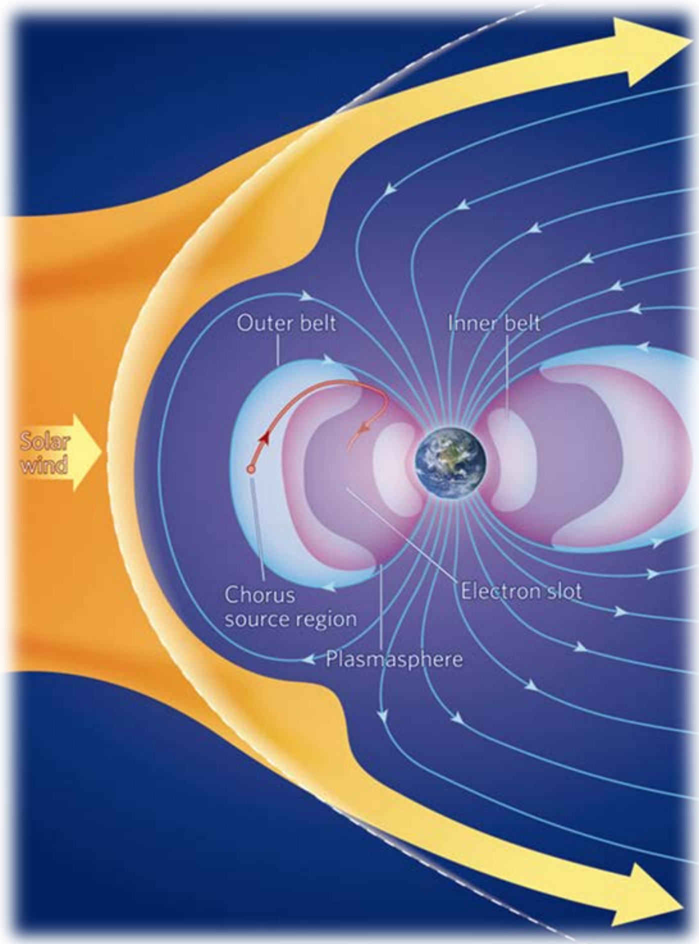
Types of Radiation

- **Ionizing Radiation** : Particles which alter the physical characteristics of an atom (removing e-)
  - **Alpha** – helium nucleus
  - **Beta** – energetic electrons
  - **Neutron** – free neutrons
  - **X-ray** – electromagnetic waves
  - **Gamma** – photons
- **Non-Ionizing Radiation** : Waves which excite atoms
  - Waves under the electromagnetic spectrum
  - **Visible light, infrared, microwave, radio wave, VLF, ELF, thermal radiation (heat)**

Three Main Sources of Radiation in Space

- **Trapped Particles** – Rotation of earths core creates magnetic fields which trap high energy particles. The Van Allen radiation belt contains electrons (10 MeV) and protons (10 MeV)
- **Galactic Cosmic Radiation** – Ionized atoms ranging from one proton to uranium nucleus traveling from deep space at nearly the speed of light
- **Solar Particle Events** – Solar activity such as coronal mass ejections release plasma, or ionized matter with high kinetic energy

Radiation Sources



Trapped Particles in Van Allen Radiation Belt

Solar Activity

Cosmic Rays

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Possible Damages to Electronics

Radiation damages semiconductor material in electronics and disrupts flow of electrons

- **Ionization Effects (Total Ionization Dose) -** Caused by charged electrons and protons degradation to silicon-based devices
- **Lattice Displacement-** Caused by neutrons, protons, alpha, heavy ion, and gamma particles which change atom arrangement of crystal lattice
- **Single Event Effects (SEE) –** Mostly effects digital devices by causing photocurrents and changing current state of memory cells

Space Mission Failures Due to Radiation

- In January 2012, the failure of a Russian Mars probe mission was blamed on memory malfunction of an on-board computer due to space radiation
- Commercial and scientific satellites operate well below Van Allen radiation belt to avoid total ionization dose effects (e.g. Starfish Prime tests destroyed 7 commercial satellites)
- Robotic missions to celestial bodies like the moon have possible long term exposure to radiation and heat due to high surface temperatures

RADIATION ABSORBING AND THERMALLY INSULATING MATERIAL (RATIM)

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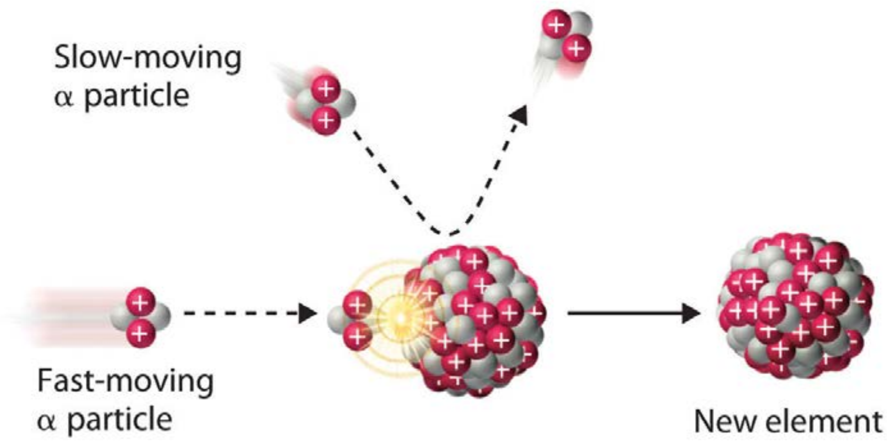
RATIM Base Materials

- **Matrix**: **High Density Polyethylene (HDPE)** – Light weight, non-conductive, insulating material Low monomer and high hydrogen content creates ideal material for absorbing radiation.
- **1st Particulate**: **Boron Carbide (B4C)** - Fairly light weight and non conductive particulate material used in the nuclear industry for its effective radiation absorbing properties
- **2nd Particulate**: **Tungsten (W)**- Very heavy element capable of blocking high energy particles

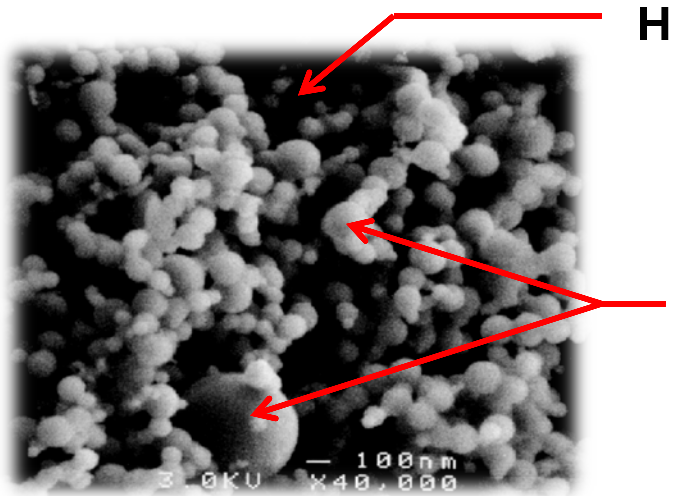
RATIM Shielding Characteristics

- High hydrogen content in HDPE helps absorb α, β, and neutrons, stop secondary emissions, and insulates heat
- Boron compounds have very high radiation absorbing cross sections, yet releases secondary particles
- Tungsten is also widely used in the nuclear industry to absorb x-ray and gamma radiation

Secondary Emissions



HDPE Matrix



Tungsten and Boron Particulates

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Covering the Ionizing Radiation Spectrum

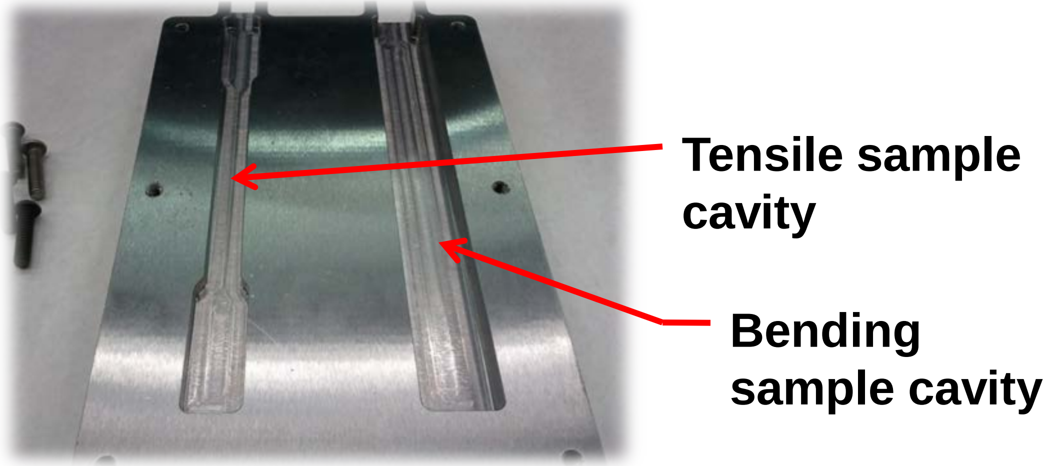
	HDPE	Boron Carbide	Tungsten
Alpha			
Beta			
Nuetron			
X-Ray			
Gamma			
Secondary			

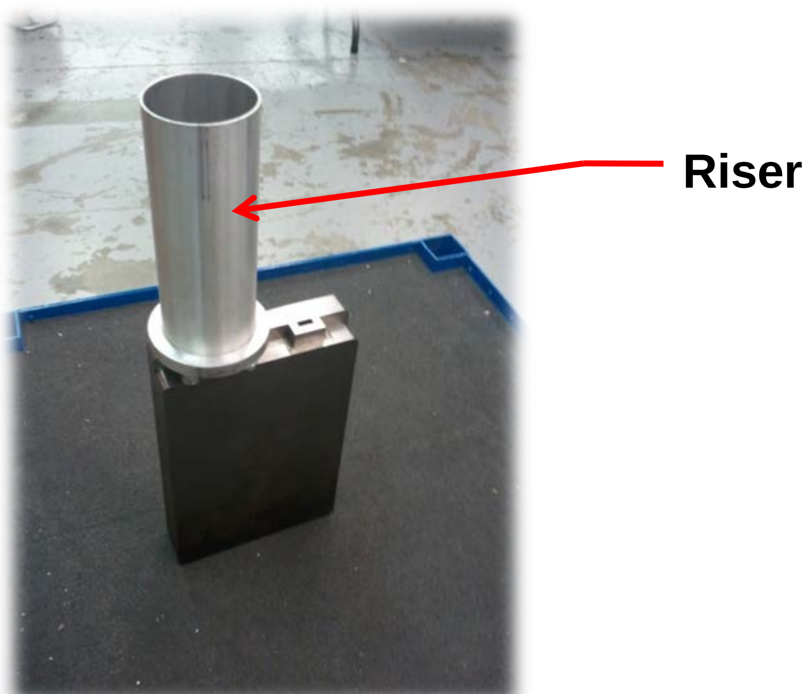
-Types of radiation each material absorbs

MANUFACTURING RATIM

Mold Design

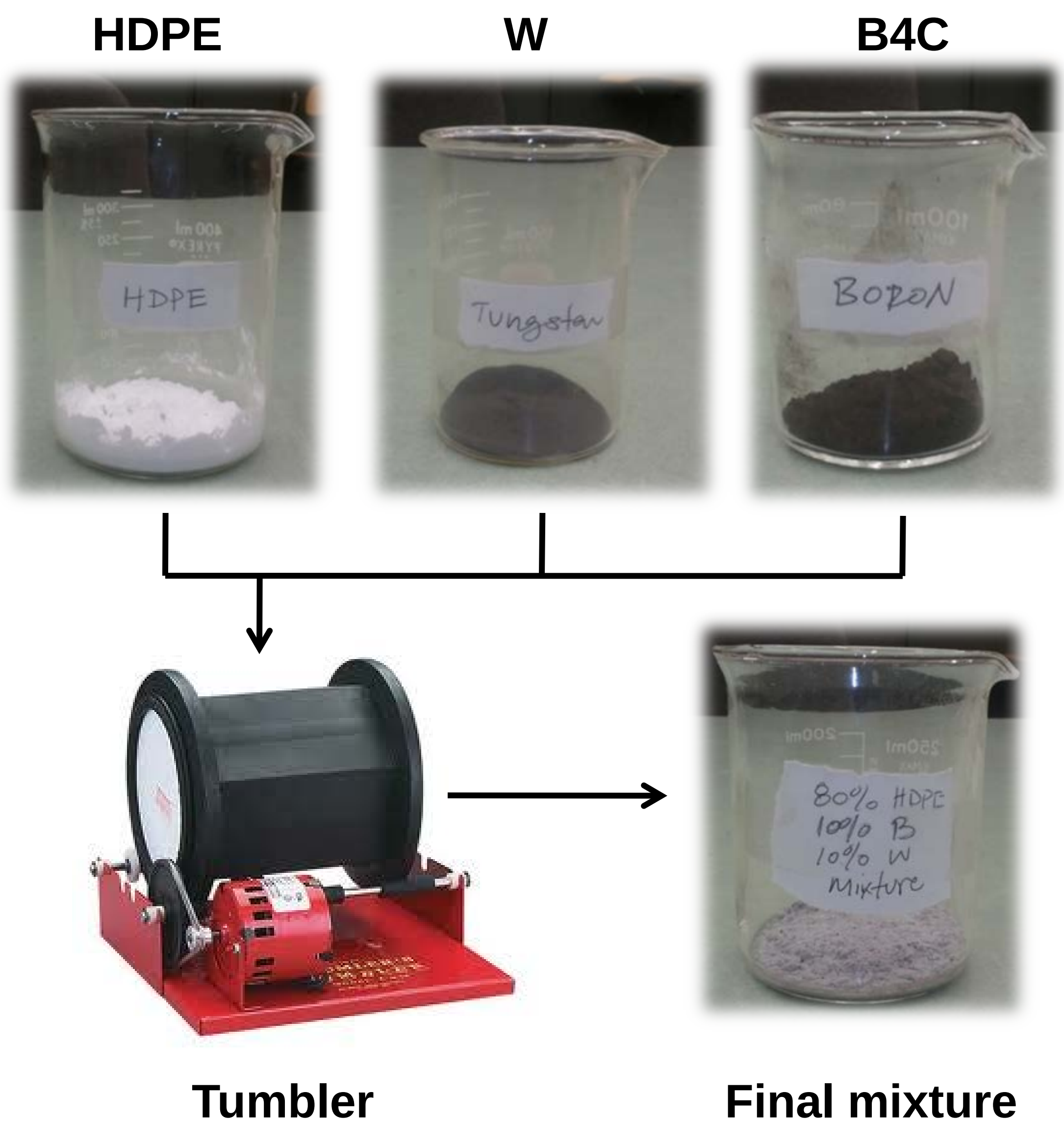
- Manufactured through thermal casting
- Mold contains cavities for bending and tensile testing
- Due to shrinkage, a riser was later designed to provide feeding





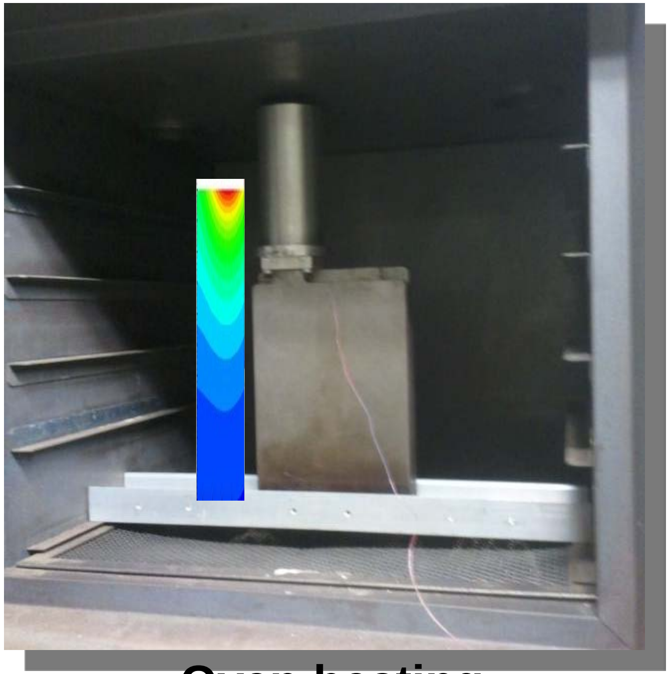
Material Mixture

- Powder form of each raw material
- 40 micron particle size for HDPE, and 149 micron for W and B4C
- Mixed with tumbler

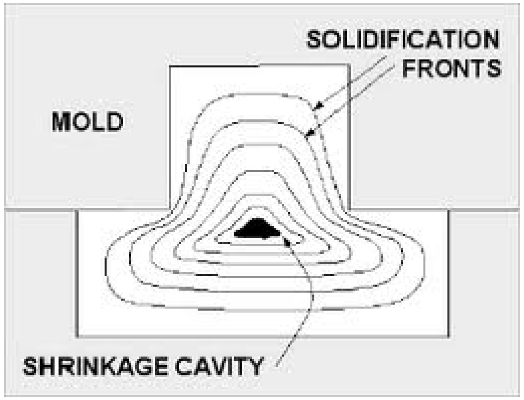


Composite Bonding

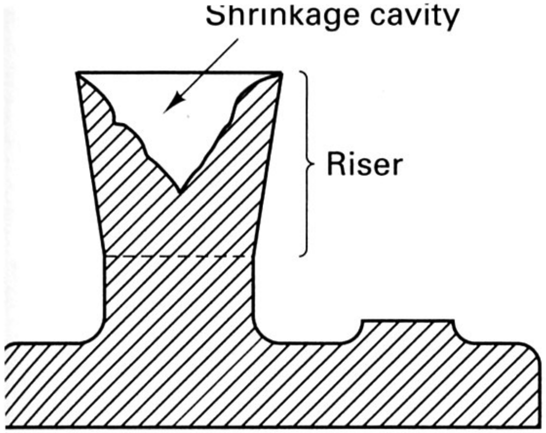
- Mixture inserted into oven set to melting temperature of HDPE (180 C/350 F)
- HDPE melts and bonds together forming matrix around W and B4C particulates
- Riser must stay heated during solidification to avoid shrinkage



Oven heating



Failed Samples



Successful Samples

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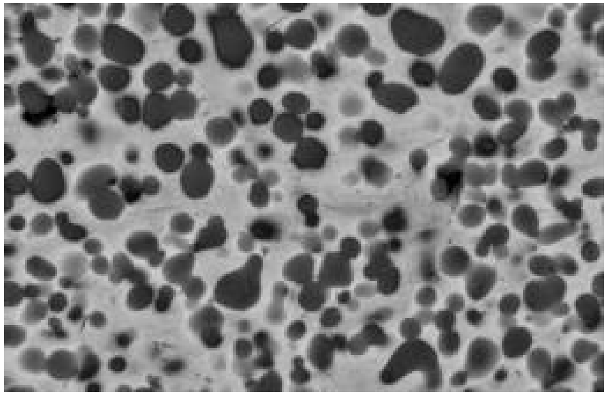
RATIM Physical Characteristics

- Isotropic material
- 1.06 g/cc density (70% matrix by volume), compared to 2.56 g/cc for Al, and 4.5 g/cc for Titanium.
- Low manufacturing and post processing costs

1” x 0.5” Cross Section

Bending Test Sample



HPDE solidifies around B4C and W

TESTING AND ANALYSIS

Mechanical Properties with Varying Compositions

- In search for relationship between composition and strength
- Intuition says the higher percentages of W and B4C would provide superior shielding, but how does that affect strength?

3 Point Bend Tester

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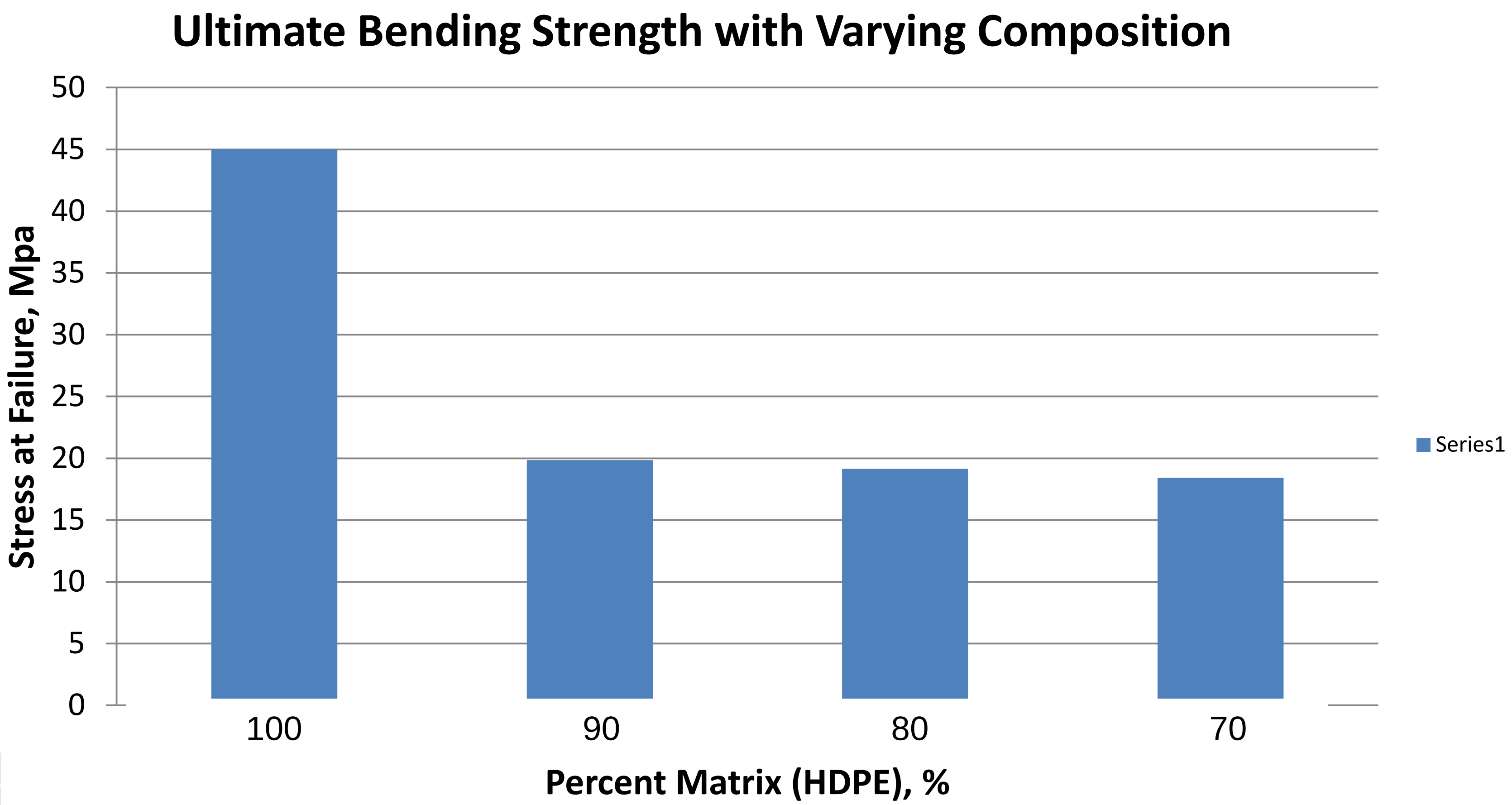
Mechanical Properties of Varying Compositions



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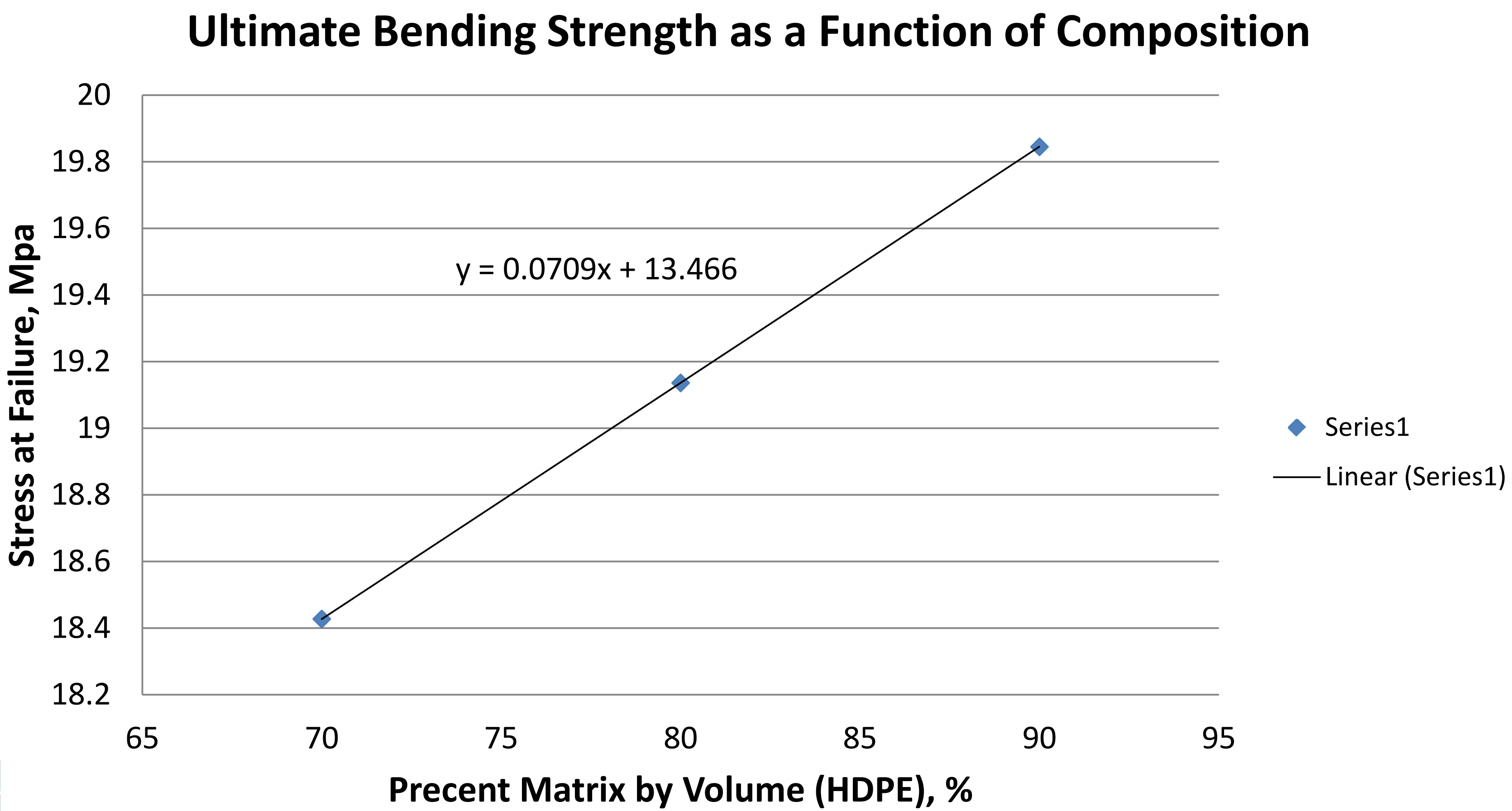
Samples consist of an equal percentage of W and B4C by volume

Considering only Composite Samples



CAL POLY POMONA

Samples consist of an equal percentage of W and B4C by volume

Strength of RATIM Compared to Traditional Spacecraft Material

	Percent Matrix, HDPE (%)	Density (g/cc)	UBS (Mpa)
RATIM	100	0.958	45.0058861
	90	1.048	19.84511513
	80	1.138	19.13636102
	70	1.228	18.42760691
Al		2.56	310
Ti		4.5	800

Effectiveness of Shielding

- Like material strength, quality of radiation shielding is sure to have correlation with percent compositions and material thickness
- Geiger counter measures in mR/hr (REM or Roentgen Equivalent Man is unit of measure for biological response to radioactivity)
- Test provides data for efficiency of tungsten blocking

Geiger counter used for testing gamma and x-ray exposure

Sample with a variable thickness

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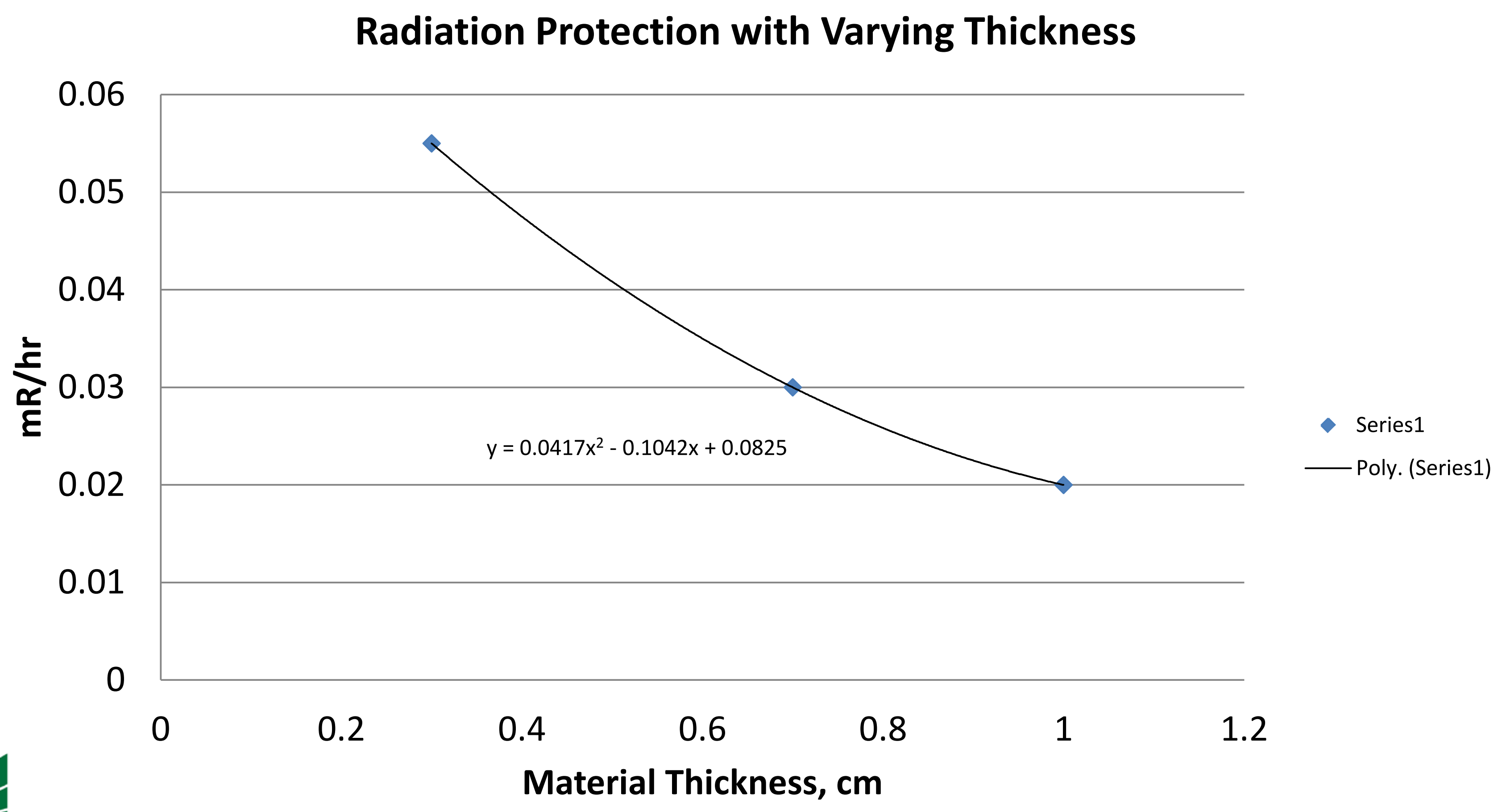
Radiation Protection Properties



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OVERVIEW AND APPLICATIONS

Future Work

- **Manufacturing:** Develop method of creating samples more efficiently and consistently with the use of injection molding and vacuums
- **Testing:** Test radiation absorbing and thermal properties with various high energy particles and thermal conditions with the use of models and FEA
  - Compare to common radiation shielding materials
  - Aug 20th : Beta and gamma sources at 1.5 MeV
- **Raw Materials:** There may be other raw materials that provide greater benefits
- **Legitimacy of Space Applications**: How will the conditions of space affect the material?
- Funding, interaction, and advice

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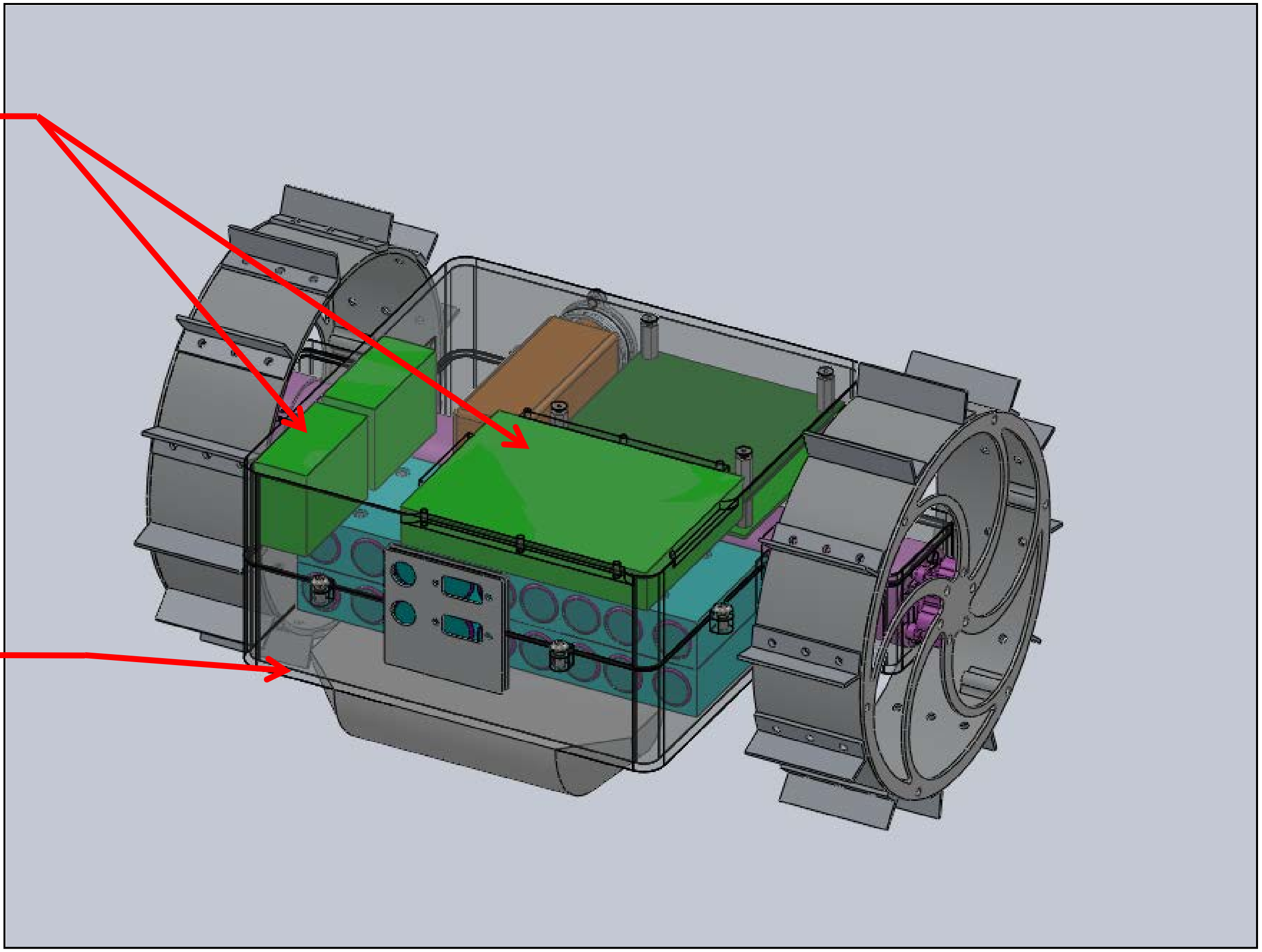
RATIM Overview

- Composite material proposed to protect electronics from the harmful conditions of space
- Weight, radiation absorption, insulation, and electrical conductivity properties are superior to traditional metallic materials
- Mechanical properties will not provide as much strength as traditional metallic materials, but can be used as a liner
- Full analysis of material properties can determine an optimal composition of base material to establish an ideal material

Applications



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Thank you for your attention!

Composite Conference 2012

Developments in Composite Cylinders for Hydrogen Storage

Norman L. Newhouse, Ph.D., P.E., Lincoln Composites
Kevin L. Simmons, Pacific Northwest National Laboratory
John Makinson, Ph.D., P.E., Lincoln Composites

DOE Hydrogen Projects

- DOE is coordinating hydrogen storage research
- Projects are funded for government laboratories and industry to meet DOE research goals
- Specific projects addressed:
  - Hydrogen Storage Engineering Center of Excellence
  - Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks
  - Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery

HSECoE Project Partners

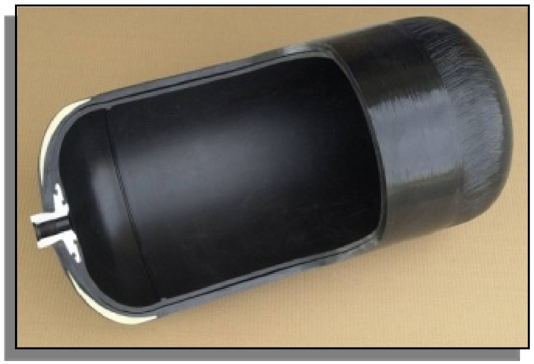
- Hydrogen Storage Engineering Center of Excellence (HSECoE)
  - PI = Don Anton, Savannah River National Laboratory
  - SRNL, PNNL, LANL, JPL, NREL, UTRC, GM, Ford, Lincoln Composites, Oregon State Univ, UQTR, Univ of Michigan, Caltech, BASF

HSECoE Project Objectives

- Develop hydrogen storage systems for On-Board Hydrogen Storage for Light Duty Vehicles
  - Design innovative system architectures for storage technologies with the potential to meet DOE performance and cost targets
  - Design components and experimental test fixtures to evaluate the innovative storage devices and subsystem design concepts and improve component design
  - Design, fabricate, and test subscale prototype systems
- Targets
  - Gravimetric capacity >5.5%
  - Volumetric capacity > 0.040 kg H2/l
  - Permeation and leakage – meet applicable standards
  - Safety – meet applicable standards

HSECoE Pressure Vessel Developments

- Phase 1 projected improvements
  - 11% lower weight
  - 4% greater internal volume
  - 10% lower cost
- Phase 2 plan
  - Confirm operating condition
  - Select baseline design and materials
  - Evaluate alternate designs and materials
  - Develop bench-top test vessel



Alternate Boss Material

- Baseline is 6061-T6 Aluminum
  - 316 Stainless Steel is another common material, used at higher pressures
  - Yield strength is not high for 6061-T6 or 316 SS
  - Stainless steel is significantly heavier and more expensive, but has better tensile strength and fatigue properties
- Investigating 7075 Aluminum to reduce weight and cost
  - High strength would allow reduction in boss size and allow aluminum use at high pressures
  - Proper heat treat is a challenge to get correct strength properties, avoid embrittlement
- Accomplishments
  - Near net shaped bosses machined from 7075-T6 Aluminum
  - Bosses have been heat treated to intended condition
  - Tensile testing confirms proper heat treatment

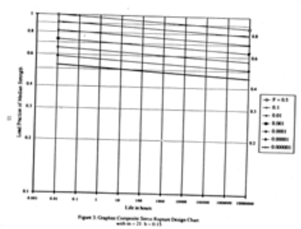
- Benefits
  - Yield strength is 2 times that of 6061-T6 or 316 SS
  - Weight of finished boss could be about 1/2 that of 6061-T6, 1/5 that of 316 SS
  - Cost of finished boss could be same to 1.5 times that of 6061-T6, 1/5 that of 316 SS

Alternative Fibers

- Baseline Fiber – T-700
  - PAN based
  - Excellent manufacturability
- Five alternate carbon fibers tested
  - Two indicated higher strength than baseline
  - Four potentially lower cost per pound
  - Initial testing did not meet expectations, strength/cost did not indicate improvement
- LC worked with two fiber suppliers to obtain improved strength
  - Subsequent testing with these fibers matched the baseline strength in burst test
  - Three fibers now could be used interchangeably
- Benefits of multiple qualified vendors
  - Expected to result in 10% to 15% lower fiber costs
  - Improved availability in times of fiber shortage

Reduced Safety Factor

- Safety factor influences performance
  - Fiber stress rupture and cyclic fatigue are directly related to stress ratio
  - Damage tolerance is affected
- Reduction in safety factor from 2.25 to 2.00 is planned
  - Studies indicate that high reliability is maintained
  - Field experience indicates safe operation as long as damage tolerance is addressed
  - Damage tolerance can be addressed by other design and testing
- Benefits of reduced safety factor



  - Cost of carbon fiber is reduced by about 10%
  - Potential for increased cylinder volume by about 2%
  - Potential for weight reduction by about 5%
  - Must be balanced against cost, envelope, and weight of other means of damage protection, if necessary

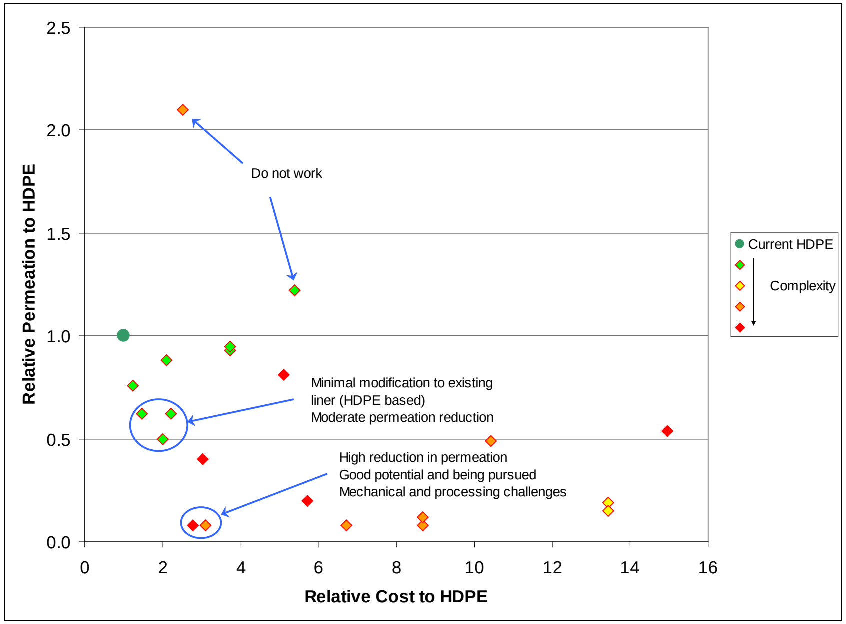
Thinner Liner

- Liner serves as a permeation barrier and winding mandrel
  - Permeation reduction is being investigated, 40% reduction currently feasible
  - Manufacturability issues with using a thinner liner (i.e. winding mandrel) are being addressed
- Benefits of thinner liner
  - Reduction in tare weight, about 4% of cylinder
  - Increase in internal volume, about 2%
  - Potential for reduction in cost, depending on cost of new liner materials

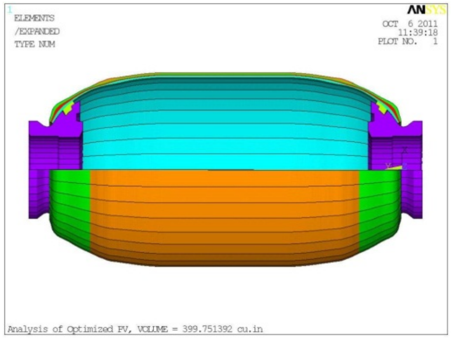
Thinner Liner

Alternate Liner Material Permeation versus Cost

- HDPE is baseline (1,1)
- Comparison of relative cost and permeation rates
- HDPE fillers show 40% reduction with limited cost increase
- Alternate materials show promise of significant permeation reduction
- Some alternate materials are prohibitively expensive

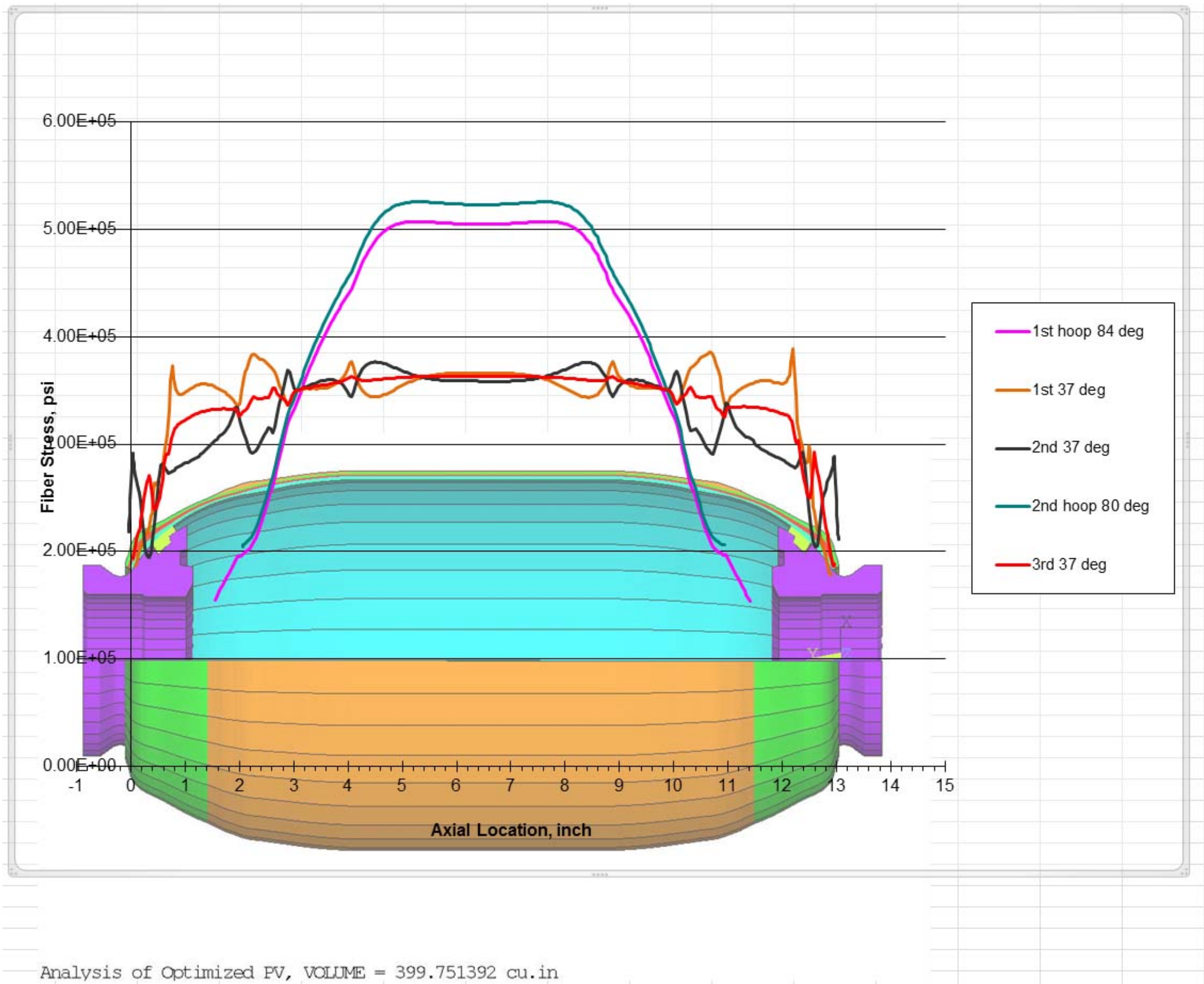


Test vessel design



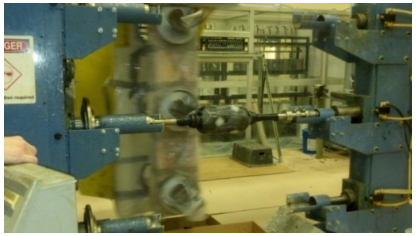
- Baseline dimensions
  - ID = 166 mm (6.54 inches)
  - OD (Liner) = 174 mm (6.84 inches)
  - OD (Tank) = 183 mm (7.18 inches)
  - OAL = 372 mm (14.64 inches)
  - Boss opening = 60.7 mm (2.39 inches)
  - Volume = 5.68 liters
- Baseline construction
  - Fiber = T700
  - Resin = epoxy
  - Liner = HDPE
  - Bosses = 6061 Aluminum
- Phase 2 bench-top test vessel will be “heavyweight” for enhanced safety in lab setting
- Alternate all-metal and metal lined composite designs also prepared

Test vessel analysis



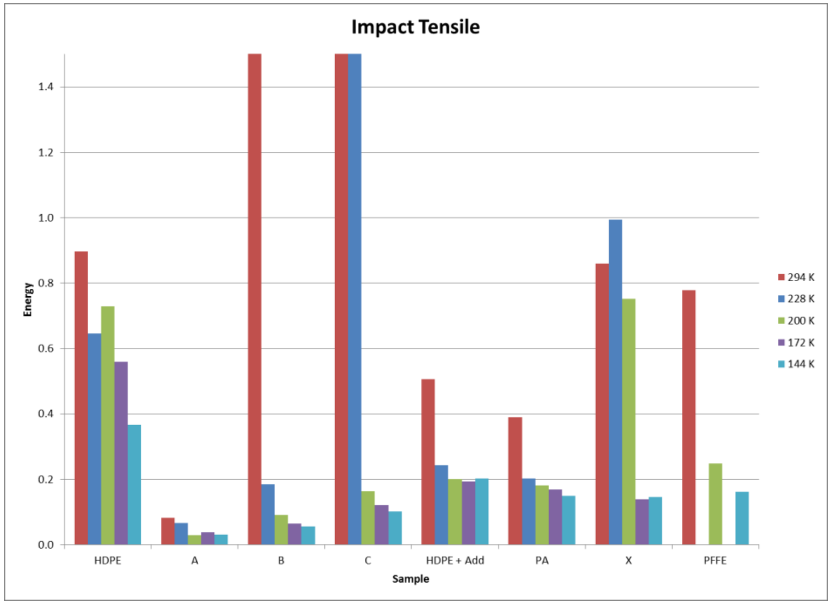
Test vessel fabrication

- 21 vessels have been fabricated
  - 3 burst to confirm strength
  - 3 used for cryo and leak testing
  - Further performance characterization
    - Strength
    - Fatigue
    - Impact
  - Available for demonstration of system components



Liner material investigation

- Tensile Impacts of
  - HDPE (baseline)
  - Modified EVOH
  - HDPE with nano-additives
  - PA
  - PTFE
- Dog-bone samples
- ~2.5 m/s

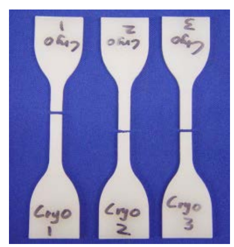


- Energy of impact provides relative values only
- Of materials tested, HDPE has best cold/cryo properties (tested to 144ºK)
- Continuing to evaluate liner materials for cold service

Cryogenic Test of Liner Materials

- Halar Room Temp.
- TS: 42 MPa
- Modulus: 1.6 GPa
- Elongation: 20%

- Halar in Liquid N2
- TS: 143 MPa
- Modulus: 4.4 GPa
- Elongation: 4.5%



Fiber materials

- T700 is baseline reinforcing fiber
  - Alternate fibers are of similar strength
  - Slight loss in strength at cryogenic temperatures
- Prototype tank will be cryo-burst
  - JPL is coordinating test
  - Tank will be holding some pressure while cooling to liquid nitrogen temperature
  - Tank will be burst with liquid nitrogen

Resin materials

- Epoxy resins have been used successfully at cryogenic temperatures
- Tensile testing confirms performance
  - Tensile strength within 5%
  - Elongation within 30%
- Resin tougheners will be evaluated
- Alternate resin materials will be considered

Cold vessel testing

- Existing vessel design, baseline materials
  - 15 x 66 in (380 x 1680 mm) 3000 psi (205 bar)
  - Start at 1000 psi (68 bar) internal pressure at 21 °C
- Insulated box with circulating fans
- Thermocouples on inside and outside of composite
- Temperatures (min achieved)
  - Liner 108 °K (-165 °C)
  - Outside composite dome 108 °K (-165 °C)
  - Outside composite cylinder 77 °K (-196 °C)
- Two cylinders - two cycles each
- No effect on room temperature burst properties.
  - 9253 psi & 9077 psi
  - Configuration nominal is 8978 psi, min required 8021 psi

DOE Cost Reduction Project

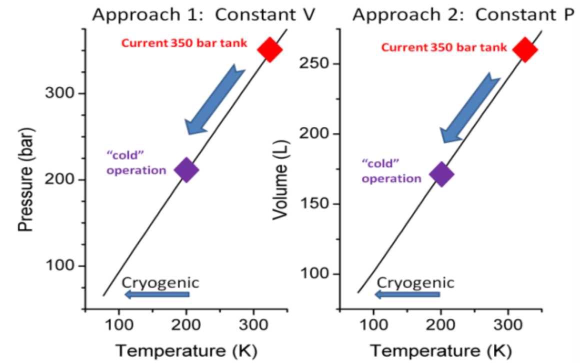
- Pacific Northwest National Laboratory is project lead
- Supporting organizations
  - AOC Resins
  - Ford
  - Lincoln Composites
  - Toray

DOE Cost Reduction Program Objectives

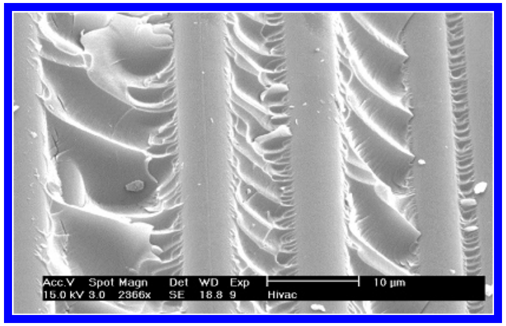
- Reduce cost up to 50%
  - Proposed 10% to 37% reduction
- Novel approaches for design, manufacturing, materials
- Maintain
  - Gravimetric performance
  - Volumetric performance
  - Safety

H2 PV Cost Reduction Investigations

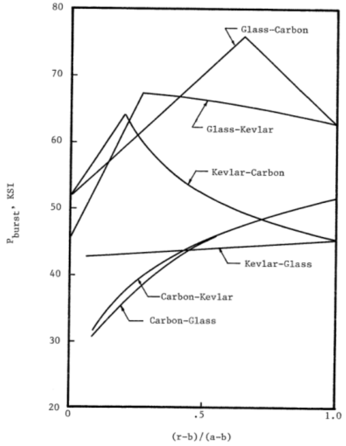
- Reduced service temperature
  - Higher density allows reduced pressure or smaller tank
  - Need to address material selection and design issues
- Lower cost resins
  - Vinylester/Polyesters
  - Address fiber sizing for VE/PE
- Resin additives
  - Nanoparticles
  - Toughening agents



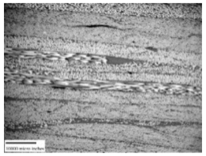
H2 PV Cost Reduction Investigations



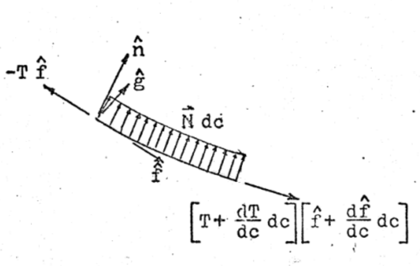
- Carbon fiber surface modifications
  - Enhance fiber-to-matrix bond
- Alternate fibers
  - Evaluate lower cost fibers
  - Layered hybrids to optimize strength utilization
  - Interspersed hybrids to optimize strength vs. durability



H2 PV Cost Reduction Investigations



- Localized reinforcement
  - Dome caps
  - Localized dome reinforcement
  - Wind pattern modification to optimize reinforcement
- Manufacturing techniques
  - Heavier winding bands
  - Multiple winding eyes



DOE Hydrogen Transport Project

- High pressure composite tanks developed for storage and transport of hydrogen and other gases
- Lincoln Composite TITAN™ tank and ISO container

Tank/Module Specifications

- Service pressure 250 bar (3625 psi) at 15C
  - Maximum fill pressure 325 bar
  - Minimum burst pressure 587.5 bar
- 8500 L water capacity
- Diameter 1067 mm (42 inch)
- Length 11.65 m (458.6 inch)
- Initial use for CNG, H2, inert gases
- ISO 1496-3/CSC for frame

Standards for Large Composite Tanks

- No standard existed for a large composite tank for transport of compressed gases
- LC developed a relevant specification
  - In cooperation with American Bureau of Shipping
  - Based on ISO 11439, ISO 11119, ASME Section X
  - Published by ABS, ABS/HOU557163
- ISO Standard 17519 is being developed
  - ISO TC58/SC3/WG35
  - Meeting held in Oslo, July 2012
  - Updated draft will be available shortly

TITAN™ Tank Qualification

- **Successful completion of all qualification tests for a 3600 pressure vessel**
  - ✓**Hydrostatic Burst Test**
  - ✓**Ambient Pressure Cycle Test**
  - ✓**LBB (Leak Before Burst) Test**
  - ✓**Penetration (Gunfire)**
  - ✓**Environmental Test**
  - ✓**Flaw Tolerance Test**
  - ✓**High Temperature Creep Test**
  - ✓**Accelerated Stress Rupture Test**
  - ✓**Extreme Temperature Cycle Test**
  - ✓**Natural Gas Cycle Test with Blowdown**

TITAN™ Module Qualification

Completed the design, manufacture and assembly of ISO container (standard dimensions) capable of storing ~600 kg H_2 @ 3600 psi.

- ✓ **Pressure vessel targeted at 3600 as infrastructure already in place to utilize**
- ✓ **Designed to meet industry standard transporting dimensions**
- ✓ **Completed stress analysis on frame**
- ✓ **Performed DFMEA**
- ✓ **Performed HazID analysis**
- ✓ **Developed pressure relief system for fire protection**

Completed Testing of ISO Container

- ✓ **Dimensional**
- ✓ **Stacking**
- ✓ **Lifting – Top and bottom**
- ✓ **Inertia Test**
- ✓ **Impact Test**
- ✓ **Bonfire**

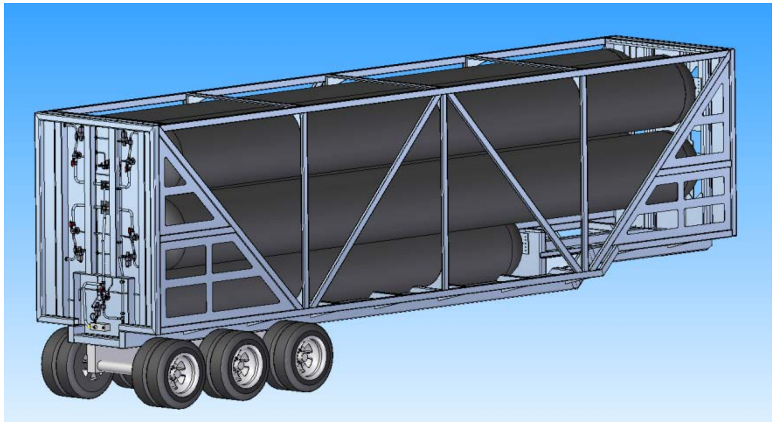
TITAN™ Approvals

- ABS has approved TITAN™ tank and module
- Approved/in service in several countries
  - Australia Peru
  - Colombia Thailand
  - Dominican Republic Vietnam
  - Malaysia

- Approved in US by DOT-PHMSA
  - SP 14951 dated February 22, 2012
  - Will enter service later this year
- Canadian Equivalency Certificate expected soon

Further Development

- Considering higher service pressure (350 bar)
- Developed new PRD system
- Developed dedicated tube trailer
  - 5 cylinders
  - 18% increase in volume



Summary

- HSECoE program is proceeding towards engineering demonstration of hydrogen storage system
- Cylinder cost reduction program is being initiated
- Hydrogen transport project has developed a large composite tube in an ISO frame, has gained regulatory approval, and is in service
- Additional information is available from DOE Annual Merit Review (AMR) proceedings and reports

Composite Conference 2012

A New Methodology for Damage Tolerant Composites Applied to COPVs

Profile Composites Inc

15-Aug-2012

Research Objective:

Identify, develop, and demonstrate *key manufacturing methods and processes*, including quality assurance and inspection methods, to enable commercial rate production of 10,000 psi carbon composite gas storage cylinders.

- **Develop and validate a fast-cycle-time production process**
- **Develop and validate prototype quality control procedures consistent with current pressure vessel standards**
- **Develop and validate NDE techniques that can be used for re-qualification of these composite cylinders**

Background

Department of Energy (DOE)/Department of Transportation (DOT)

- DOE funding assisted with initial proof of principal
- DOT supporting refinement, testing, and requirements to certify

DRIVEN By: Safety, Reliability, and Repeatability

UNITED STATES
DEPARTMENT OF TRANSPORTATION

A&P Technology

HIGH-PERFORMANCE CARBON FIBER
TORAYCA

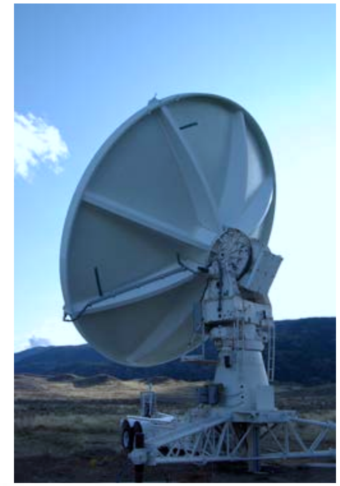
Profile Composites

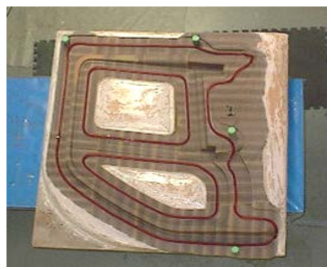
ncms
National Center for Manufacturing Sciences

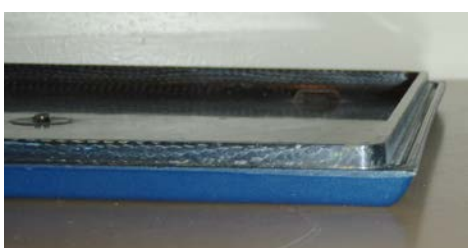
Parker

Bayer MaterialScience

Company Background





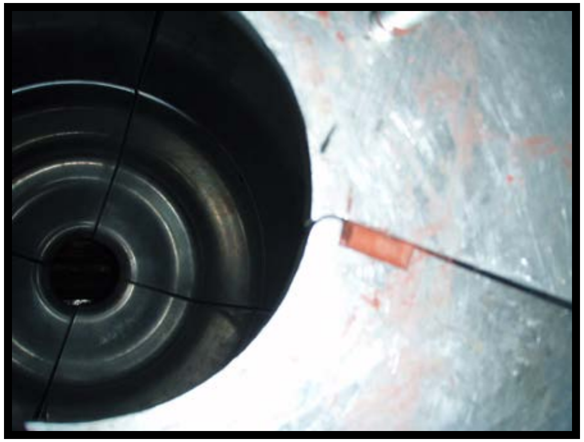


Approach

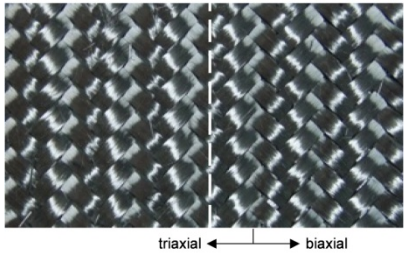
Resin Transfer Molding of COPVs

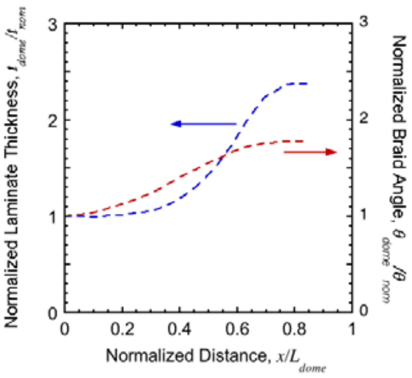
- Apply a multi-axial dry-fiber braid overwrap to the liner (Type III/IV)
- Load the wrapped tank in the molding tool
- Inject resin under controlled pressure/temperature
- Heat and cure
- Cool and de-mold

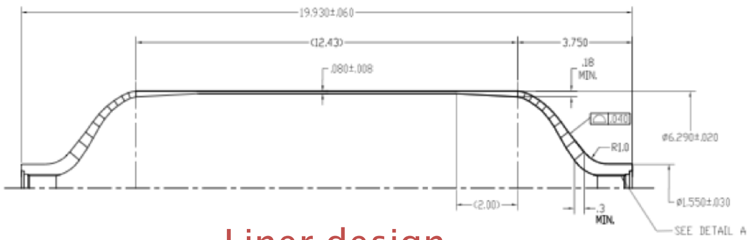
Tooling and Systems



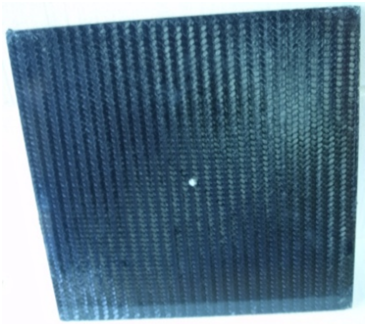
Braid architecture



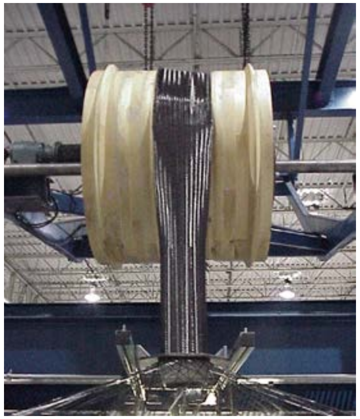




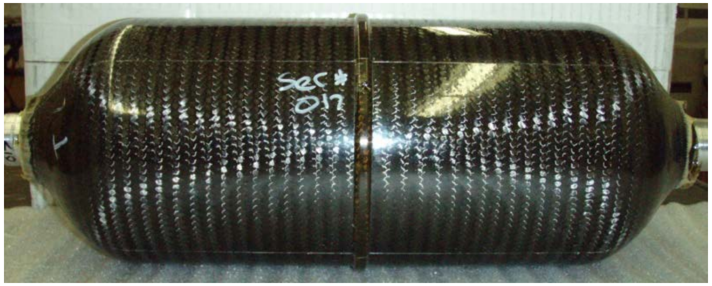
Liner design

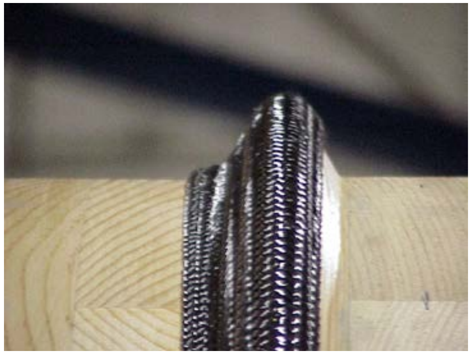


Mechanical properties
Physical properties
Fiber/resin compatibility



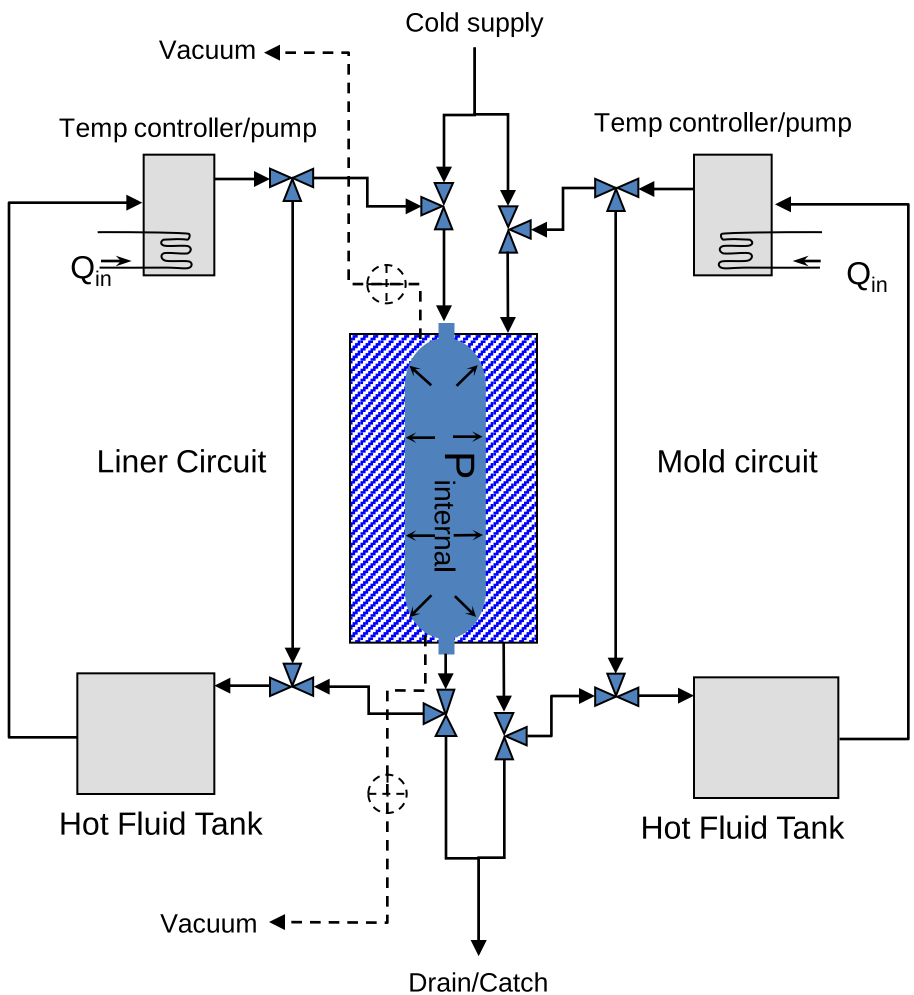
Laminate design





RTM Processing Approach

1. Pre-heat liner and mold
2. Initial inject
3. Secondary inject
4. Purge/pack sequence
5. Heat to cure
6. Cure
7. Cool
8. De-mold



Rapid Manufacturing Results

- Achieved well under 30 minutes cycle time for tank production

<u>20,000 Vehicle/year Production</u>

- Requires 3 production cell only with 4 tool stations
- 5 day/week operation
- 2 shifts and provides full redundancy (i.e. 2 cells could meet capacity at 7dpw)

In-Process Testing for Vessel Performance

System Checks

NDE for Braid/RTM COPVs

- Laser shearography
- Thermography
- Internal profilometry
- Acoustic emission
- In-situ resin flow and cure sensing
- Initiated embedded fiber optics for manufacturing process control and SHM

Failed Vessel Meeting Safety Factors

THANK YOU!

UNITED STATES
DEPARTMENT OF TRANSPORTATION

A&P Technology

HIGH-PERFORMANCE CARBON FIBER
TORAYCA

Profile Composites

ncms
National Center for Manufacturing Sciences

Parker

Bayer MaterialScience

Developing Standards for Nondestructive Evaluation of COPVs Used in Aerospace Applications

Jess M. Waller and Regor L. Saulsberry
NASA-JSC White Sands Test Facility

Session 5:

Non-Destructive Evaluation (Health Monitoring)

Composite Conference 2012

Las Cruces, NM

Wednesday, August 15, 2012

ASTM E07 Standards for NDE of Composites 2005 to present §

2005

Flat Panel Composites

2010

2011

COPVs

2012

2013

POD

Metal & Brittle Matrix Composites

Test Methods for Accept-Reject

Designation: E 2533 – 09

Standard Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications[1]

Designation: E 2580 – 07

Standard Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2582 – 07

Standard Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

Designation: E 2581 – 07

Standard Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

Designation: E 2662 – 09

Standard Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E2661/E2661M – 10

Standard Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

Nondestructive Evaluation of Flat Panel Composites: Standard Practices and Guide

5-year re-approval of E 2580, E 2580 and E 2581

ASTM WK29034

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29034 - New Practice for Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

ASTM WK29068

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29068 - New Practice for Examination of the Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

Nondestructive Evaluation of COPVs: Standard Practices, Feasibility of Guide

§ funding for technical oversight provided by the NASA NDE Working Group (NNWG) and ASA Technical Standards Program (NTSP)

NDE of COPV Issues

- COPVs are currently accepted by NASA based on design and qualification requirements and generally not verified by NDE for the following reasons:
  - Manufacturers and end users often do not have experience and validated methods for detecting flaws and defects of concern
    - If detected, the flaws are not adequately quantified and it is unclear how they may contribute to degradation in mechanical response
    - Carbon-epoxy COPVs are extremely sensitive to impact damage and impacts may be below the visible detection threshold
      - If damage is detected, this usually results in rejection since the ‘effect of defect’ on mechanical response is generally unknown
- NDE response has not been fully characterized, probability of detection (POD) established, and NDE methods validated for evaluation of the as-manufactured and as-received COPV condition

COPV Issues (con't)

COPVs demonstrate a large amount of variability in burst pressure and stress rupture progression rate (Weibull statistics)

- NDE processes need to be integrated into manufacturing to reduce variability (by detecting out-of-family behavior) and improve quality
- NDE can often be applied at each major step from fabrication through qualification by targeting the following areas of concern:
  - Crack and grain boundary issues during liner spinning
  - Weld flaws after welding
  - Bridging during winding
  - Liner to composite adhesive disbond from CTE mismatch during cure
  - Composite weak areas from poor wetting or outgassing during cure
  - Growth of pre-existing flaws during autofrettage
  - Creation of new flaws during autofrettage
  - Excessive fiber breakage during autofrettage
  - Stress/strain distribution between liner/overwrap after autofrettage
  - Liner deformation and buckling issues after autofrettage

NDE of COPV Standard Considerations

- The new Standards can have either a manufacturing or end-user bias; NDE prerogatives will differ for each:
  - need to inspect liner before wrapping or after autofrettage places responsibility on COPV manufacturers
  - need to periodically inspect liner during service places responsibility on end user
- In other words, the NDE procedures described can focus on any one of the following areas during the life cycle of the COPV:

  (a) product and process design and optimization

  (b) on-line process control

  (c) post-manufacture inspection

  (d) in-service inspection

  (e) health monitoring

Current COPV Manufacturer NDE

- **Used during:**
  - (a) product and process design and optimization
  - (b) on-line process control
  - (c) after manufacture inspection
- **Penetrant Testing (PT)**
  - ATK: the manufacturer of the MSL Cruise-Stage Propellant tank, had previously developed an "*Enhanced Special Penetrant Inspection Process*" (PSI 90-000141)
  - GD: PT done before welding
- **Radiography (RT)**
  - — Weld inspection (welded liners and PVs only)
  - — Pre- & post-proof (autofrettage)
    - — Tangential x-ray (buckling)
- **Phased Array Ultrasound (UT)**
  - ATK: used to detect delamination, foreign object debris (FOD) and bondline defects
  - Need to consider incorporating procedure into WK29034
- **Helium Leak Test (LT)**
- **Visual Inspection (VI)**
- **Acoustic Emission (AE), Eddy Current Testing (ET) and Laser Profilometry (LP) all show promise and/or are being implemented**

WK 29068 Background
Special NDE

- NASA-STD-5009 *Nondestructive Evaluation Requirements for Fracture Critical Metallic Components*
  - If Standard NDE requirements cannot be met, or smaller cracks or crack-like flaws than those shown in Table 1 or 2 have to be detected, then the inspection processes shall be considered Special NDE; and the following requirements shall apply:
    - A 90/95 percent flaw detection capability shall be demonstrated before a Special NDE inspection can be implemented
    - The Special NDE crack size can be any demonstrated size
- What are the critical flaw sizes for COPV metal liners having thicknesses from 2.3 mm (0.090 in.) down to 0.3 mm (0.010 in.), and the effective POD at that flaw size?
- For COPV composite overwraps and the overwrap/liner interface (WK29034), what are the critical flaw types?
  - delamination
  - porosity
  - bondline separation
  - bridging (welded liners only)

Current and Considered Peer Review

- NASA
  - GSFC (Parker)
  - JPL (Grimes-Ledesma, Lewis)
  - JSC (**Castner**, Koshti)
  - KSC (Hamilton, Russell)
  - LaRC (Burke, Madaras, Prosser, **Wincheski**)
  - MSFC (Russell, Suits, Walker)
  - WSTF (**Saulsberry, Spencer, Waller, Yoder**)
- Other Government
  - USAF (Voeller, Carreon)
  - NIST (McColskey, Fekete)
  - DOT (**Toughiry**)
  - FAA (Broz)
- COPV Manufacturers
  - ATK (Deemer, Papulak, Thompson)
  - General Dynamics (Heckman)
  - Lincoln Composites (**Newhouse**)
- Academia
  - University of Denver (Hamstad)
- Commercial Aerospace
  - Aerospace Corp. (Kenderian, Chang)
  - Boeing (**Engel**)
  - Honeywell (Singh)
  - Lockheed (Nightengale, Rownd)
  - Pratt & Whitney/UTC (**James**)
  - Space X (Lavoie)
- NDE Equipment Manufacturers, Test Labs and Consultants
  - A-Scan Labs (**Collingwood**)
  - Assoc. of Engineers & Architects of Israel (**Muravin**)
  - DigitalWave (Gorman)
  - Jentek Sensors (**Washabaugh**)
  - MAST, Inc. (**Djordjevic**)
  - Mistras/PAC (**Carlos**)
  - LTI (**Newman**)
- Standards Development Orgs.
  - AIAA (Hamilton)
  - ASME (Koehr)

NASA New Project Starts for FY12-13

- FY12-13 Funding Approved

- Submit ready-for-review drafts to ASTM E07.10 in February 2012

NNWG New Project Start

FY12-13 Schedule/Milestones

Milestone	Description	Milestone Date
1	a) Status ASTM E07 and technical writing teams on draft progress b) Initiate 5-year re-approval cycle for E2580-07, E2581-07 and E2582-07 c) Establish feasibility of new Standards for NDE of composites	1/2012
2	Submit WK29034 and WK29068 to ASTM for 1st round of balloting	2/2012 5/2012
3	Status ASTM E07 and technical writing teams on balloting progress	6/2012
4	a) Submit WK29034 and WK29068 to ASTM for 2nd round of balloting b) Re-approval *with* change: POCs begin revision or submit of E2580, E2581 and E2582 for first round of balloting	10/2012
5	a) Status ASTM E07 and technical writing teams on balloting progress b) Status NNWG on FY12/current accomplishments c) Propose NNWG FY14-on effort (if needed)	1/2013
6	Respond to Spring balloting call as needed, submit WK29034 and WK29068 to ASTM for 3rd round of balloting (S/C or main)	3/2012
7	Status ASTM E07 and technical writing teams on balloting progress, resolve any negatives	6/2013
8	Submit WK29034 and WK29068 to ASTM for 4th round of balloting (main)	7/2013
9	a) Secure formal adoption by ASTM of 2 Standards on NDE of COPVs b) Obtain re-approval of E2580-12, E2581-12 and E2582-12	9/2013
10	Disband E07.10 TG on NDE of Aerospace Composites, or define carry-on effort for FY14 onwards	12/2013

WK 29068

Standard Practices for Nondestructive Evaluation of Thin-Walled Metallic Liners in Filament Wound Pressure Vessels Used in Aerospace Applications

Item Registered

http://www.astm.org/DATABASE.CART/WORKITEMS/WK29068.htm

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ASTM WK29068

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29068 - New Practice for Examination of the Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

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1. Scope

1.1 This Practice discusses nondestructive testing (NDT) methods for detecting defects and flaws in thin-walled metallic pressure vessels (PVs) and composite overwrapped pressure vessels (COPVs) used in aerospace applications. In general, these COPVs have metal liner thicknesses less than 2.3 mm (0.090 in.) and a filament wound composite overwrap. 1.2 Although this Practice focuses on PVs and COPVs used at ambient temperature, it also has relevance to a) composite pressure vessels (CPVs), and b) COPVs and CPVs used at cryogenic temperatures. NDT of the composite overwrap of COPVs is beyond the scope of the Practice, however, a general overview of applicable NDT methods is provided in Guide E2533. 1.3 This Practice applies primarily to high pressure COPVs used for storing compressed gases

Work Item Status:

Date Initiated: 06-02-2010

Technical Contact: Jess Waller

Status: Draft Under Development

Standards Tracker

Standards Subscriptions

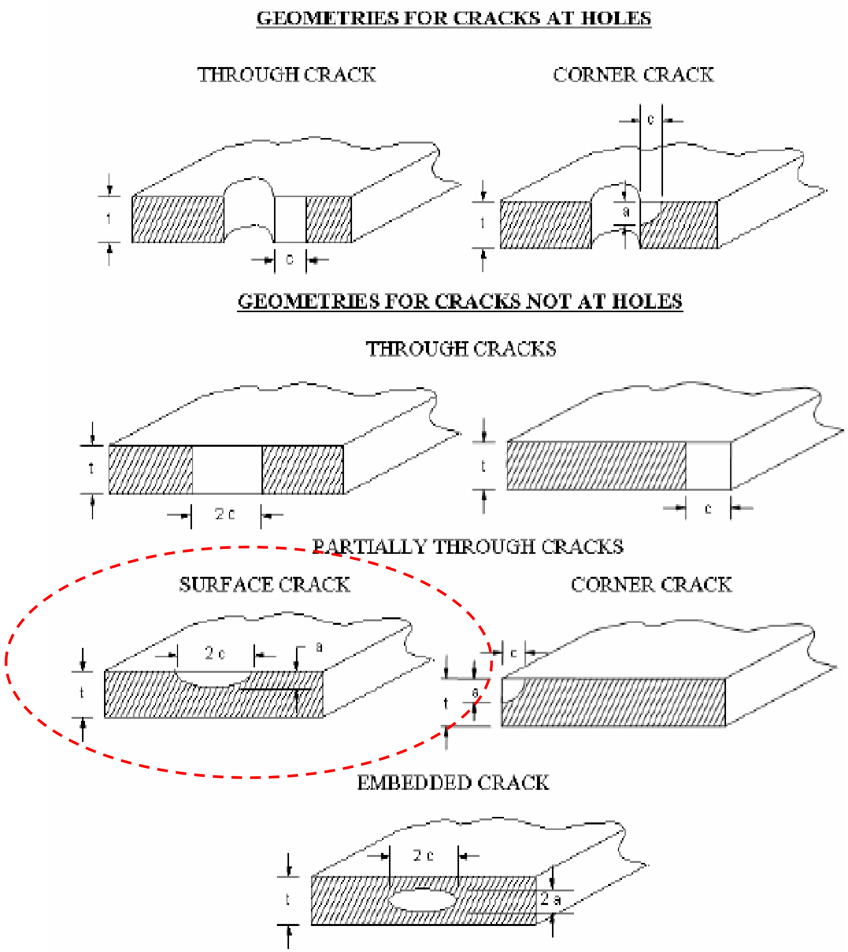
WK 29068 Background
Standard NDE and POD

The new ASTM Standard for NDE of COPV Liners operates under the backdrop of NASA NDE requirements documents

- NASA-STD-5009 *Nondestructive Evaluation Requirements for Fracture Critical Metallic Components*
  - Rely on NDE to ensure significant crack-like flaws are not present in critical areas
  - NDE shall detect the initial crack sizes used in the damage tolerance fracture analyses with a capability of 90/95 (90 % POD at a 95 % confidence level)
  - Standard NDE methods shall be limited to:
    - ET:
      SAE-ARP-4402 or SAE-AS-4787 or NASA-approved internal specs
    - PT:
      ASTM E1417 Level IV sensitivity, SAE-AMS-2647 or NASA-approved internal specs
    - RT:
      ASTM E1742 or NASA-approved internal specs
      minimum sensitivity shall be 2-1T
      film density shall be 2.5 to 4.0
      beam axis within +/-5 degrees of crack plane orientation
    - UT:
      ASTM E2375 or NASA-approved internal specs
  - No reference in NASA documentation for Laser Profilometry (LP) or Leak Testing (LT) - unique to WK29068 and supporting ASTM documents

WK 29068 Background
Standard NDE and POD

For COPV liners, interested in detection of ‘partially through’ surface cracks



Also, need exists to detect/monitor liner buckling and other defects for which accept-reject exist or is prudent

WK 29068 Background
Standard NDE and POD

Per NASA-STD-5009, for standard NDE, 90/95 POD needs to be established for the following minimum detectable crack sizes:

U. S. CUSTOMARY UNITS (inches)

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a*	Crack Dimension, c*
Eddy Current NDE				
Open Surface	t ≤ 0.050 t > 0.050	Through PTC[1]	t 0.020 0.050	0.050 0.100 0.050
Edge or Hole	t ≤ 0.075 t > 0.075	Through Corner	t 0.075	0.100 0.075
Penetrant NDE				
Open Surface	t ≤ 0.050 0.050<t <0.075 t > 0.075	Through Through PTC	t t 0.025 0.075	0.100 0.150 - t 0.125 0.075
Edge or Hole	t ≤ 0.100 t > 0.100	Through Corner	t 0.100	0.150 0.150
Magnetic Particle NDE				
Open Surface	t ≤ 0.075 t > 0.075	Through PTC	t 0.038 0.075	0.125 0.188 0.125
Edge or Hole	t ≤ 0.075 t > 0.075	Through Corner	t 0.075	0.250 0.250
Radiographic NDE				
Open Surface	t ≤0.107 t > 0.107	PTC PTC Embedded	0.7t 0.7t 2a=0.7t	0.075 0.7t 0.7t
Ultrasonic NDE Comparable to a Class A Quality Level (ASTM-E-2375)				
Open Surface	t ≥ 0.100	PTC Embedded**	0.030 0.065 0.017 0.039	0.150 0.065 0.087 0.039

[1] PTC - Partly through crack (Surface Crack)
* See figure 1 for definitions of "a" and "c" for different geometries.
** Equivalent area is acceptable, ASTM-E-2375 Class A.

lacks sensitivity for COPVs

Background

Need for Quantitative NDE of COPVs

- Identify current best practice that is able to detect flaw sizes lower than attainable using Standard NDE methods, i.e., focus is on 'Special' NDE methods

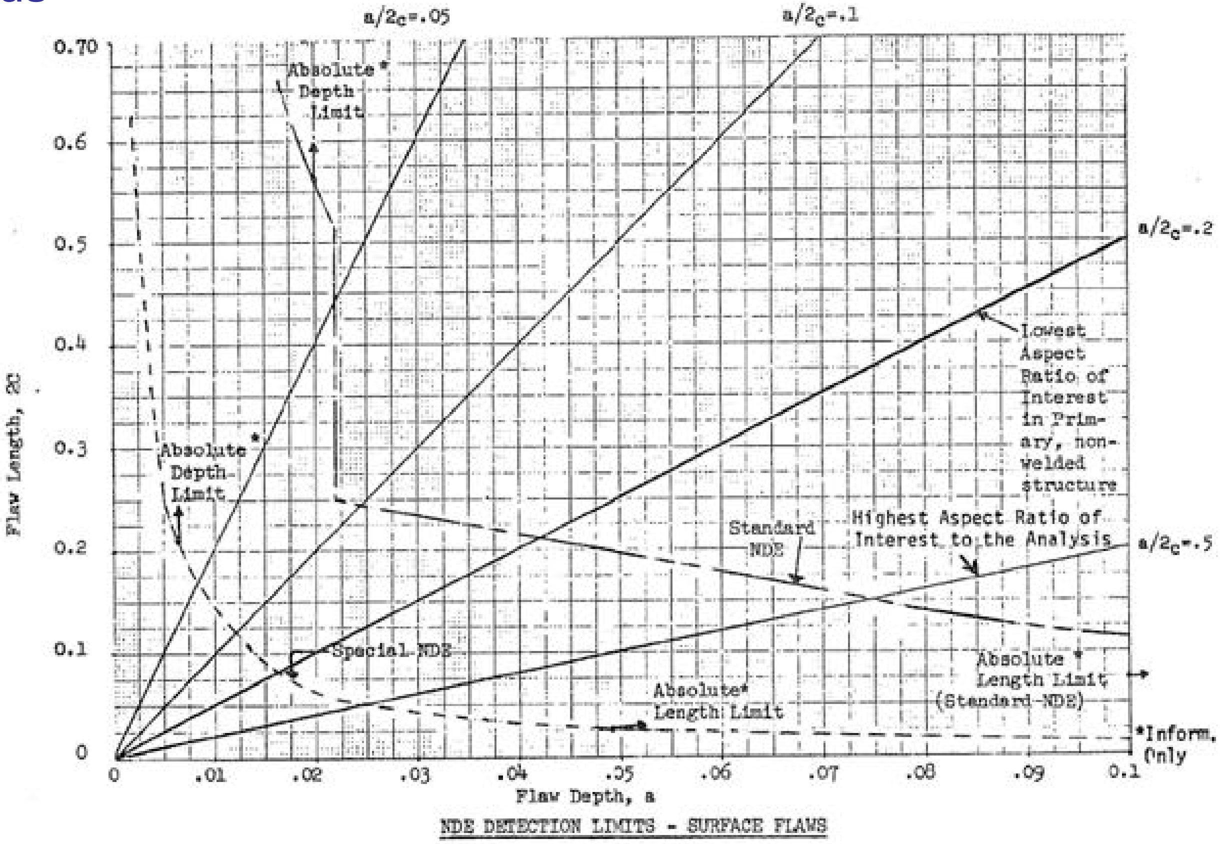
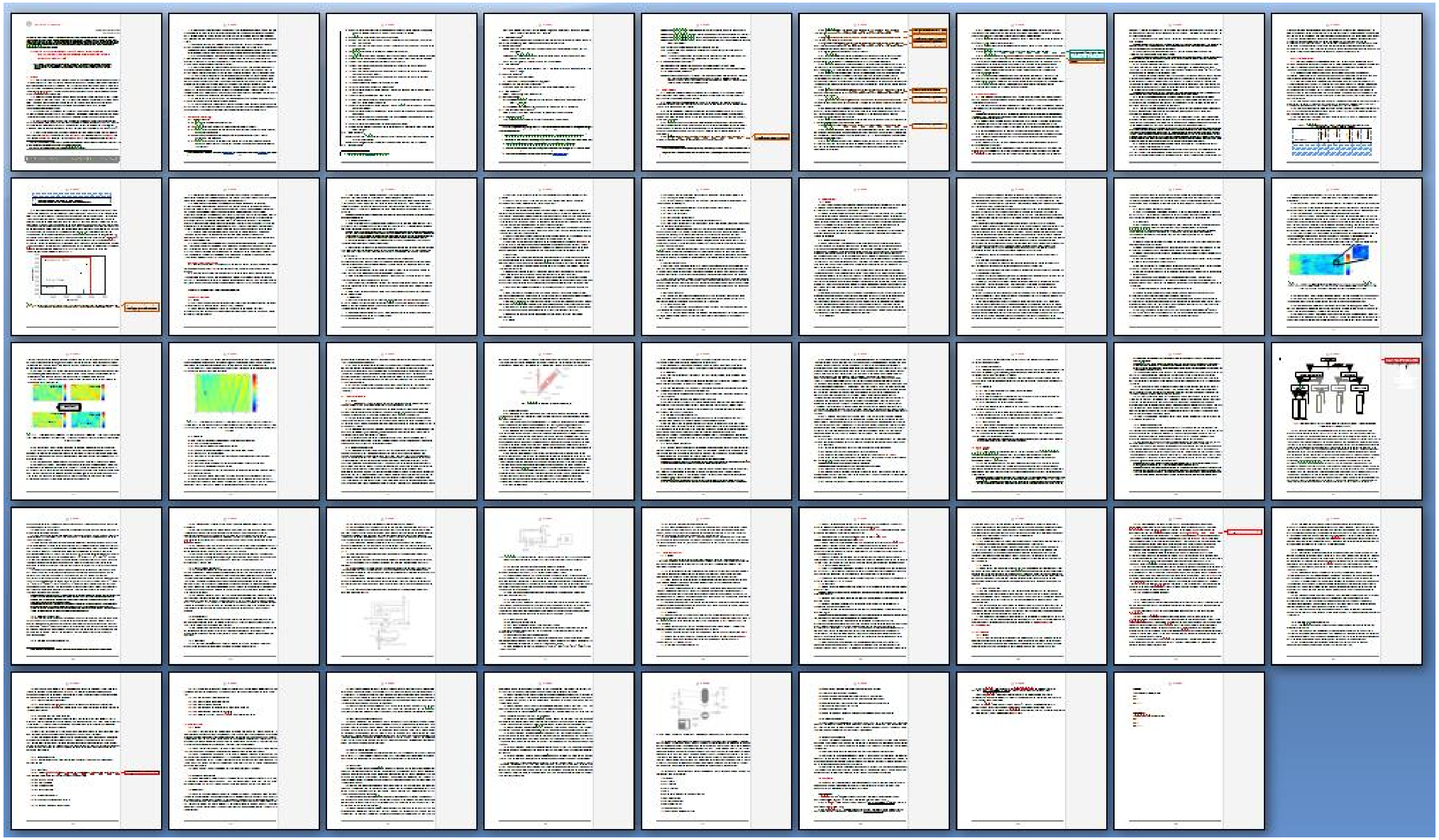


Figure 5.0-1. Orbiter Fracture Control Program NDE Detection Limits

Candidate NDE Methods for COPV Liners

- A-List: NDE performed at 90% POD and 95% confidence level (90/95), but need to know relevance of 90/95 flaw size relative to critical and minimum detectable flaw sizes
  - eddy current (ET)
  - penetrant testing (PT)
  - radiography (RT) (e.g., weld inspection)
  - ultrasound (UT) (Lamb wave; phased array, pulse-echo)
- A-List, POD not applicable or not performed
  - laser profilometry (detect pitting, buckling, radius & thickness changes)
  - leak testing (LT) (detect through cracks)
- B-List: Supplemental:
  - acoustic emission (AE) (COPVs with liner welds before wrapping)
  - visual testing (VT) (borescopy superseded by laser profilometry)

WK 29068 COPV Liner Draft Exists



- Contains procedural NDE detail for AE, ET, LT, Profilometry, PT and RT
- Underwent administrative ASTM balloting in February
- In NASA review currently (NESC)

WK 20968 Liner Writing Teams

- Acoustic Emission: Muravin
  - Carlos (E07.04 liaison)
  - New section completed since June 2011 Anaheim meeting
  - Newhouse added to team
    - AE protocol currently in ASME Section X , Apppendix 8
- Eddy Current: Wincheski
  - Washabaugh (E07.07 liaison)
- Penetrant Testing: Castner
  - Collingwood (E07.03 liaison)
- Radiography: Engel (interim lead)
  - Kropas-Hughes (E07.01 liaison)
- Leak Testing: Waller (interim lead)
  - Anderson (E07.08 liaison)
- Laser Profilometry: Saulsberry
  - Clausing (E07.10 liaison)
- Ultrasound: James
  - Ruddy (E07.06 liaison)

WK 29034

Standard Practices for
Nondestructive Evaluation of the Composite
Overwrap in Filament Wound Pressure Vessels
Used in Aerospace Applications

Item Registered

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ASTM WK29034

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29034 - New Practice for Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

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1. Scope

1.1 This Practice discusses nondestructive testing (NDT) methods for detecting flaws, defects, and accumulated damage in filament wound pressure vessels, also known as composite overwrapped pressure vessels (COPVs), used in aerospace applications. In general, these vessels have metal liner thicknesses less than 2.3 mm (0.090 in.), and fiber loadings in the composite overwrap greater than 60 percent by weight. 1.2 Although this Practice focuses on COPVs used at ambient temperature, it also has relevance to 1) composite pressure vessels (CPVs), 2) monolithic metallic pressure vessels, and 3) COPVs and CPVs used at cryogenic temperatures. 1.3 This Practice applies to 1) low pressure COPVs used for storing liquid propellants at maximum allowable working pressures (MAWPs) up to 35

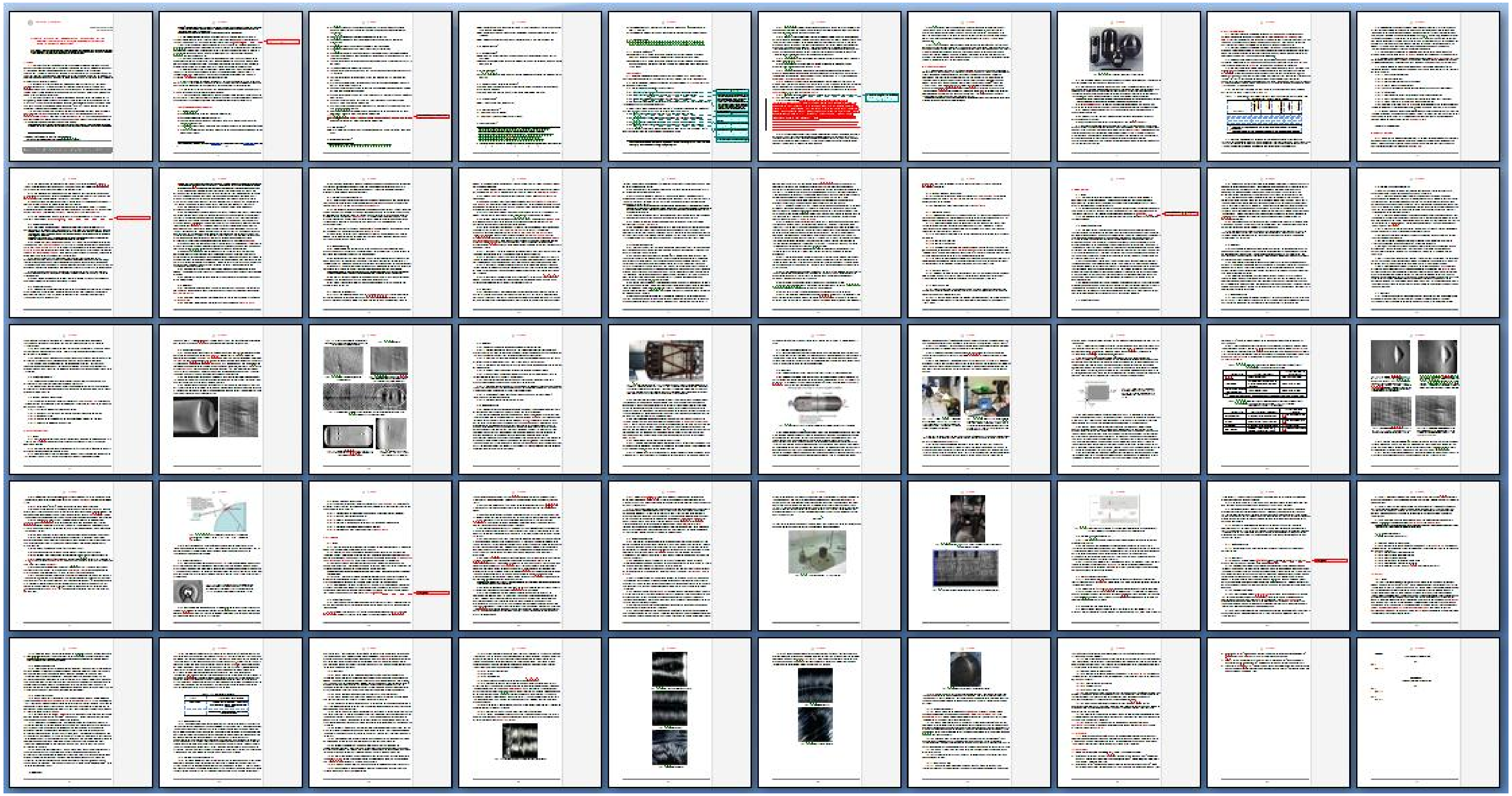
Work Item Status:
Date Initiated: 06-01-2010
Technical Contact: Jess Waller

Status: Draft Under Development

Standards Tracker

Standards Subscriptions

WK 29034 COPV Overwrap Draft Exists



- Contains procedural NDE detail for AE, ET, Shearography, UT and VI
- Underwent administrative ASTM balloting in May
- In NASA review currently (NESC)

WK 29034 Overwrap Writing Teams

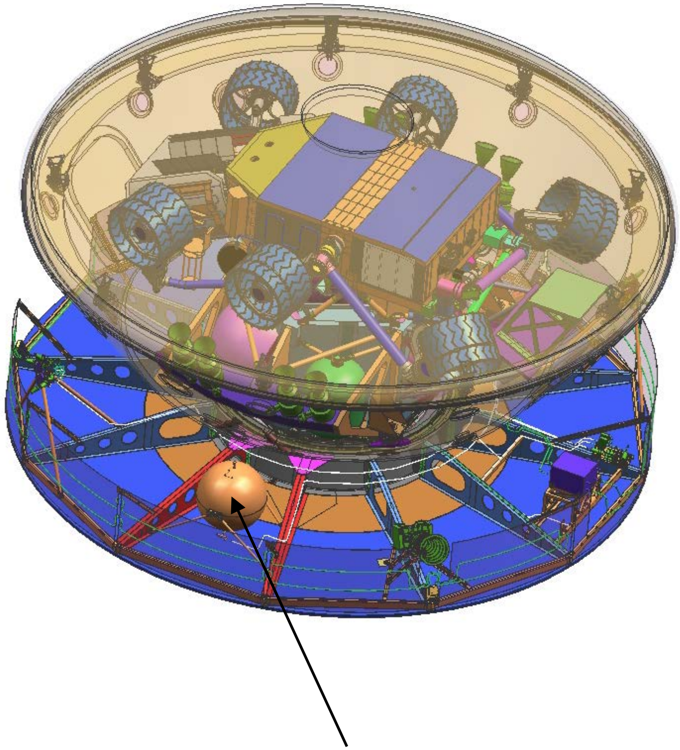
- Acoustic Emission: Muravin, Waller
  - Carlos (E07.04 liaison)
  - Gorman (Digital Wave Corp.)
  - Hamstad (University of Denver)
  - NASA: Madaras (LaRC), Nichols (WSTF), Walker (MSFC)
  - Newhouse (Lincoln Composites, collab. with DWC and DOT)
  - Toughiry (DOT)
  - v. K. Hill (Embry-Riddle Aeronautical University (ERAU))
- Eddy Current: Washabaugh
  - Washabaugh (E07.07 liaison)
- Shearography: Newman
  - Clausing (E07.10 liaison)
- Ultrasound: James
  - Ruddy (E07.06 liaison)
  - ATK (Deemer, Papulak, Thompson) – pulse echo and phased array UT
  - Burke (NASA LaRC) – captured water column focused UT
  - Djordjevic (MAST, Inc.) – laser guided wave laser UT
  - Engel (Boeing)
  - Spencer (WSTF)
- Visual Inspection: Yoder
  - Clausing (E07.10 liaison)

WK 29034 and 29068 Plans

- Submit for Fall 2012 E07.10 S/C balloting
  - WK 29068 (liner)
    - Retain AE section if database or prior precedent exists for AE procedure to characterize welds and is pertinent for thin-walled metal COPV liners
    - Incorporate negatives and comments from February ASTM admin ballot
    - Accomplish NASA peer review
  - WK 29034 (composite overwrap)
    - Consider adding section from phased array UT
    - Incorporate negatives and comments from May ASTM admin ballot
    - Accomplish NASA peer review
    - Accomplish peer review by M. Hamstad

Examples of POD Requirements for NASA Hardware

- Monolithic titanium propellant tank for MSL procured under ANSI/AIAA S-080-1998
  - NDE methods provide 90/95 POD for crack size used for fracture mechanics safe-life analysis
  - Flaw shape or crack aspect ratio (a/2c) must be considered over range of 0.1 to 0.5
- Agency Penetrant POD Requirements
  - Orbiter Fracture Control Program previously established crack length minimum limit for penetrant inspection of 0.050 in. (for 0.5 aspect ratio) and requires validation testing
  - NASA-STD-5009 does not set minimum detection limits, but requires validation testing for crack sizes less than Standard NDE sizes



Mars Science Laboratory (MSL) Propellant Tank

Current POD Activities/Resources

NASA NDE Working group (NNWG, Dr. Edward Generazio)

http://www.nnwg.org/Recent Publications/Directed Design.pdf

NASA Engineering and Safety Center (NESC, Dr. William Prosser)

ASTM E07.10 (various)

http://www.astm.org/Standards/E2862.htm

http://www.nxtbook.com/nxtbooks/astm/sn_20120708/#/54

Directed Design of Experiments for Validating Probability of Detection Capability of NDE Systems (DOEPOD)

E. R. Generazio[1]

[1]National Aeronautics and Space Administration, Hampton, VA 23681

ABSTRACT. The capability of an inspection system is established by applications of various methodologies to determine the probability of detection (POD). One accepted metric of an adequate inspection system is that there is a 95% chance that the POD is greater than 90% (90/95 POD). Directed DOEPOD has been developed to provide an efficient and accurate methodology that yields observed POD and confidence bounds for both Hit-Miss or signal amplitude testing. Specifically, DOEPOD demands utilization of observance of occurrences. Directed DOEPOD does not assume prescribed POD logarithmic or similar functions, so that multi-parameter curve fitting or model optimization approaches are not required.

Keywords: Probability of Detection, POD, NDE, NDI, NDT, Nondestructive
PACS: 02.50.Cw, 81.70.–q

INTRODUCTION

Directed DOEPOD utilizes the concept of probability of a Hit (POH) at any flaw size. That is, the number of Hits observed per set of samples exhibiting flaws of similar characteristics (e.g., flaw lengths). The determination of POH at any selected flaw size is a measured or observed quantitative value between zero and one, and knowledge of POH also yields a quantitative measure of the lower confidence bound (value). This process is statistically referred to as "observation of occurrences" and is distinct from use of functional forms that estimate or predict POD. The driving parameters of DOEPOD are the observed POH and the lower confidence bounds (values) of the observed POH. The binomial distribution has been used previously for determining POD by observation of occurrences. Prior work[1,2] used a selection of arrangements for grouping flaws of similar characteristics. Yee (1976) used smoothing optimized probability and overlapping sixty point methods grouping by number of flaws into a class and by cumulative sums of fixed flaw size class intervals, while Rummell (1982) used fixed class widths. These binomial approaches have lead to the acceptance of using the 29 out of 29 (29/29) point estimate[1,2,3] method, in combination with validation that the POD is increasing with flaw size, in order to meet the requirements of MSFC-STD-1249[3] and NASA-STD-(I)-5009[4]. DOEPOD extends work in binomial applications for POD by adding the concept of lower confidence bound maximization as the driver for establishing 90/95 POD. DOEPOD satisfies the requirement for critical applications where validation of inspection systems, individual procedures, and operators are required even when a full POD curve[5] is estimated or predicted.

DOEPOD CONCEPTS

DOEPOD is based on the application of the binomial distribution to a set of flaws that have been grouped into classes, where each class has a width. The classes are allowed to vary

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ASTM INTERNATIONAL

Designation: E2862 – 12

Standard Practice for Probability of Detection Analysis for Hit/Miss Data[1]

This standard is issued under the fixed designation E2862; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice defines the procedure for performing a statistical analysis on nondestructive testing hit/miss data to determine the demonstrated probability of detection (POD) for a specific set of examination parameters. Topics covered include the standard hit/miss POD curve formulation, validation techniques, and correct interpretation of results.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1316 Terminology for Nondestructive Examinations

2.2 *Department of Defense Handbook:*

MIL-HDBK-1823A Nondestructive Evaluation System Reliability Assessment[3]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *analyst, n*—the person responsible for performing a POD analysis on hit/miss data resulting from a POD examination.

3.1.2 *demonstrated probability of detection, n*—the calculated POD value resulting from the statistical analysis on the hit miss data.

3.1.3 *false call, n*—the perceived detection of a discontinuity that is identified as a find during a POD examination when no discontinuity actually exists at the inspection site.

3.1.4 *hit, n*—an existing discontinuity that is identified as a find during a POD demonstration examination.

3.1.5 *miss, n*—an existing discontinuity that is missed during a POD examination.

3.1.6 *probability of detection, n*—the fraction of nominal discontinuity sizes expected to be found given their existence.

3.2 *Symbols:*

3.2.1 a—discontinuity size.

3.2.2 a_p—the discontinuity size that can be detected with probability p.

3.2.2.1 *Discussion*—Each discontinuity size has an independent probability of being detected and corresponding probability of being missed. For example, being able to detect a specific discontinuity size with probability p does not guarantee that a larger size discontinuity will be found.

3.2.3 $a_{p|c}$—the discontinuity size that can be detected with probability p with a statistical confidence level of c.

3.2.3.1 *Discussion*—$a_{p|c}$ is calculated by applying a statistical uncertainty bound to a_p. The uncertainty bound is a function the amount of data, the scatter in the data, and the specified level of statistical confidence. The resulting value represents how large the discontinuity with POD equal to p could be when uncertainty associated with estimating a_p is accounted for. Hence $a_{p|c} > a_p$. Note that POD is equal to p for both $a_{p|c}$ and a_p. a_p is based solely on the hit/miss data resulting from the examination and represents a snapshot in time, whereas $a_{p|c}$ accounts for the uncertainty associated with limited sample data.

[1] This practice is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.10 on Specialized NDT Methods.

Current edition approved Jan. 15, 2012. Published February 2012. DOI:10.1520/E2862-12.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from Standardization Documents Order Desk, DODSSP, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5098, http://dodssp.daps.dla.mil.

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update

E07/NONDESTRUCTIVE TESTING

Detection Analysis for Hit/Miss Data

A new ASTM International standard provides the necessary background and describes the step-by-step process for analyzing nondestructive testing hit/miss data resulting from a probability of detection examination, including minimum requirements for validating the resulting POD curve.

The new standard, E2862, Practice for Probability of Detection Analysis for Hit/Miss Data, has been developed by Subcommittee E07.10 on Specialized NDT Methods, part of ASTM International Committee E07 on Nondestructive Testing.

"A probability of detection demonstration test and analysis is the best available method for quantifying the detection capability of a nondestructive testing system," says Jennifer R. Brown, senior statistician, Pratt and Whitney Rocketdyne, and a member of E07.10. "However, a POD demonstration test and analysis can be a pointless exercise without a basic understanding of the NDT system as well as a general understanding of the underlying statistical method on which the POD analysis is based."

E2862 will be useful to anyone who is responsible for performing a probability of detection analysis on hit/miss data resulting from a POD examination.

Brown notes that E2862 will provide this understanding and will be useful to anyone who is responsible for performing a probability of detection analysis on hit/miss data resulting from a POD examination as well as those who are recipients of, and base decisions on, the results of such an analysis. The U.S. National Aeronautics and Space Administration requires probability of detection demonstration tests on nondestructive testing systems that are used evaluate fracture critical hardware.

To purchase ASTM standards, visit www.astm.org and search by the standard designation, or contact ASTM Sales (phone: 877-909-ASTM; sales@astm.org).

CONTACT Technical Information: Jennifer R. Brown • Pratt and Whitney Rocketdyne • West Palm Beach, Fla. • Phone: 561-796-2230 • Email: jennifer.brown@pwr.utc.com ■ ASTM Staff: Kathleen McClung • Phone: 610-832-9717 • Email: kmcclung@astm.org ■ Upcoming Meeting: Jan. 27-31, 2013 • Plantation, Fla.

snonline

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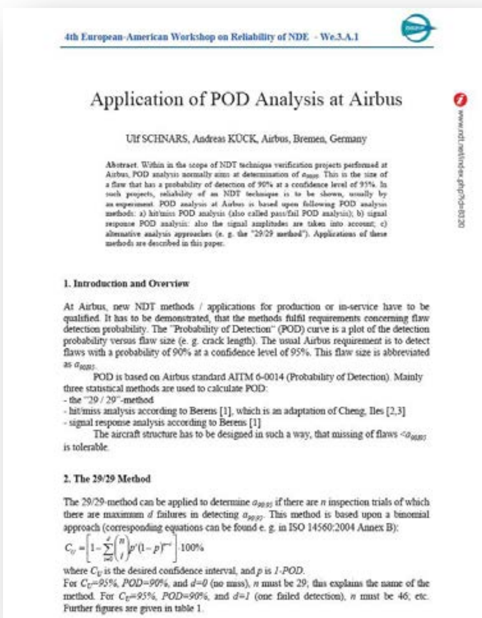
POD on Composite Overwraps

- Issues:
  - Effect-of-defect needs to be established for given flaw types
    - cut tow
    - tow termination errors
    - porosity
    - impact
    - delamination
    - disbond (buckling)
    - bridging, etc.



4th European-American Workshop on Reliability of NDE - We.3.A.1

www.ndt.net/index.php?id=8320

Application of POD Analysis at Airbus

Ulf SCHNARS, Andreas KÜCK, Airbus, Bremen, Germany

Abstract. Within in the scope of NDT technique verification projects performed at Airbus, POD analysis normally aims at determination of $a_{90/95}$. This is the size of a flaw that has a probability of detection of 90% at a confidence level of 95%. In such projects, reliability of an NDT technique is to be shown, usually by an experiment. POD analysis at Airbus is based upon following POD analysis methods: a) hit/miss POD analysis (also called pass/fail POD analysis); b) signal response POD analysis: also the signal amplitudes are taken into account; c) alternative analysis approaches (e. g. the "29/29 method"). Applications of these methods are described in this paper.

1. Introduction and Overview

At Airbus, new NDT methods / applications for production or in-service have to be qualified. It has to be demonstrated, that the methods fulfil requirements concerning flaw detection probability. The "Probability of Detection" (POD) curve is a plot of the detection probability versus flaw size (e. g. crack length). The usual Airbus requirement is to detect flaws with a probability of 90% at a confidence level of 95%. This flaw size is abbreviated as $a_{90/95}$.

POD is based on Airbus standard AITM 6-0014 (Probability of Detection). Mainly three statistical methods are used to calculate POD:
- the "29 / 29"-method
- hit/miss analysis according to Berens [1], which is an adaptation of Cheng, Iles [2,3]
- signal response analysis according to Berens [1]

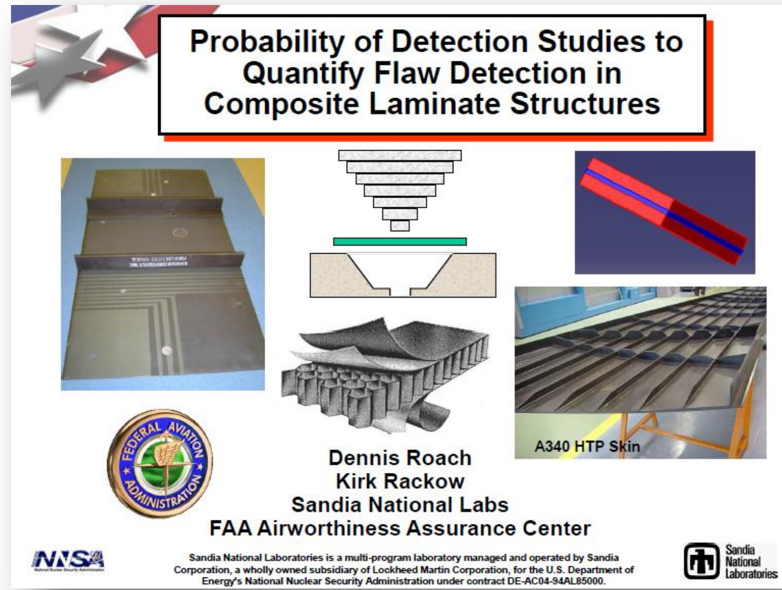
The aircraft structure has to be designed in such a way, that missing of flaws $< a_{90/95}$ is tolerable.

2. The 29/29 Method

The 29/29-method can be applied to determine $a_{90/95}$ if there are n inspection trials of which there are maximum d failures in detecting $a_{90/95}$. This method is based upon a binomial approach (corresponding equations can be found e. g. in ISO 14560:2004 Annex B):

$$C_U = \left[1 - \sum_{i=0}^{d} \binom{n}{i} p^i (1-p)^{n-i}\right] \cdot 100\%$$

where C_U is the desired confidence interval, and p is $1\text{-}POD$.
For C_U=95%, POD=90%, and d=0 (no miss), n must be 29; this explains the name of the method. For C_U=95%, POD=90%, and d=1 (one failed detection), n must be 46; etc. Further figures are given in table 1.



  - ATK 29-29 Method (Airbus)
    - Based on hit-miss analysis according to Berens[1]
  - Sandia POD Method (FAA)
    - Commonly observed flaws bracketed using POD test specimens

[1] Berens, Alan P. (1989): NDE Reliability Data Analysis. In: *Metals Handbook, Vol. 17, AMS International, Metals Park, Ohio, 689-701.*

Composite Conference 2012

Overview: NASA NDE Working Group (NNWG) "Smart COPV" Project

WSTF: Regor Saulsberry

GRC: Don Roth,

LaRC: Eric Madaras

MSFC: Curtis Banks,

DFRC: Lance Richards

KSC: Rick Russell

NNWG "Smart COPV" Core Team

- NASA WSTF/Regor Saulsberry - Project Management and WSTF Tasks
- GeoControl Systems WSTF/Jess Waller - Polymer Science/AE
- NASA WSTF/Charles Nichols - AE Analysis, method development/automation
- NASA LaRC/Eric Madaras - Wireless Acoustic Emission (AE) detection systems
- NASA GRC/Don Roth - Acoustic Emission Analysis Applet Software (assisted by WSTF/Josh Simmons)
- NASA DFRC/Lance Richards - Multiaxial Fiber Bragg Grating (FBG) grids
- NASA MSFC/Curtis Banks - Fiber Optics AE (FOAE), piezoelectric sensor arrays (Acellent Technologies and Métis Design Corporation), polarization maintaining (PM) Fiber damage detection and MSFC Office of the Chief Technologist (OCT) developments
- NASA KSC/Richard Russell - Magnetic Stress Gage (MSG) Structural Health Monitoring (SHM)

- Funding: NNWG HQ/Ed Generazio - Delegated Program Manager

Potential Extended Agency “Smart COPV” SHM Team

- NASA JSC/Scott Forth - Manned Space Flight Pressure Vessel Analysis (i.e., ISS, MPCV, commercial)
- NASA JSC/Ajay Koshti - Manned Space Flight Programs NDE
- NASA JSC/George Studor - wireless instrumentation
- MASA NDE Fellow - Bill Prosser – NESC NDE TDT
- NASA JPL/Lorie Grimes Ledesma – Composite Pressure Vessel Working Group
- NASA KSC/Paul Schallhorn - launch services (represents Boeing and Commercial Spaceflight participants)
- NASA WSTF/Nate Greene - Department of Transportation (DOT) and other govt. and industry teams
- NASA WSTF/Jon Haas - ISS stress rupture testing
- NESC GRC/John Thesken - structural analysis
- NESC GRC/Jim Sutter - composite materials
- NASA LaRC/Mark Shuart - CoEx
- NASA LaRC/Eric Burke - SBIR SHM subtopic manager
- NASA MSFC/James Walker - CoEx $\Rightarrow$ Composites for Exploration; CCTD $\Rightarrow$ Composite Cryogenic Tank Development; “Structural Integrity Toolbox for Design, Certification and In-Service Monitoring of Composite Cryo-Tanks” (OCT funded under the CCTD Project)
- NASA MSFC/Pravin Aggarwal (Structural Design and Analysis Division at MSFC)
- NASA MSFC/Jimmy Miller - SMH sensors
- NASA MSFC/John Vickers – CoEx, Composite, Cryotank Technologies

Background

- This project directly targets the Reliability/Life Assessment/Health Monitoring in OCT Roadmap TA12, (Materials, Structures, Mechanical Systems and Manufacturing) and is crosscutting to other discipline road maps.
  - TA07 (Human Exploration Destination Systems) discusses the criticality of having integrated health monitoring/management systems to free up the crew to cope with the real Mission. The necessary specialized software development for this is also deemed critical.
  - TA02 (In-Space Propulsion Technologies) discusses the criticality of having integrated SHM (ISHM).
  - SHM is also deemed to be of great importance to the Avionics SC and is also a focus of their Charter and road mapping activity
- The Smart COPV Roadmap (tied to OCT road map TA12) will be refined and kept updated

Background – Promising Methods

- Several promising SHM methods have been developed from programs:

  NNWG:

  – Stress Rupture NDE Development project

  – In-situ Carbon Fiber Micromechanics project

  – Multiaxial FBG Systems for Real-time NDE Inspection project plus Acousto-Optics project

  – Magnetic Stress Gage (MSG) Health Monitoring of COPVs (Keys off of a successful SBIR)

  Other NASA SHM Programs:

  – Advancements have been made by team participants working NASA's Lightweight Spacecraft Structures & Materials (LSSM) and several other precursor programs, i.e., active ultrasound (UT) methods (Acellent and Metis structural health monitoring)

- In process manufacturing NDE methods such as Profilometry, automated Eddy Current (EC) and UT scanning methods can screen for defects and quantify mechanical response variations

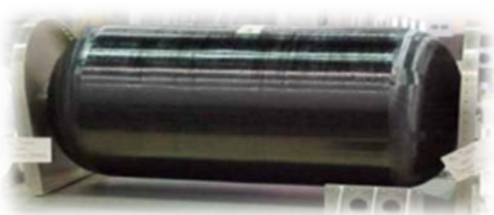
  – These tools should help produce more consistent structures which better follow models and better conform to design criteria and evolve COPV performance.

  – Resulting COPVS with integrated SHM systems make for "Smart COPVs" capable of monitoring critical structural response (health) and alerting crew to hazards.

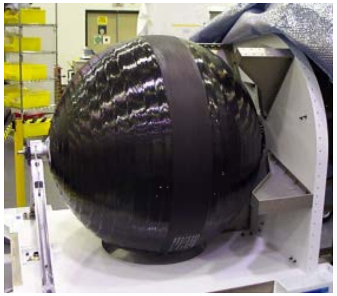
  – Plan to explore other potential COPV improvements such as toughed matrix materials.

Background – Current Needs

- Micrometeoroids and Orbital Debris (MMOD) and stress rupture of carbon-epoxy COPVs used on ISS
- Ground stress rupture to better characterize stress rupture degradation rates
- ISS Nitrogen-Oxygen Recharge System (NORS) MMOD concerns
- Multi-Purpose Crew and Service module, and nearly **all future long duration NASA spacecraft missions**
  - Incidental but direct benefits for COPVs used in DOT liquid natural gas and hydrogen storage applications
  - Other composite structures of interest are load bearing, fracture critical composite materials used in DoD, commercial aerospace and NASA applications, especially where cyclic loading is experienced



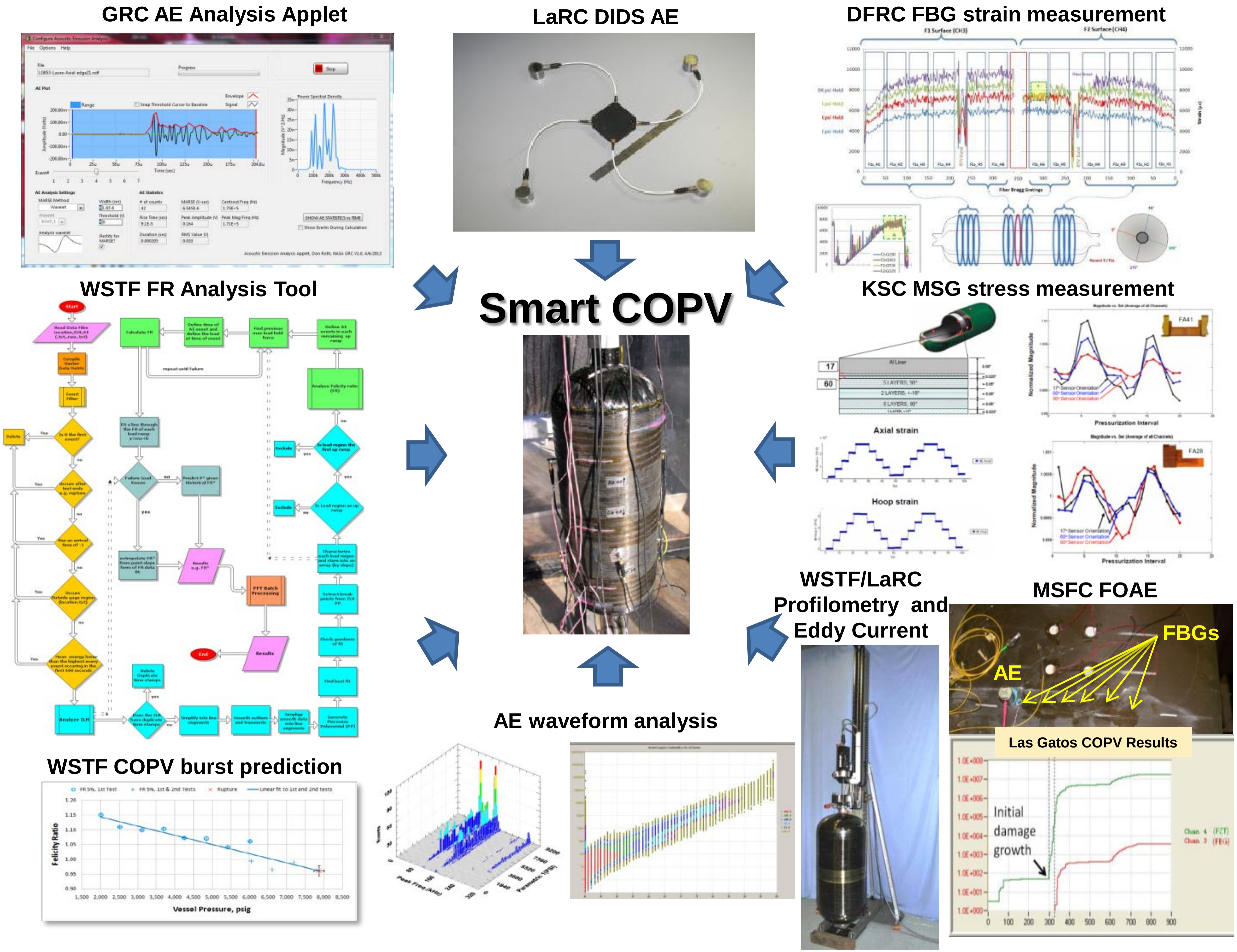
Nitrogen Tank Assembly (45”L×19.7”D)



High Pressure Gas Tank (HPGT) – Oxygen COPV (37.89”D)

Overall Project Objectives

- Better COPVs: evaluate mechanical response, create more uniform fiber tension, explore other improvements such as toughened resins to reduce risk and improve reliability of COPVs for NASA missions
- Evaluate, down-select and integrate the most promising NDE/SHM technologies from NNWG and other projects into COPVs
- Develop down-selected technologies, raising the technology readiness level (~TRL-6) such that an integrated end-to-end "Smart COPV" demonstration is accomplished by FY15
- Seek other program synergy to help provide the resources to better accomplish objectives and meet needs
  - let us know if you want to participate
- Current center focus areas are discussed in the following slides and in more detail in presentations to follow


GRC AE Analysis Applet
LaRC DIDS AE
DFRC FBG strain measurement
WSTF FR Analysis Tool
Smart COPV
KSC MSG stress measurement
Axial strain
Hoop strain
Pressurization Interval
WSTF/LaRC Profilometry and Eddy Current
MSFC FOAE
FBGs
AE
Las Gatos COPV Results
Initial damage growth
AE waveform analysis
WSTF COPV burst prediction
Felicity Ratio
Vessel Pressure, psig
FR 5%, 1st Test
FR 5%, 1st & 2nd Tests
Rupture
Linear fit to 1st and 2nd tests
Start
End
Results
FFT Batch Processing
Analyze ILH
Peak Freq.(kHz)

COPV Life Cycle Considerations

COPV manufacturer

End User (NASA)

Product - Process Design and Optimization → On-line Process Control → Acceptance/ post manufacturing NDE → Structural Health Monitoring

Apply finding from previous testing and material considerations

Integrated Profilometry, EC, and UT

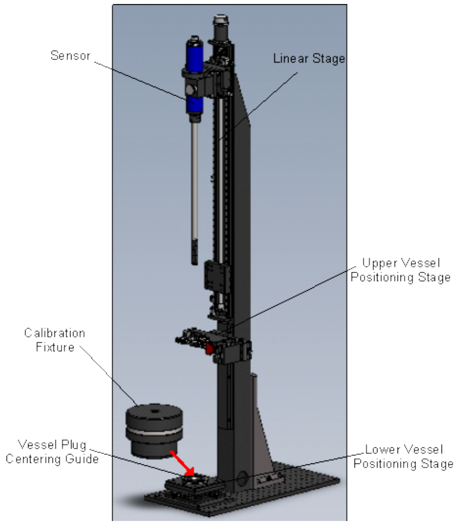
AE, DIDS AE, MSG, FBG, FOAE, PZT

- COPV variability is an ongoing issue, necessitating implementation of complementary non-SHM NDE during the manufacturing phase
  - Profilometry has proven to be useful:
    - Evaluate mechanical response through out manufacturing: bare liner, wrapping and autofrettage (plot each together)
      - Mapping liner buckling and irregularities
      - Laser vision/optical measurements of pitting and surface defects
      - non-uniform or out-of-family liner expansion
- Other Promising techniques help improve quality and eliminate COPV variability:
  - External EC for liner crack detection prior to wrapping – needs flaw detection quantification
  - Prototype Interior EC for liner inspection after wrapping and autofrettage
  - Captured water column focused UT may be added – has worked well on composite panels

Composite Conference 2012

Sub-project Details by Center

WSTF COPV Profilometry and Eddy Current Scanners



Original Internal Profilometer

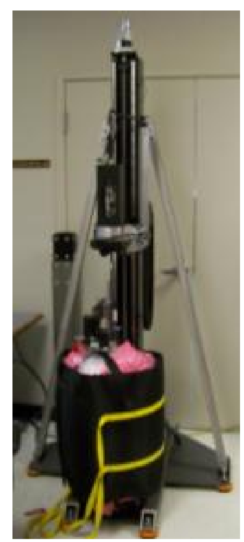
External Profilometer added to Original Scanner

External Eddy Current (EC) Probe added

12-foot Orion Internal Profilometer developed and verified on simulator vessel

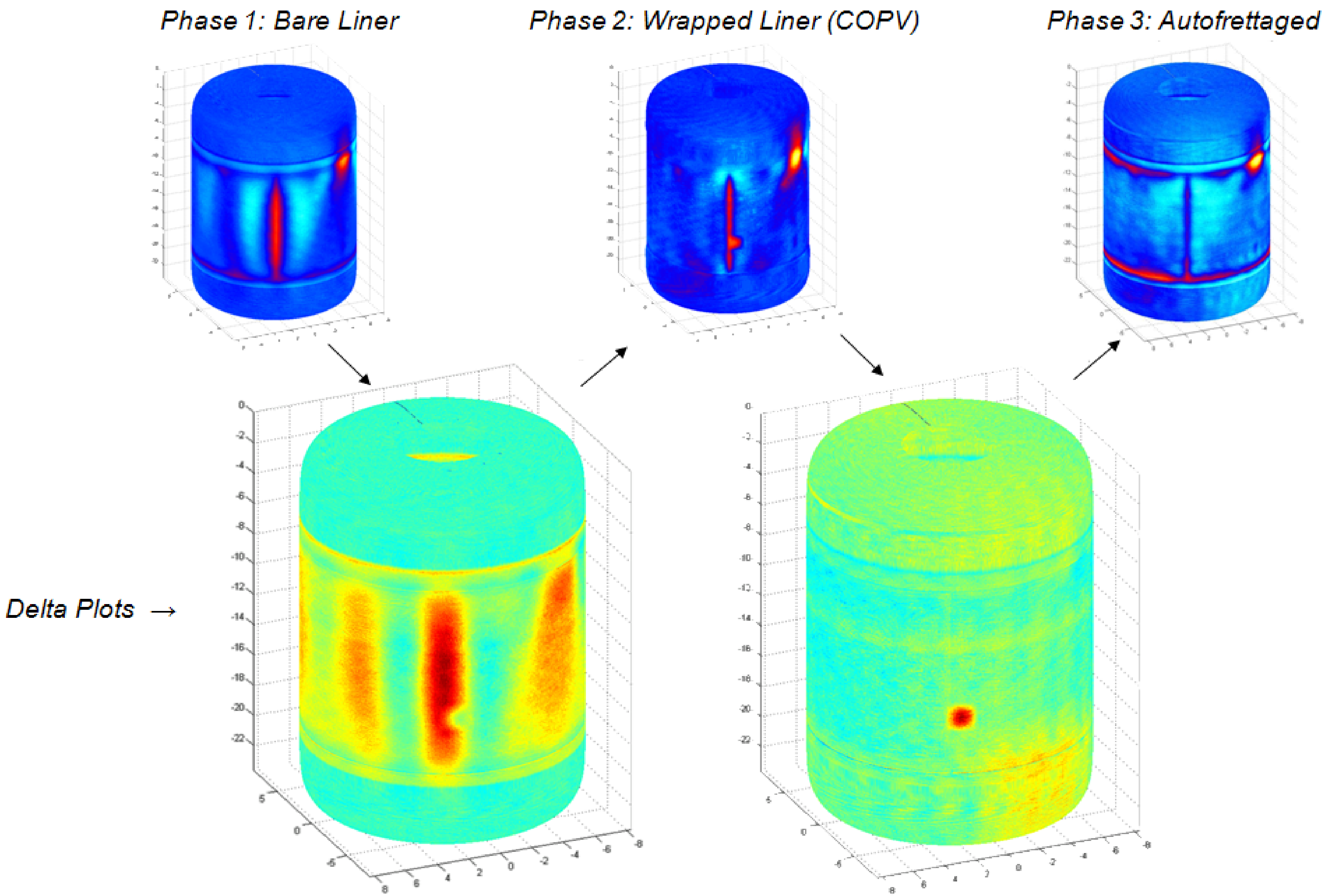
X-Y Coupon Scanner developed

Articulated sensor developed to inspect COPV domes in NORS Internal Profilometer

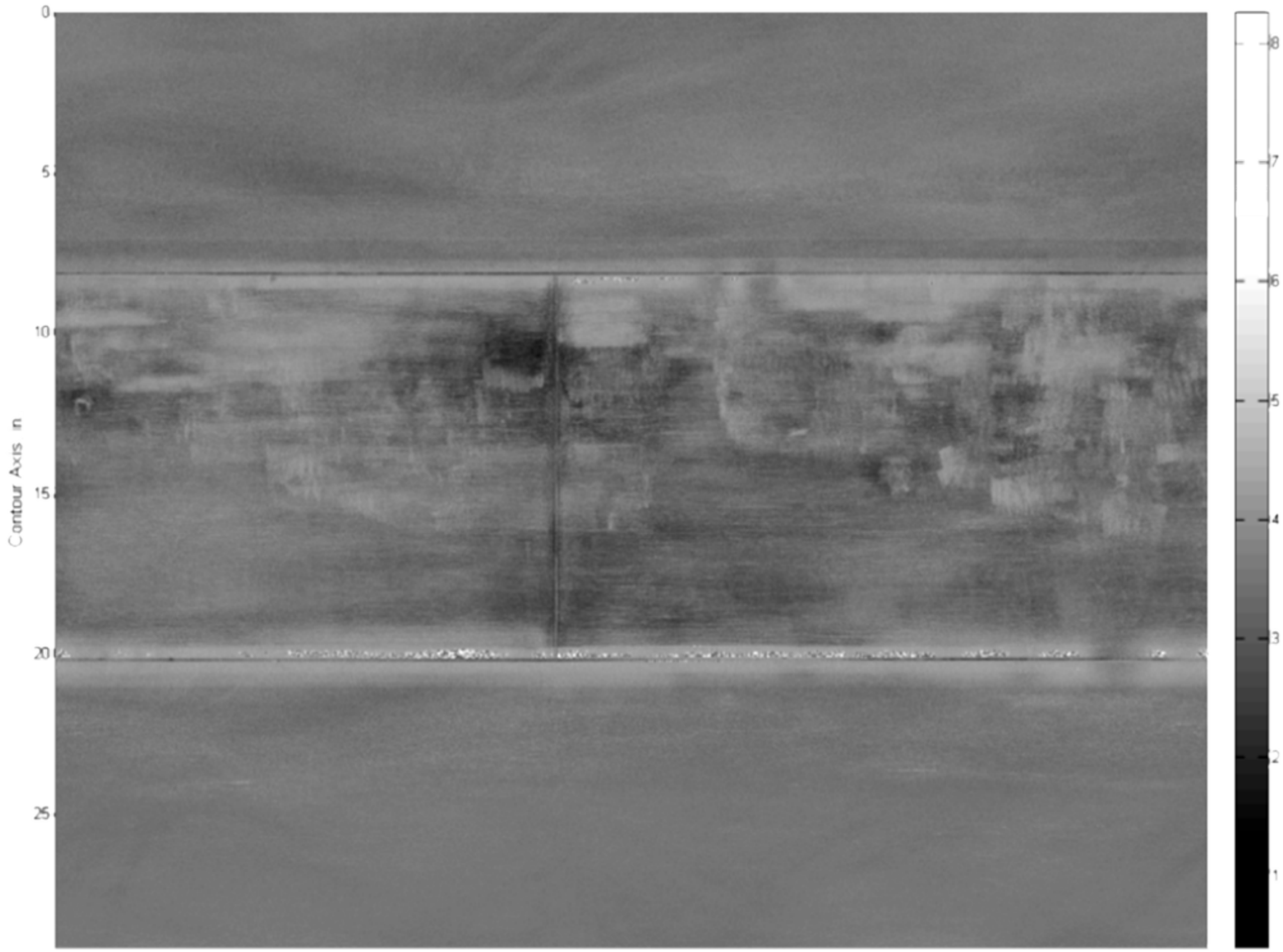


7-foot NORS Internal Profilometer developed, verified and actively being used by the ISS NORS Program

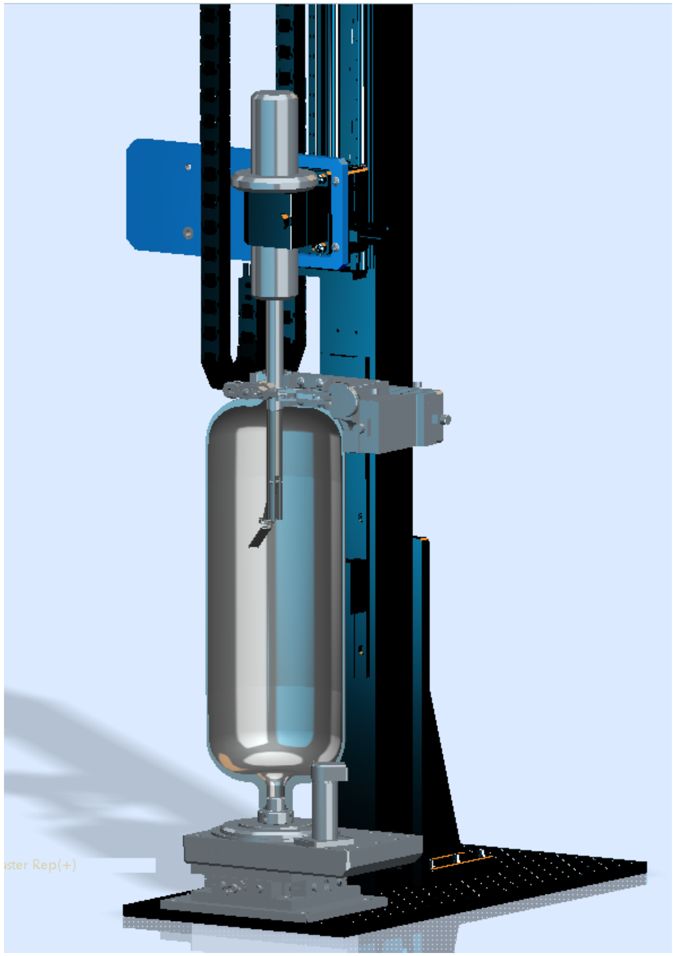
ISS NORS Dev. 4 Changes



ISS NORS Dev. 4 Laser Video



NESC Assisting with Internal EC Scanner Developed (shown deployed)



Internal EC probe shown interfaced to existing laboratory stage

Collapsible internal EC probe deployed for scans (conceptual design)

WSTF: Automated AE for COPV Pass/Fail

Goal: Develop AE SHM for COPVs

- Automate FFT batch processing
- Implement AE pattern recognition
- Promulgate consensus pass/fail criteria for COPVs

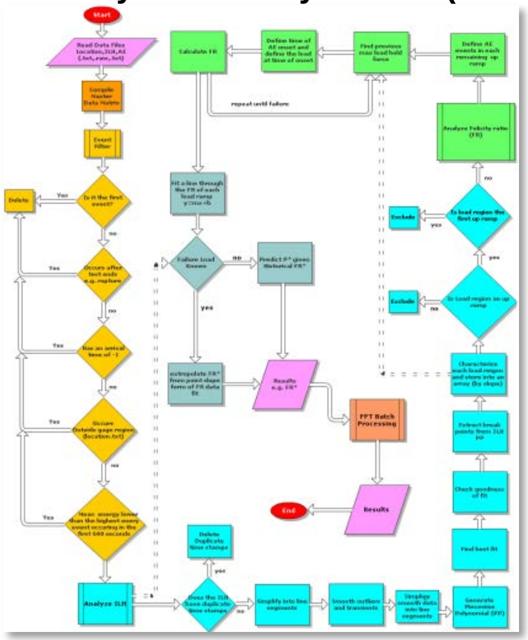
Approach:

- Determine 'in-family' behavior of well-characterized test articles
- Predict behavior of unknown based on population response
- Tailor method to actual in-service pressure schedules

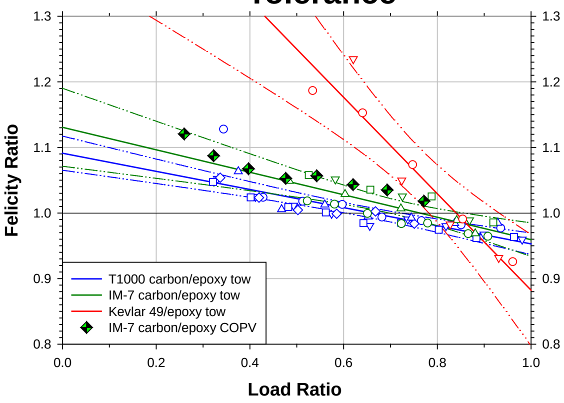
Status: In-house software & AE methods developed

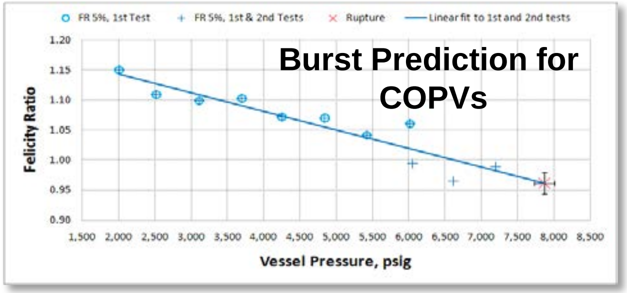
- FR analysis and decay rate software developed (needs some debugging)
  - Statistical methods developed
  - Application of above methods to COPVs demonstrated
  - Preliminary Exponentially Weighted Moving Average (EWMA) 'knee' method
- Data acquisition parameters optimized
- Response surfaces for C/Ep materials-of-construction generated
- Burst pressure for a COPV predicted

Felicity Ratio Analysis Tool (FRAT)



C/Ep Comparative Damage Tolerance





Burst Prediction for COPVs

C/Ep Strand Testing

WSTF: Initial Supporting Activity – FY12

- Planning, roadmaps and tests used to better define AE signal feature trends and
AE-based COPV burst pressure projections:
  - Charles Nichols, Jon Tlyka and Jess Waller discussing details of AE method development and Software in separate presentations
  - Partnership with Scott Forth on Large-scale ISS COPV Stress Rupture Programs
    - Strain, pressure, temperature, and limited AE data were collected from ISS flight-representative COPVs during long-term tests
      - 80 COPVs under test in a SR Test Systems
      - More are likely to be cycled through testing in the next couple of years (~160 available)
      - Trying to evaluate trends indicative of impending failure using improved noise reduction and data acquisition techniques
      - Scott Forth hopes to be able to implement "Smart COPV" techniques in testing starting next year.

GRC: Acoustic Emission Analysis Applet

Goal:

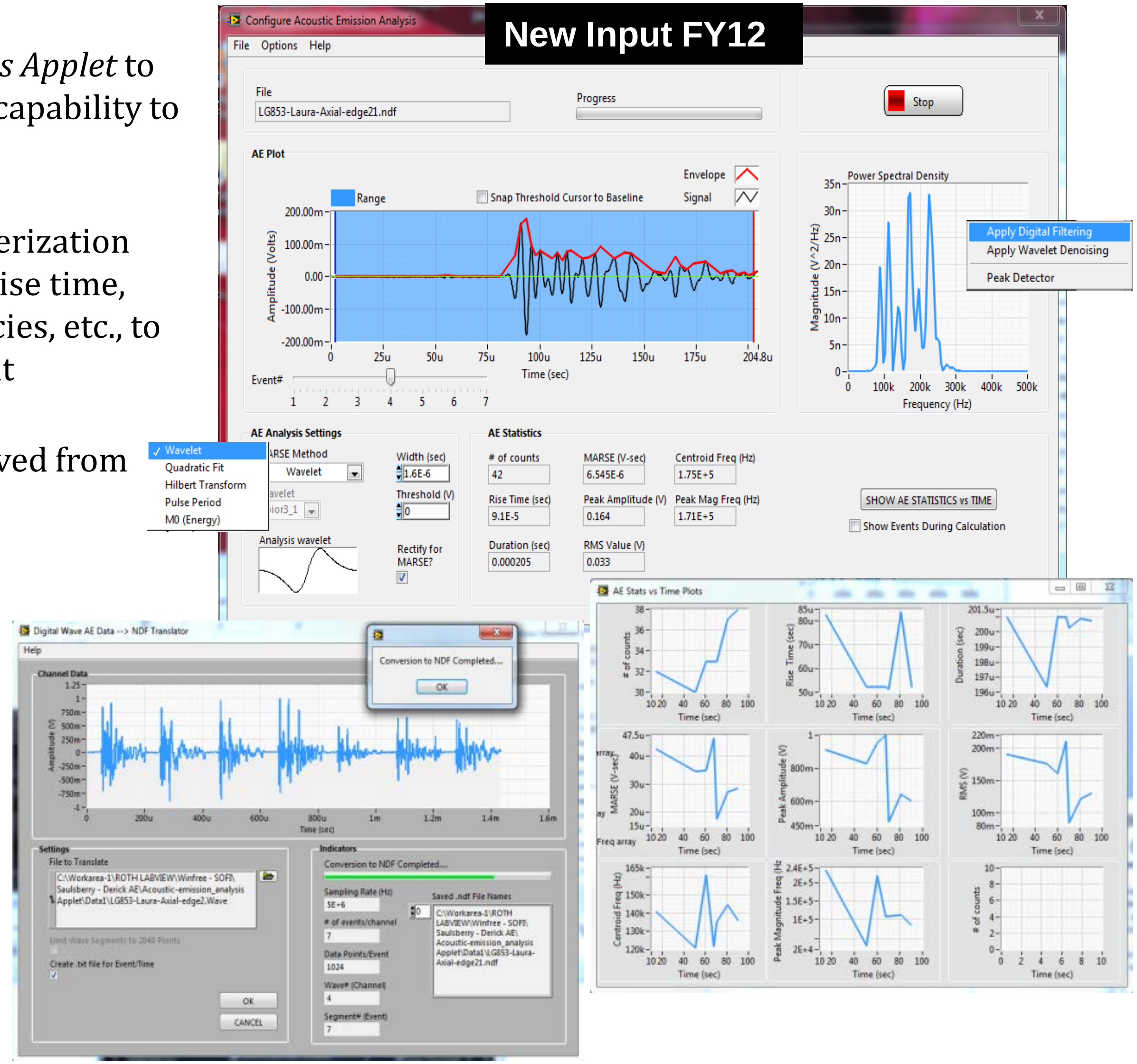
- Develop an *Acoustic Emission Analysis Applet* to produce a ‘Smart’ real-time analysis capability to support NASA missions

Approach:

- Use consensus AE waveform characterization parameters, e.g., amplitude, counts, rise time, duration, centroid and peak frequencies, etc., to differentiate composite damage event

Status:

Acoustic Emission Analysis Applet derived from AEAA software:



- Rewrote for UNLIMITED data set size
- All events available for viewing in Applet using slider control
- Translator from .WAVE → NDF incorporated into Applet
- Can subset and threshold events for analysis
- Time/Event File generated
- AE Statistics vs. Time generated/saved to spreadsheet file
- User Manual written
- Currently being beta-tested by WSTF

LaRC - Application of DIDS Hardware to COPVs

Goal:

- Demonstrate the ability of flight certified hardware to perform AE measurements in COPVs

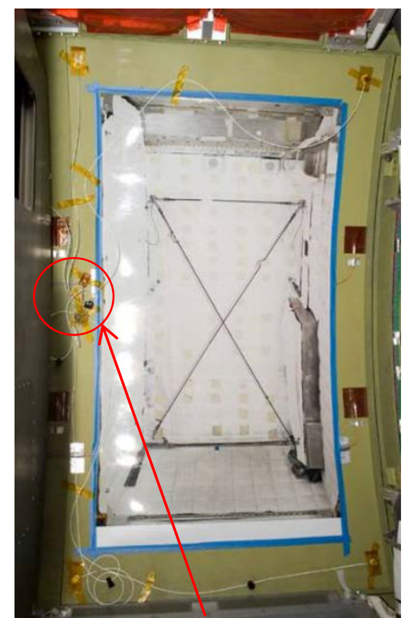
Approach:

- Evaluate the ability of the Distributed Impact Detection System (DIDS) to capture AE events during testing
- Evaluate system's throughput vs. the requirements of a measuring a COPV
- Assess the DIDS' ability to function as an IVHM system

Status:

- DIDS hardware has been certified for on-orbit application and is currently on orbit

DIDS system with sensors and short cables



DIDS system installed behind rack in Node 2

MSFC: Acousto-Optic NDE

Goals:

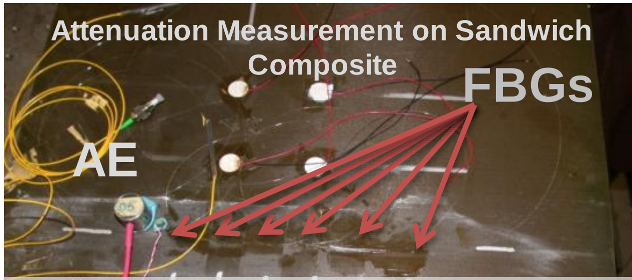
The goals of this study are (a) se the small size and wide acoustical bandwidth of Fiber Bragg Gratings (FBGs) to measure transient acoustical signature, and (b) investigate the possibility of incorporating strain and temperature measurement as well

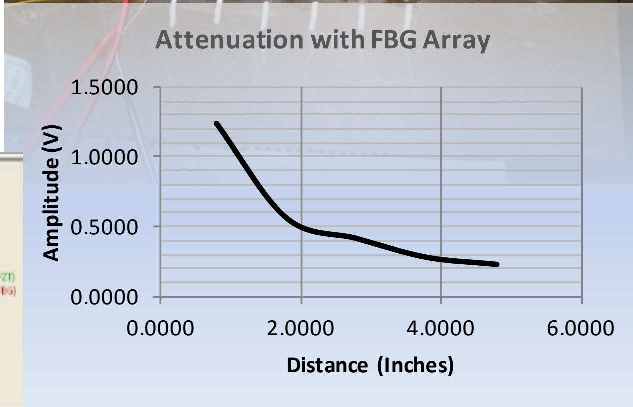
Approach:

- Compare FBG-AE to PZT-AE in laboratory pitch/catch
- Compare FBG-AE Felicity ratio with PZT AE
- Measure FBG-AE on multiple-composite structure

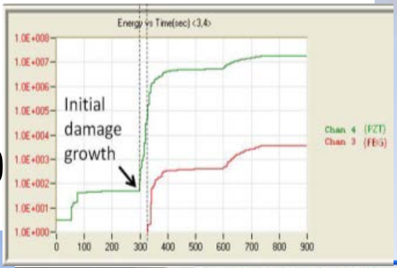
Status:

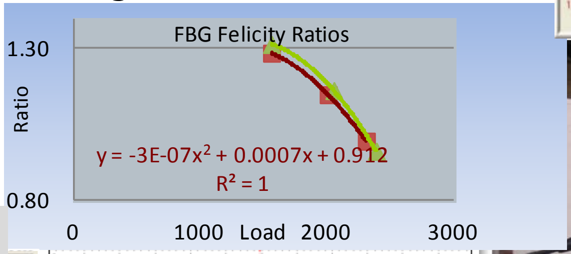
- Tested & compared FBG-AE to PZT-AE
- Performed Felicity measurements
- Leverage OCT and "Composite for Exploration (CoEx) developments and funding.



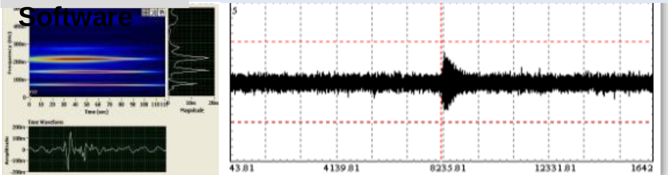


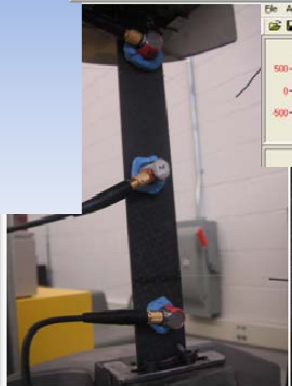
Las Gatos COPV Results

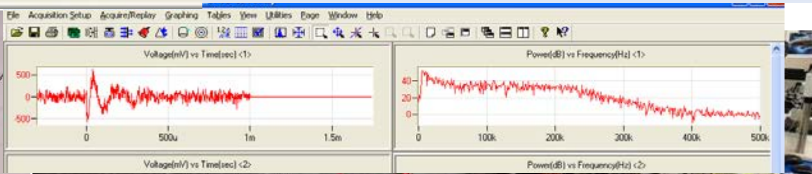


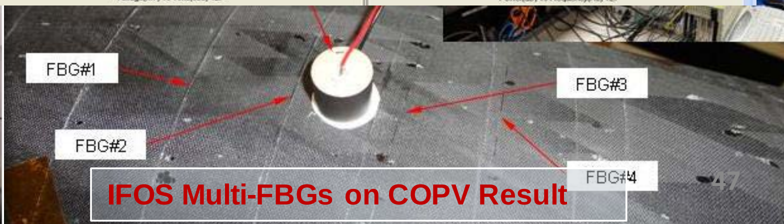


GRC Software









IFOS Multi-FBGs on COPV Result

MSFC: Smart Layer for Smart COPV

Goals:

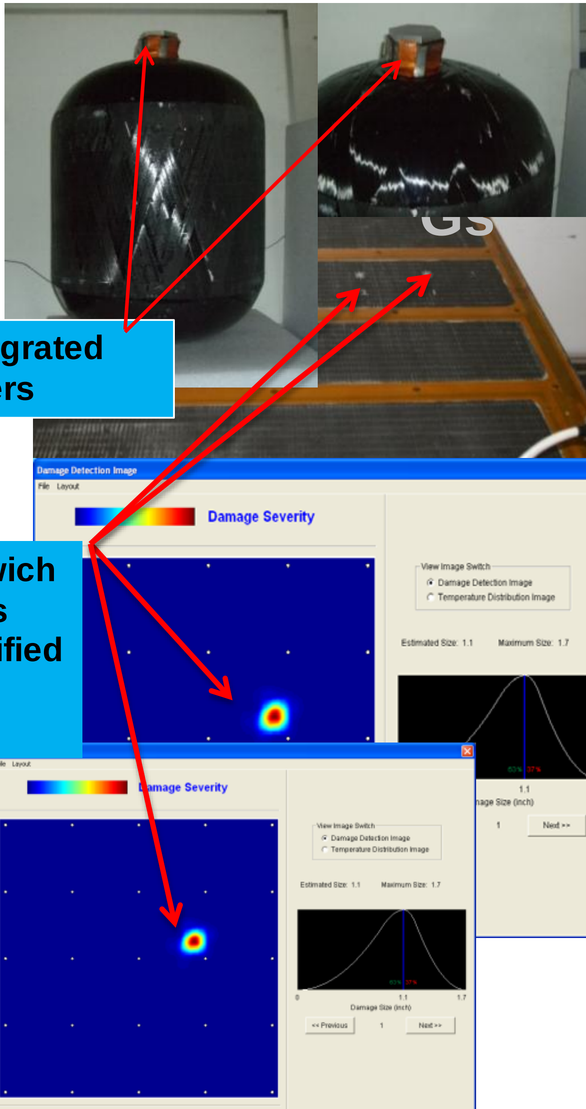
Define Critical Damage Accumulation (CDA) in COPVs before stress rupture occurs and corroborate (CDA) with a know NDE inspection standards: AE Felicity ratio; Additional, damage severity and location is desired.

Approach:

1. Perform cycle testing of COPV until Kaiser effect is violated. At reduced loading, damage index will be measured.
2. Leverage funding from OCT and CoEx programs

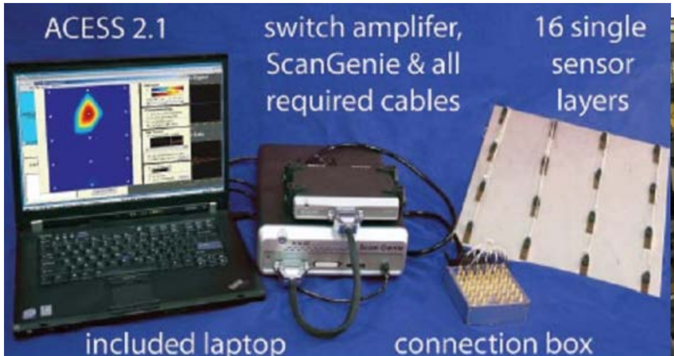
Status:

1. Tested composite laminate.
2. Currently have three 18’” COPV that will be tested at MSFC and WSTF.



COPV integrated Smart layers

Impacts on sandwich foam. Damage was located and quantified by Acellent Smart Patch.



DFRC: Surface Mounted and Embedded Fiber Bragg Gratings

Objectives

- Perform real-time in-situ structural monitoring of COPVs by acquiring 100s of fiber Bragg grating measurements from sensors embedded within the composite structure of the COPV
- Develop analytical and experimental methods to reliably interpret strain measurements from embedded FBG sensors
- Develop a robust "early-warning" indicator of COPV catastrophic failure

Approach

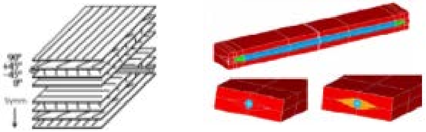
- Analytically model the embedded FBG sensors
- Attach 100s of FBG sensors to outer COPV surface
- Conduct baseline testing of surface FBGs
- Overwrap bottle (surface FBGs become embedded)
- Instrument new sensors on new outer surface
- Test to failure; correlate data at each step

Status:

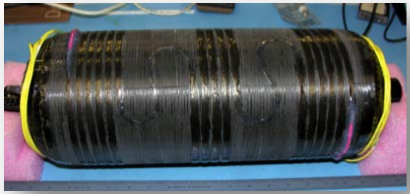
- Hypercomp COPV Testing Complete
    - Instrumented COPV with 1600 FBGs (800 embedded and 800 surface mounted)
- GD T1000 Bottle – Surface sensor testing complete
- Bottle being overwrapped this week (4/27)
- Burst tests accomplished in June 2012 at WSTF
    – Additional testing planned for FY2013

Theoretical development

Coupon testing



Analysis and Modeling



Sensor Installation

Embedding / Fabrication

Failure Testing

KSC: Magnetic Stress Gages (MSGs)

Rick Russell’s detail presentation to follow

Project Objectives

- Demonstrate the ability of NDE sensors to measure stresses on the inner wrap layers of COPV overwrap.
- Results will be correlated with other NDE technologies such as acoustic emission (AE)
- Project builds upon a proof-of-concept study which demonstrated the ability of MSGs to measure stresses at internal overwraps and upon current AE research being performed at WSTF
- Ultimate goal is to utilize this technology as a key element of health monitoring under the “Smart COPV” Program

Overall Project Schedule & Milestones

Year	Qtr	AE Method & Sys Dev WSTF / LaRC / GRC	AE Software Dev GRC /WSTF	Magnetic Stress Gage Dev KSC / LaRC	Embedded AO Dev MSFC	Surface and Embedded FBG Dev DFRC
FY12	Q1	Perform statistical analysis and down select burst prediction algorithms. Perform COPV AE feasibility studies and preliminary test method development.	Work with WSTF to outline AE updates to Acoustic Emission Analysis Applet (AEAA) software .	KSC: Test plan development and objective refinement for magnetic stress gage (MSG) application to COPVs.	Acousto-optic (AO) acoustic emission SHM sensor and method development .	Develop instrumentation plan and procedure development for in-situ structural strain monitoring of COPVs using FBGs.
	Q2	March: Hydrostatic tests of a GD COPV instrumented with FBG and AE sensors. July: Test w/ embedded and surface FBGs & surface AE sensors.				
	Q3	Direct AEAA algorithm development. Develop software for automated burst prediction. Investigate other techniques including extensional/flexural wave analysis.	Validate AEAA software performance using large COPV files.	LaRC: Demonstrate the ability of flight certified hardware to perform AE measurements in COPVs	Test selected AO sensors and systems	Develop analytical and experimental methods to reliably interpret strain measurements from embedded FBG sensors
	Q4	Annual reporting to NNWG. Assess successes and faults for each method. Team vote to decide development continuation.				
FY13	Q1 - Q4	Down select AE platform for hardware integration w/ DIDS incl. sensors. 2D laminate plate tests.	Add WSTF AE algorithms to AEAA	KSC: Develop MSG system and test plan for COPV applications. Test 3-7 COPVs. LaRC: Develop the wireless Distributed Impact Detection System (DIDS) as an Integrated Vehicle Structural Health component for COPV structures.	Comparative validation of AO AE to PZT AE sensors	Analytically model the embedded FBG sensors using profilometry data generated by WSTF
FY14	Q1 - Q4	Develop test methods to match ISS pressure profiles. Addtl. COPV tests. Develop agency Accept/Reject criteria.	Structural health monitoring integration efforts for each technique as capabilities allow.	KSC: Develop capabilities and plan for long term testing. LaRC: Support the application of the DIDS hardware to C/Ep coupon testing. Support a COPV-level DIDS demonstration.	System integration efforts with WSTF/GRC automated AE monitoring software	Test to failure; correlate data at each step
FY15	Q1 - Q3	Produce automated AE system with integrated alarms to meet robust flight hardware/ software requirements	System level Testing with Team-Selected Sensor Grids and SHM Equipment.	KSC: Provide input for Smart COPV SHM demonstration. LaRC: Support COPV level DIDS application.	System level testing with AO SHM Equipment.	Develop a robust "early warning" indicator of COPV catastrophic failure
	Q4	Demonstrate Smart COPV SHM system and report to NNWG. Assess successes and faults of each method and system. Discuss plans to integrate selected systems on ISS systems with the ISS Program Manager.				

Smart COPV: Overall Project Products

- Plans and roadmap(s) tied to OCT Road Map TA12 that drive the program
- Manufacturing NDE systems: EC to screen for liner flaws, Profilometry to characterize COPV mechanical response and captured water column focused UT
  - Further development and validation of EC and UT needs additional funding assistance
- Test report following completion of the COPV System Level Test in FY15
  - Will contain evaluations of "Smart COPV" response to stress rupture progression and impact damage for techniques selected.
- End-to-end demonstration of the "Smart COPV" concept with real-time COPV SHM system developed, includes end-to-end demonstrations of:
  - Surface and embedded FBG SHM System
  - Real-time AE (wired, optical and wireless AE failure prediction)
  - Integrated software
  - Composite layer stress/strain evaluation using by sensing unique stress in different wrap angles with MSG sensors
  - Final expected Technology Readiness Level is expected to be approximately TRL6 (will still need to be raised to 7 or higher for flight considerations)

Questions?

Backup

Smart COPV Development Areas

1. Damage quantification through AE Monitoring (WSTF, LaRC, GRC)
   a. Measures transient elastic stress waves emitted by new and growing composite flaws
   b. Automated near real-time data analysis
2. FOAE and Strain Monitoring and simultaneous measurement of acoustic emission activity (MSFC)
   a. Strain growth or deflection detected
   b. Strain correlated with AE activity thus assessing proximity to catastrophic failure
5. Active/Passive Piezoelectric Sensing , SBIR developed-COTS (MSFC)
3. Multi-axial FBG Strain Mapping and Trend Analysis (DFRC)
   a. Maps the localized strain fields relative to principal overwrap lay-up directions using optical sensors
   b. Hundreds of strain readings taken in near real-time over a COPV surface allow for FEA-like measurements
   c. Tensor analysis of embedded and surface strains possible for failure prediction modeling
4. MSG Sensing Technology (KSC)
   a. Measures real-time stress in the COPV's layers and may spot preferential wrap angle failures due to design or tow tension issues

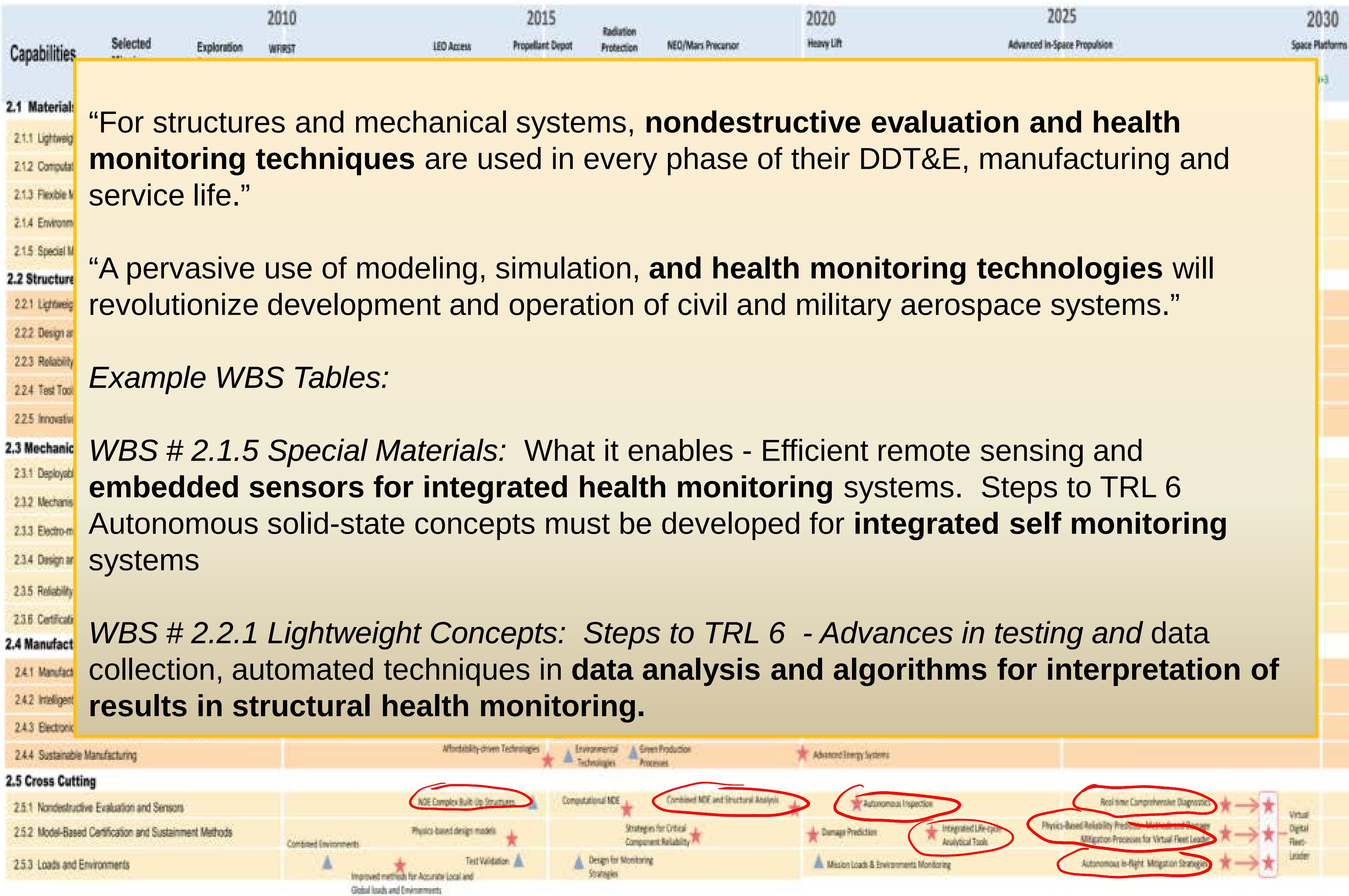
Smart COPV - Path Forward

- AE software is currently a post-processing tool but will be adapted as SHM tool
  - AE Stats vs. Time/Pressure updated as events occur
- Create Condensed data Format (one file containing "first hit" events vs. one file for every channel)
- Incorporate Joint-Time Frequency and Dispersion Curve Analysis Tools
- Use of the event waves and AE stats vs. Time & Pressure profiles as inputs to "smart" algorithms such as neural networks in order to predict upcoming failure or remaining life

Capabilities Roadmap: Materials, Structures, Mechanical Systems and Manufacturing

Pull to TRL 6 / Further Push Technologies
Extensive Push/Game-changing Technologies
Cross Capabilities

Background (Cont'd)



"For structures and mechanical systems, **nondestructive evaluation and health monitoring techniques** are used in every phase of their DDT&E, manufacturing and service life."

"A pervasive use of modeling, simulation, **and health monitoring technologies** will revolutionize development and operation of civil and military aerospace systems."

Example WBS Tables:

WBS # 2.1.5 Special Materials: What it enables - Efficient remote sensing and **embedded sensors for integrated health monitoring** systems. Steps to TRL 6 Autonomous solid-state concepts must be developed for **integrated self monitoring** systems

WBS # 2.2.1 Lightweight Concepts: Steps to TRL 6 - Advances in testing and data collection, automated techniques in **data analysis and algorithms for interpretation of results in structural health monitoring.**

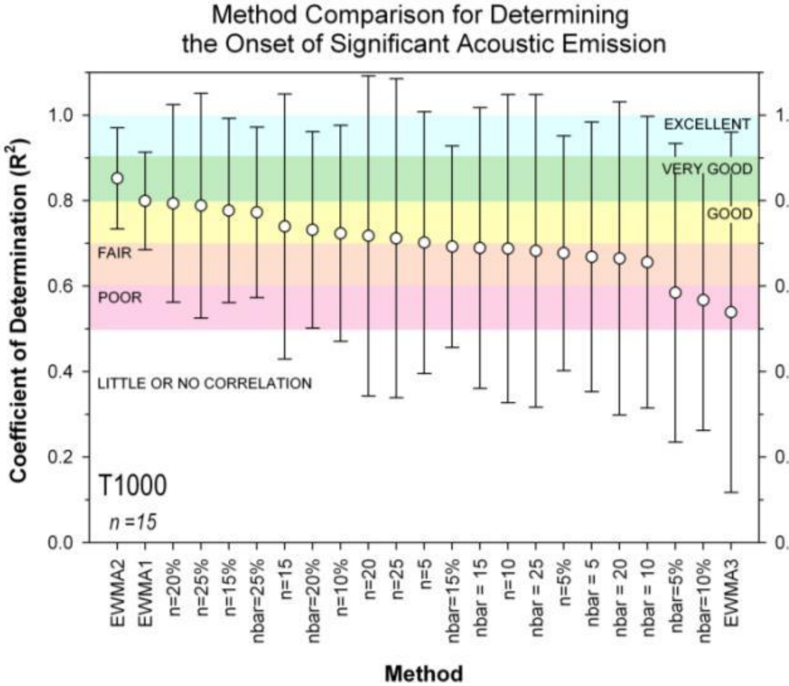
WSTF – USRP and Coop Student Supported Progress

- The WSTF-component of the "Smart COPV" project is in part the culmination of extensive USRP-funded work on AE of composites and COPVs over the past 3 years:

1. Arick Reed A. Abraham, Kenneth L. Johnson, Charles T. Nichols, Regor L. Saulsberry, and Jess M. Waller. *Use of Statistical Analysis of Acoustic Emission Data on Carbon-Epoxy COPV Materials-of-Construction for Enhanced Felicity Ratio Onset Determination*, Final NASA USRP Report, White Sands Test Facility, January 2012.
2. Jonathan M. Tylka, Jess M. Waller, Kenneth L. Johnson, Charles T. Nichols, Regor L. Saulsberry, *Use of Numerical Analysis of Acoustic Emission Data to Optimize Failure Prediction in Carbon-Epoxy Materials of Construction*, Final NASA USRP Report, White Sands Test Facility, December 2011.
3. Charles T. Nichols, Jess M. Waller, Regor L. Saulsberry, Kenneth L. Johnson, Douglas E. Weathers, Jonathan M. Tylka, Intern*, Optimized Software Approaches to Predict Rupture in Fracture-Critical Composite Components and Implications for Structural Health Monitoring*, Biennial Research and Technology Development Report – Johnson Space Center, December 2011.
4. Jess M. Waller, Charles T. Nichols, Regor L. Saulsberry, *Acoustic Emission and Development of Accept-Reject Criteria for Assessing Progressive Damage in Composite Materials,* Biennial Research and Technology Development Report – Johnson Space Center, December 2011.
5. Jess Waller, Regor Saulsberry, Charles Nichols, Daniel Wentzel, Eduardo Andrade, Doug Weathers, Elise Kowalski, *Use of Modal Acoustic Emission to Monitor Micromechanical Damage Progression in Carbon Fiber/Epoxy Tows and Implications for Related Composite Structures*, ASNT Fall Conference and Quality Testing Show, Houston, TX, November 18, 2010.
6. Douglas Weathers, Charles Nichols, Jess Waller, Regor L. Saulsberry, *Automated Determination of Felicity Ratio for Composite Overwrapped Pressure Vessels*, Final NASA USRP Report, White Sands Test Facility, August 2010.
7. Charles T. Nichols, Jess Waller, Regor Saulsberry, *Acoustic Emission Lifetime Estimation for Carbon Fiber/Epoxy Composite Overwrapped Pressure Vessels*, Final NASA USRP Report, White Sands Test Facility, August 2010.
8. Elise Kowlaski, Jess Waller, Regor Saulsberry*, Acoustic Emission Attenuation Characterization of Carbon Fiber/Epoxy Composite Overwrapped Pressure Vessels*, Final NASA USRP Report, White Sands Test Facility, August 2010.
9. Jess Waller, Regor Saulsberry, Charles Nichols, Daniel Wentzel, *Use of Modal Acoustic Emission to Monitor Damage Progression in Carbon Fiber/Epoxy Tows and Implications for Composite Structure*s, 37th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE) Conference, San Diego CA, July 18-25, 2010.
10. Charles T. Nichols, Jess Waller, and Regor Saulsberry, *Use of Acoustic Emission to Monitor Progressive Damage Accumulation in Carbon Fiber Reinforced Composites*, Final NASA USRP Report, White Sands Test Facility, December 2009.
11. Jess Waller, Charles Nichols, Eduardo Andrade, Regor Saulsberry, *Use of Acoustic Emission to Monitor Progressive Damage Accumulation In Kevlar® And Carbon Fiber Reinforced Composites*, 2009 Composite Pressure Vessel and Structures Summit, White Sands Test Facility, Las Cruces, NM, September 23, 2009.
12. Jess Waller, Regor Saulsberry, Eduardo Andrade*, Use Of Acoustic Emission to Monitor Progressive Damage Accumulation in Kevlar® 49 Composites*, 36th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE) Conference, Kingston, RI, July 26-31, 2009.
13. Eduardo Andrade, Jess Waller, Regor Saulsberry, *Use of Acoustic Emission to Monitor Progressive Damage Accumulation in Kevlar® 49 Composites*, Final NASA USRP Report, White Sands Test Facility, April 2009.

WSTF COPV Health Monitoring
Proof of Concept Strand and COPV Tests

- Preliminary acoustic emission trends:
  - Infant mortality linked to significant energy levels reached prior to reaching the previous pressure state
  - Significant damage accumulation evidenced by AE response w/out stimulus
  - Statistical methods show potential for accurate burst pressure prediction
    - Exponentially Weighted Moving Average (EWMA) Felicity ratio determination methods 1 and 2 demonstrate the least variability in IM7 and T1000 tensile tests and in a limited number of COPV tests
  - The EWMA burst pressure determination method has not been evaluated on a significant number of COPVs
    - Previous FR methods evaluated exhibit significantly more variability in COPV tests

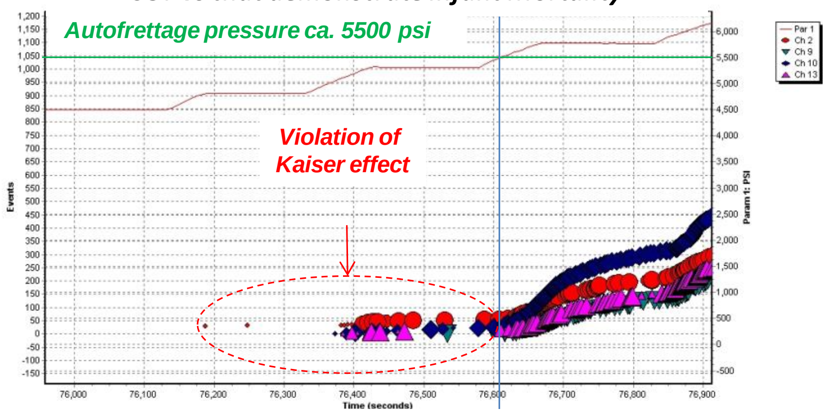


Test results from Felicity ratio determination methods. Data from T1000 C/Ep stands taken from the COPV manufacturing process.

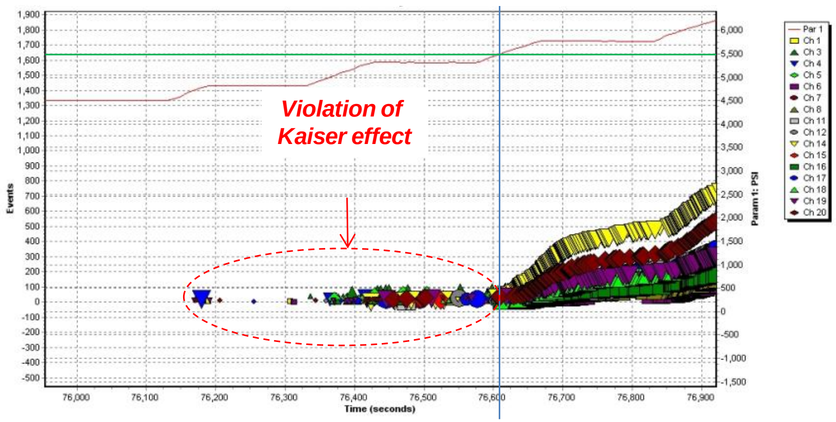
WSTF – COPV Infant Mortality Precursors

- COPV-specific test results:
  - Infant mortality precursors:
    - Significant energy levels noted prior to reaching the previous pressure state
  - Failure precursors:
    - Felicity ratios below a structurally and method dependent limit
    - AE event occurrence during unloaded sections of load profiles
    - Significant energy levels

COPVs that demonstrate Infant Mortality



COPVs with Typical Performance



Budget Topics:

Smart Composite Overwrapped Pressure Vessel - Integrated Structural Health Monitoring System to Meet Mission Assurance Needs

Significant Accomplishments:

1) **Four promising NDE technologies have been down selected for further development**
   a) **Acoustic Emission (AE) (microscopic composite damage)**
      i. **Modal AE**
      ii. **Distributive Impact Detection System (DIDS) AE[‡]**
      iii. **NDE Wave Imaging Processor (AEAA)-AE analysis applet**
   b) **Multiaxial Fiber Bragg Grating (FBG) grids (strain)[‡]**
   c) **Fiber optic acoustic emission (FOAE) (damage and strain)**
   d) **Eddy current (ET) Magnetic Stress Gages (MSGs) (stress)**

2) **Core Team has been assembled and biweekly planning telecons are being held to map out FY13 effort and beyond**
   1. **WSTF: J. Waller/C. Nichols (modal AE)**
   2. **LaRC: E. Madaras (DIDS AE)**
   3. **GRC: D. Roth (AE analysis applet)**
   4. **DFRC: L. Richards (multiaxial FBG)**
   5. **MSFC: C. Banks (FOAE)**
   6. **KSC: R. Russell (ET MSGs)**

3) **FBG strain sensors have been shown effective on General Dynamics COPVs in a variety of orientations. Hoop FBG sensors are effective on HyPerComp COPVs.**

4) **AE analysis applet being developed by GRC to perform unique stand-alone AE data reduction tasks**
   a) **Will handle unlimited file sizes from AE vendors (32-bit software)**
   b) **Performs batch processing enabling tracking of damage evolution**
   c) **Produces AE wave statistics commonly used to measure health**
      i. **Amplitude, rise time, duration, counts**
      ii. **Energy (Measured area of the rectified signal envelope)**
      iii. **Spectral density (partial power)**
   d) **Statistics can be used in cluster analyses to enable key signal characteristics to be quickly identified, e.g. late life, high frequency, high partial power events, flagged as indicators of impending failure**

[‡] **Certified for flight applications and/or ruggedized flight hardware exists**

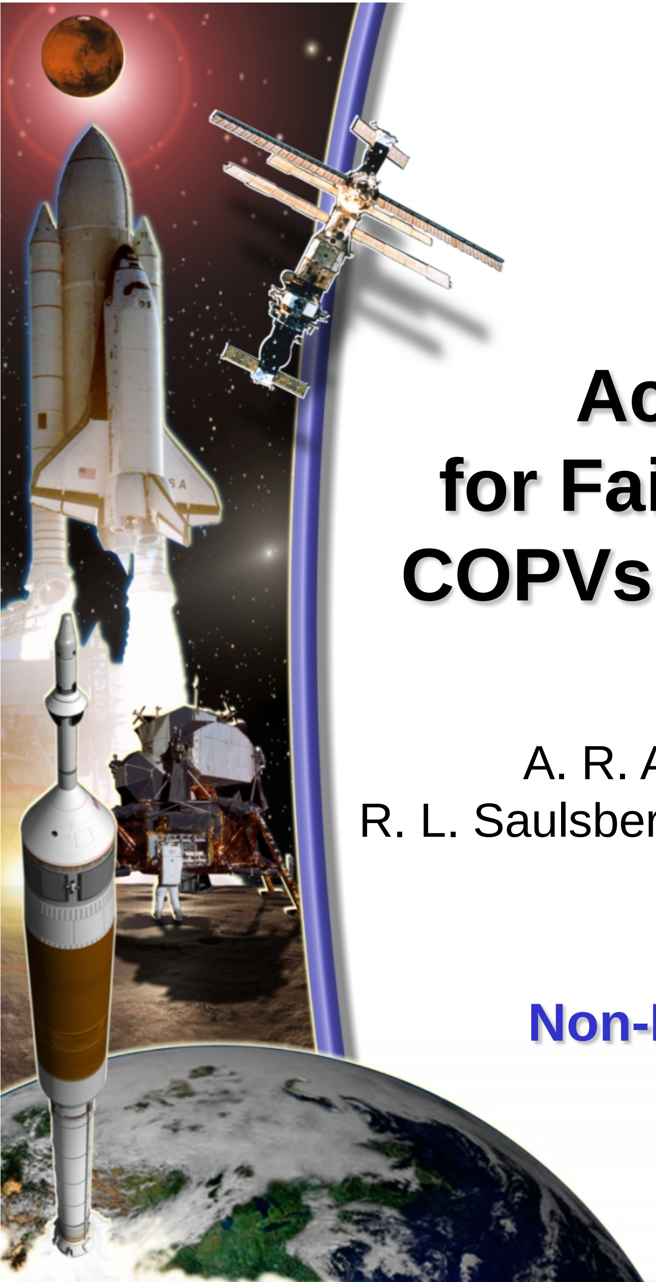
Schedule/Plan/ Milestones:

Year	Qtr	DFRC	GRC	MSFC	KSC / LaRC	WSTF
FY12	Q1	Development of FBG sensors/methods for embedment in COPVs	Outline AE updates to NDEWIP software	Acousto-optic method and sensor development	Eddy current sensor and method development	Down select Felicity ratio algorithms; AE method development
	Q2	Feb. 27, 2012: Hydrostatic test of DFRC Bottle 2, Phase 2 instrumented with 800 FBG, 6 SG, and 6 PZ AE sensors				
	Q2 - Q3	COPV-level test of selected FBG arrays	Add WSTF AE algorithms to NDEWIP	Test selected AO sensors and systems	COPV-level test of EC sensors	Assist GRC with algorithms; global JFT algorithm dev.
	Q4	Reporting to NNWG. Assess successes and faults for each method. Team vote to decide development continuation.				
FY13		Model validation of COPV FBG strain results	Validation of new NDEWIP AE modules	Comparative validation of AO AE to PZT AE sensors	Validation of EC and new NDEWIP AE modules	NDEWIP AE mods. software validation
FY14		Structural health monitoring integration efforts for each technique as capabilities allow				
FY15		System level Testing with Team-Selected Sensor Grids and SHM Equipment				

An integrated plan outlining activities from the contributing NASA Centers will be provided in May 2012 that provides specific detail to the overall plan given above. In the meantime, biweekly telecons are being held to facilitate collaboration between the contributing Centers, to define interim and long term goals, and to allocate future funding accordingly.

Issues /Concerns:

- **The down-selected NDE technologies have varying Technology Readiness Levels (TRLs). The impetus will be the pull of the technologies to a TRL 6 flight demonstration level, ultimately opening up the possibility of autonomous inspection during service using a real-time wireless SHM system. However, before this can be achieved, less mature NDE technologies (e.g., FOAE) and factors influencing data quality (composite aging and conditioning) must be better understood. This, in turn, will entail testing at the single tow and composite laminate level, before application to a COPV can be made.**
- **Embedment of NDE sensing technologies continues to be an issue and will likely remain so.**



Developing Novel Acoustic Emission Procedures for Failure Prediction of Carbon-Epoxy COPVs and Related Composite Materials

A. R. Abraham, E. Andrade, K. L. Johnson, C. T. Nichols,
R. L. Saulsberry, J. M. Tylka, J. M. Waller, D. E. Weathers, D. J. Wentzel

Session 5:

Non-Destructive Evaluation (Health Monitoring)

Composite Conference 2012

Las Cruces, NM

Wednesday, August 15, 2012

Background

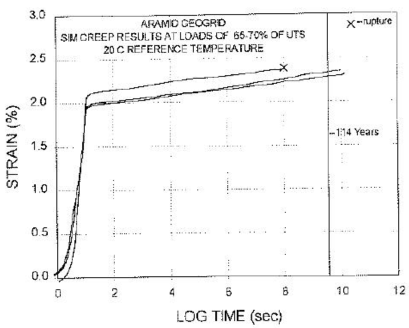
Issues:

- COPVs can be at risk for catastrophic failure
  - Risk of insidious burst-before-leak (BBL) stress rupture[1] (SR) failure of carbon-epoxy (C/Ep) COPVs during mid to late life
  - Risk of lower burst strength of C/Ep COPVs subjected to impact damage
- Issues with manufacturing defects and inspectabilty of COPVs on NASA spacecraft (ISS, deep space)
- Lack of quantitative NDE is causing problems in current and future spacecraft applications
  - Must increase safety factor or accept more risk
  - Thinner liners are driving need for better flaw detection in liner and overwrap

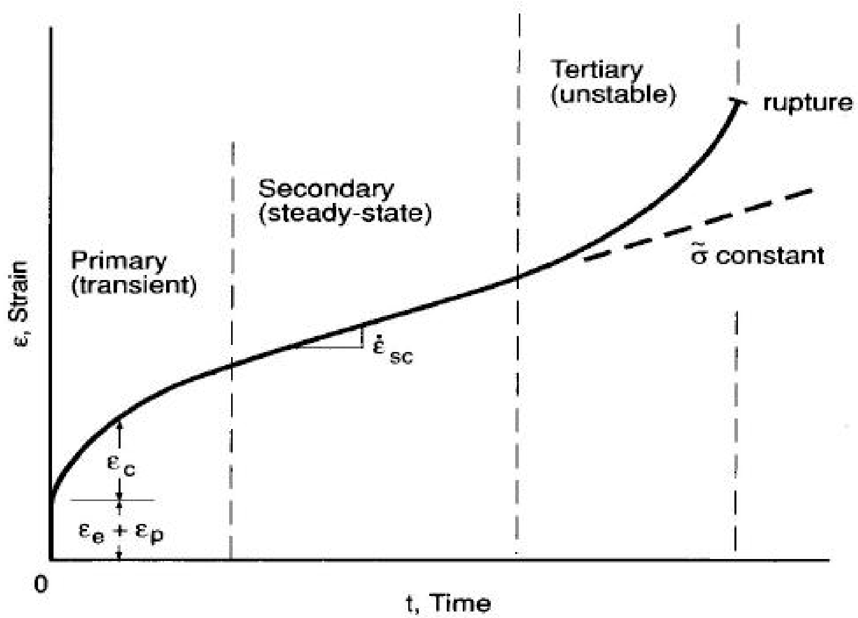
[1] *SR defined by AIAA Aerospace Pressure Vessels Standards Working Group as "the minimum time during which the composite maintains structural integrity considering the combined effects of stress level(s), time at stress level(s), and associated environment."*

Strain vs. Time Behavior During Creep

Classical Case



carbon or PPTA (Kevlar®)



BBL rupture of a COPV

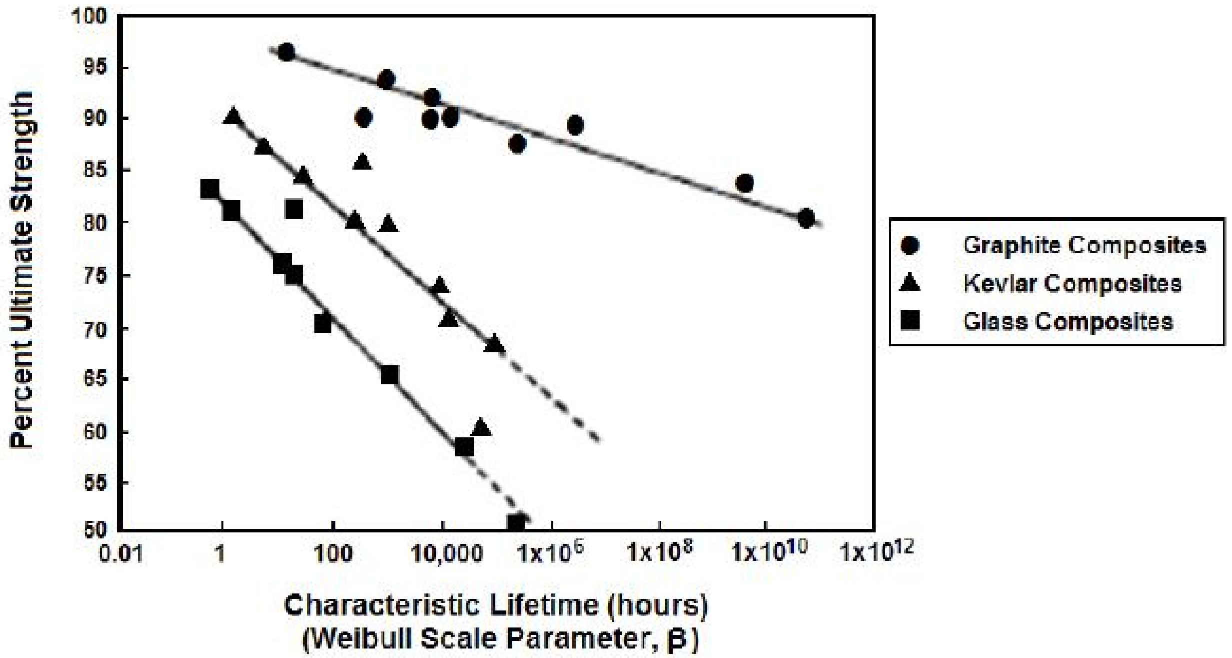
distinct tertiary creep phase

(ductility observed before rupture)

The problem with advanced fibers such as carbon or Kevlar® is that no ductility is observed before rupture during tertiary creep, so the stress rupture occurs with little or no advance warning

Effect of Fiber Choice on Stress Rupture

C/Ep COPVs are susceptible to stress rupture, although to a lesser extent than glass or Kevlar® fiber composites



Characteristic lifetimes of graphite, Kevlar® and glass-reinforced composites loaded to different percentages of the ultimate strength. Each symbol represents the median life (50%) under sustained loads as percentage of the ultimate strength of the material §

§ J. T. Shaffer, "*Stress Rupture of Carbon Fiber Composite Materials*", in Proc. 18th Intl. SAMPE Technical Conference, p. 613 (1986).

COPVs on ISS

- Presently have 17 high pressure COPVs on ISS (most are C/Ep)
  - Up to seven additional COPVs are planned and under development
- Long term reliability risk levels are 10^{-6} or lower except for NTA and SpaceDRUMS COPVs, which have risk levels of 10^{-4} to 10^{-5} §
  - Reliability <u>much</u> lower if C/Ep overwrap sustains impact damage

	Subsystem	No.	Shape	Size, in.	Commodity	Materials		Supplier	FOS	MEOP psi
						Liner	Wrap			
TNT equiv.	ECLSS/ACS HPGT	4	Sphere	37.89	Oxygen, Nitrogen	301 SS	IM-7W	GD	2.0	5000
	ECLSS/MCA	1	Cylinder	7.22 L x 3.55 D	Calibrated air	Al	S-Glass	SCI	3.4	3000
reliability risk	TCS/NTA	2	Cylinder	45 L x 19.7 D	Nitrogen	Al	T-1000	GD	2.52	3000
astronaut fatal.	EVA/SAFER	3	Cylinder	9 L x 6 D	Nitrogen	SS	T-1000	ARDÉ	3.0	10,000
	Environments/PCU	2	Sphere	15.37	Xenon	301 SS	T-1000	ARDÉ	4.17	3000
reliability risk	Payloads/ SpaceDRUMS	5	Cylinder	17.1 L x 8.5 D	Argon	Al	T-1000	GD	2.28 -	2350
	Payloads/ VCAM*	1	Cylinder	8.1 L x 3.68 D	Helium	Al	Gr/ep-2150	Carleton	3.4	1985
	AMS-02*	2	Sphere	12.4; 15.8	Carbon dioxide, Xenon	301 SS	T-1000	ARDÉ	3.05-4.4	1440-2900
	ECLSS&TCS/NORS**	0	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	CIPAA***	4	Cylinder	4.04 D x 9.6 L	Carbon dioxide	Al	Gr/E-Glass	Carleton	4.67	4500

*The VCAM and AMS systems have not been manifested.

**The NORS system is still under development.

***The CIPAA system is transported to and from the ISS with each Shuttle mission. The very high FOS indicates a very low risk of rupture.

§ E. Y. Robinson, R. Kohli, "*Preliminary Stress Rupture Risk Assessment for Graphite/Epoxy Composite Overwrapped Pressure Vessels on the International Space Station*", Aerospace Report No. ATR-2009(5298)-6, Sept. 30, 2009.

Goals

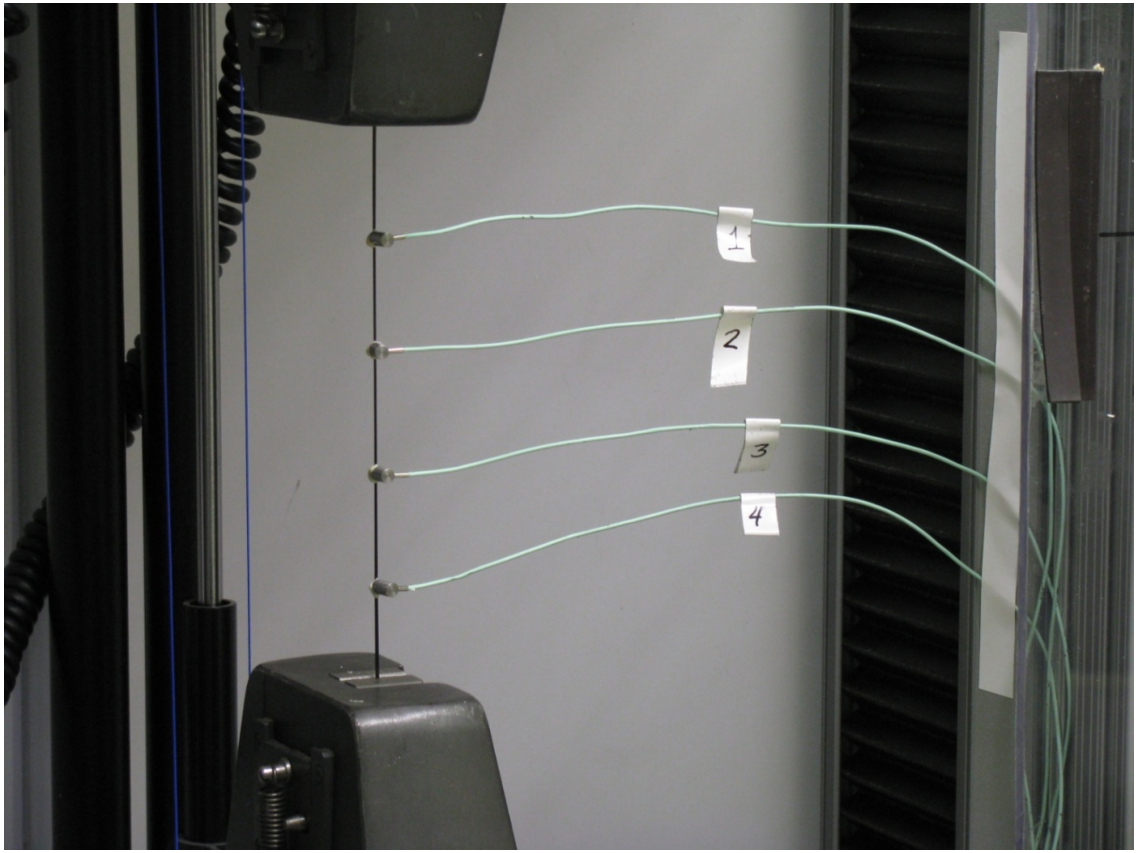
- Develop quantitative AE procedures specific to C/Ep overwraps, but which also have utility for monitoring damage accumulation in composites in general
- Lay groundwork for establishing critical thresholds for accumulated damage in composite components, such as COPVs, so that precautionary or preemptive engineering steps can be implemented to minimize or obviate the risk of catastrophic failure
  - Felicity ratio (*FR*), coupled with fast Fourier transform (FFT) frequency analysis shows promise as an analytical pass/fail criterion
    - Would fail COPVs at a critical *FR (FR**) below 1.0, indicative of severe accumulated damage
    - Could also fail COPVs at a known levels cumulative of fiber breakage or matrix cracking

Felicity Ratio Analysis

(IM7 & T1000 composite tow)

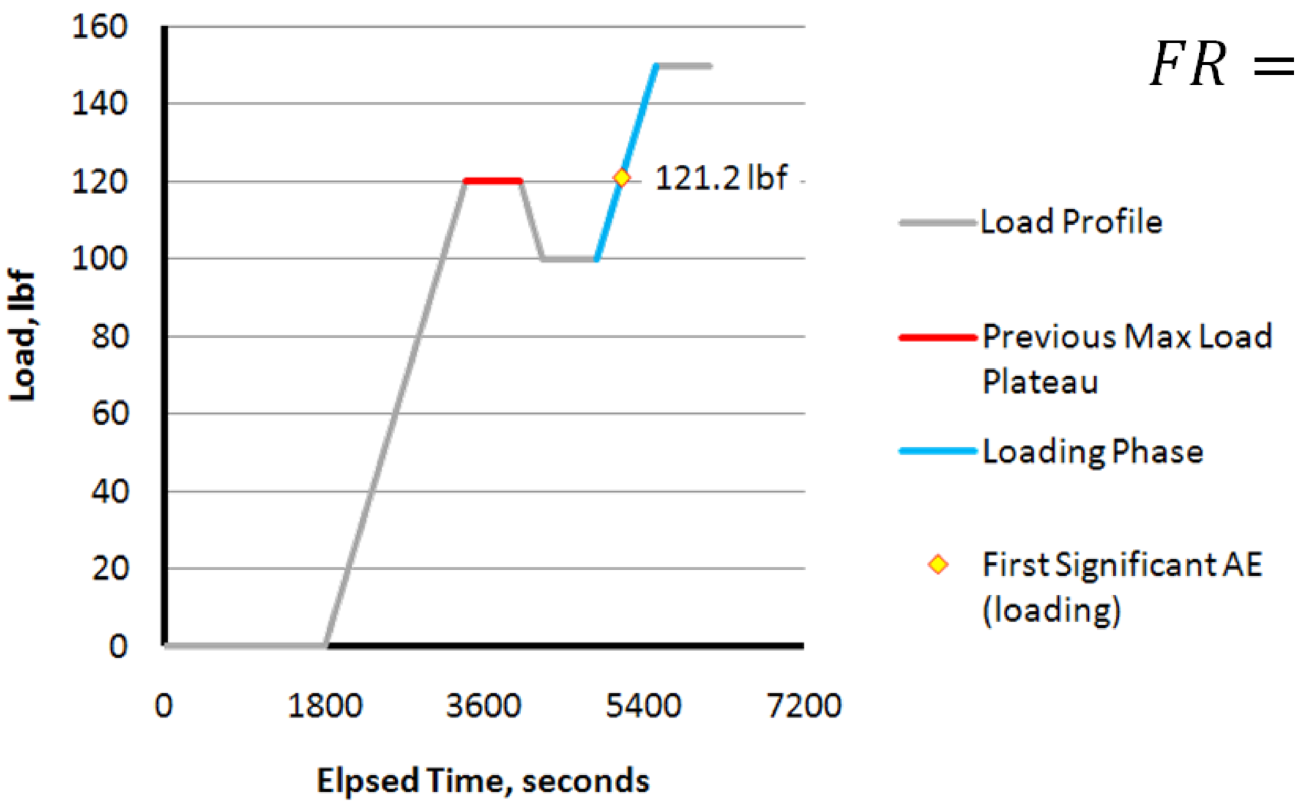
Experimental

Acoustic Emission (AE) Sensors: Each channel (4 used) was connected to a DWC PA-0, 0 dB Gain preamplifier, and then to a broadband high fidelity B1080 piezoelectric sensor with a frequency range 1 kHz to 1.5 MHz. Sensors were mounted on cardboard-tabbed C/Ep tow specimens (8-in. gage length) using Lord Corp. AE-10 acrylic adhesive



Felicity ratio (FR)

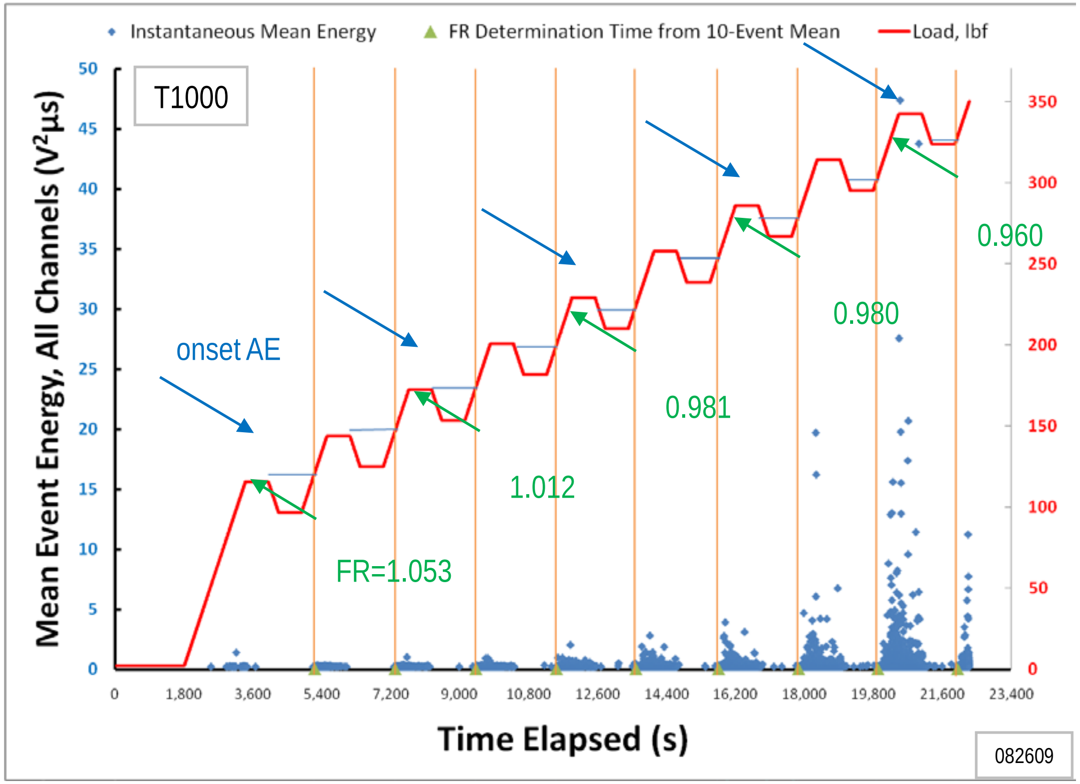
$$FR = \frac{stress\ at\ onset\ of\ significant\ acoustic\ emission\ during\ loading}{maximum\ previous\ stress\ plateau}$$



$$FR = \frac{121.2}{120} = 1.01$$

Experimental

- For purposes of quick turn-around, an intermittent load hold (ILH) stress schedule (red trace) was used



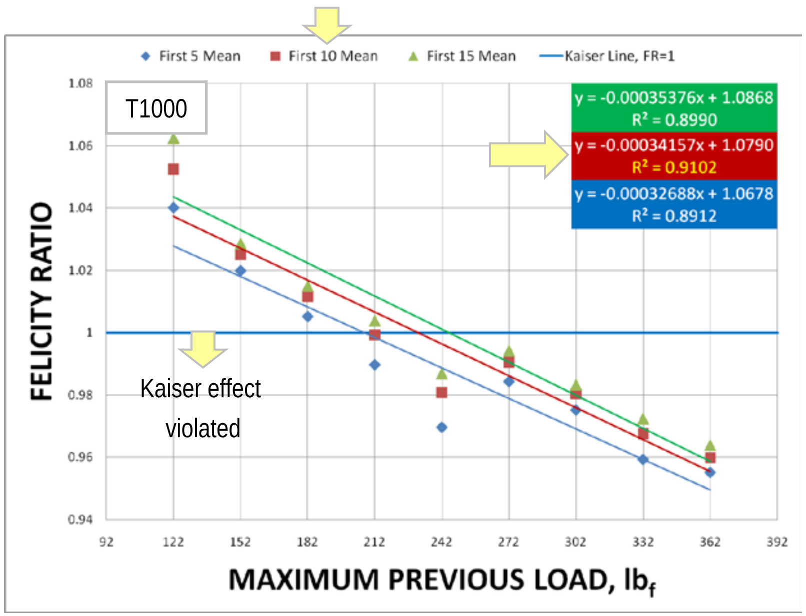
- ILH profile is based on the pressure tank examination procedure described in ASTM E 1067 §

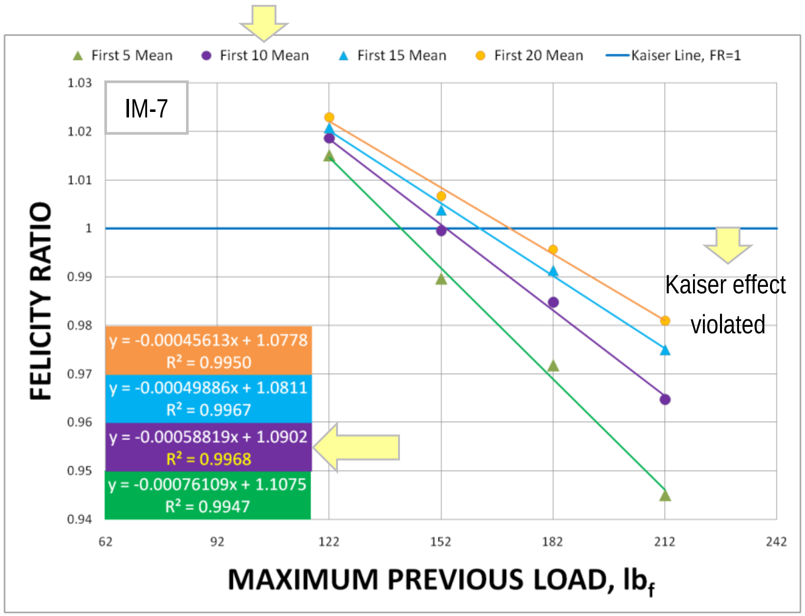
§ ASTM E1067, *Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels*, American Society for Testing and Materials, West Conshohocken, PA, 19428- (2011).

Results & Discussion

composite tow

- Linear decrease in FR with load noted for T1000 ($R^2 > 0.9$) and IM-7 ($R^2 > 0.99$) C/Ep, similar to the behavior noted for Kevlar® 49-epoxy K/Ep





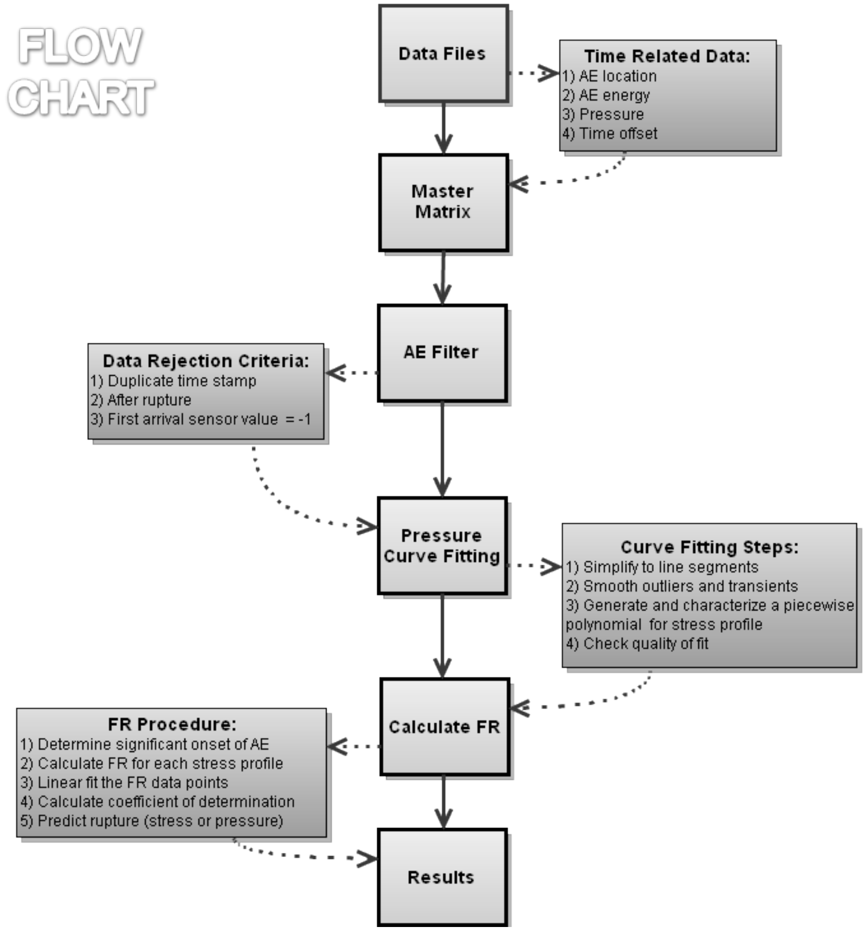
- For same material and averaging method, the slope of least squares fit is indicative of damage tolerance
- Kaiser effect violated at FR<1 $\Rightarrow$ onset of severe accumulated damage
- C/Ep produced more AE than K/Ep (but AE less energetic on average)

Data Reduction Enhancements

Results & Discussion

Data Reduction Enhancements

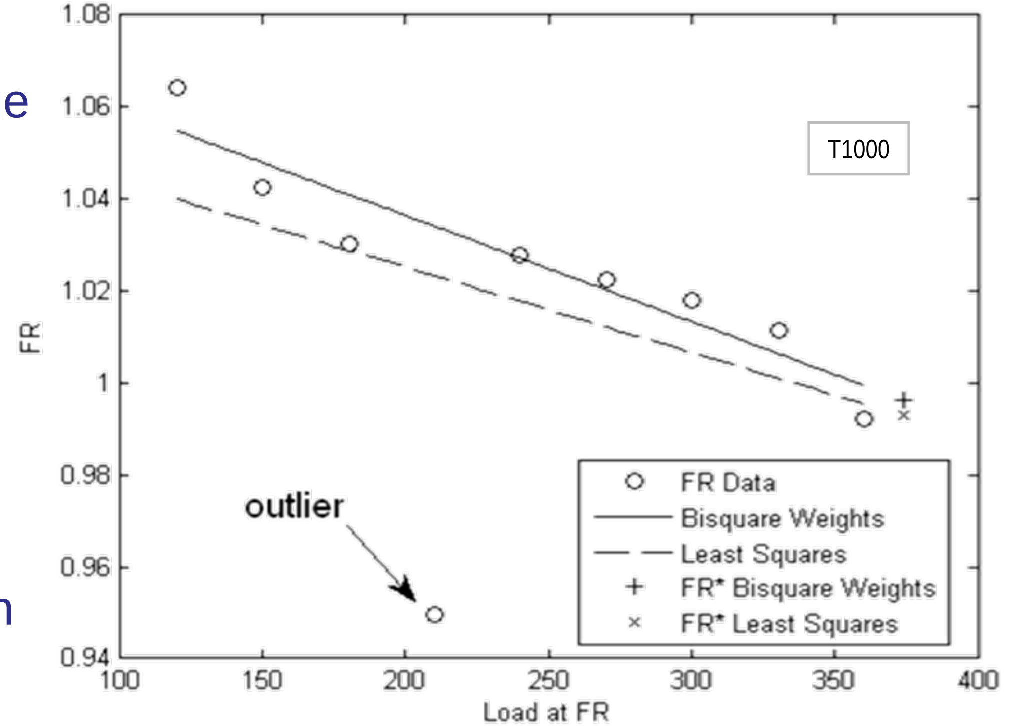
- Felicity Ratio Analysis Tool (FRAT) written
  - Automates AE data reduction
  - Optimizes best fit using least squares or bisquare fitting



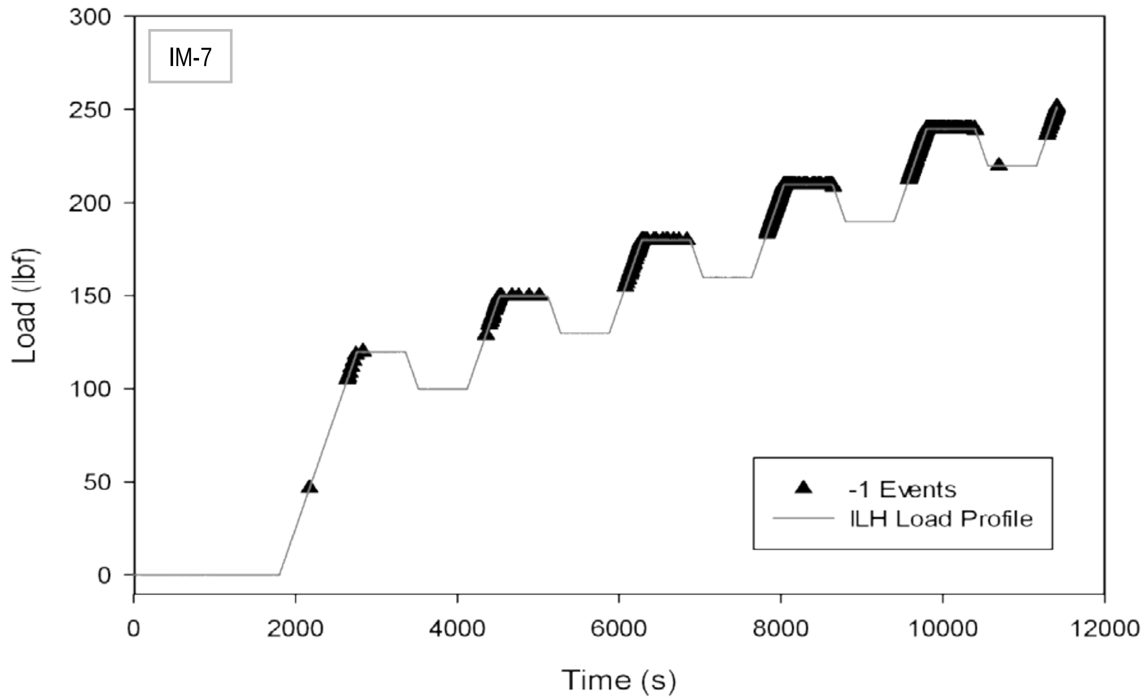
Results & Discussion

Data Reduction Enhancements

- Linear Least Squares (LLS)
  - Gives outliers too much leverage over fit
  - Must manually remove outliers
  - Minimizes square of residuals
- Bisquare weighting
  - Very similar process to LLS
  - Weights residuals of each point and down weights points of high leverage.
    - Automatically remove outliers
  - Minimizes weighted square of residuals



Results & Discussion
Data Reduction Enhancements

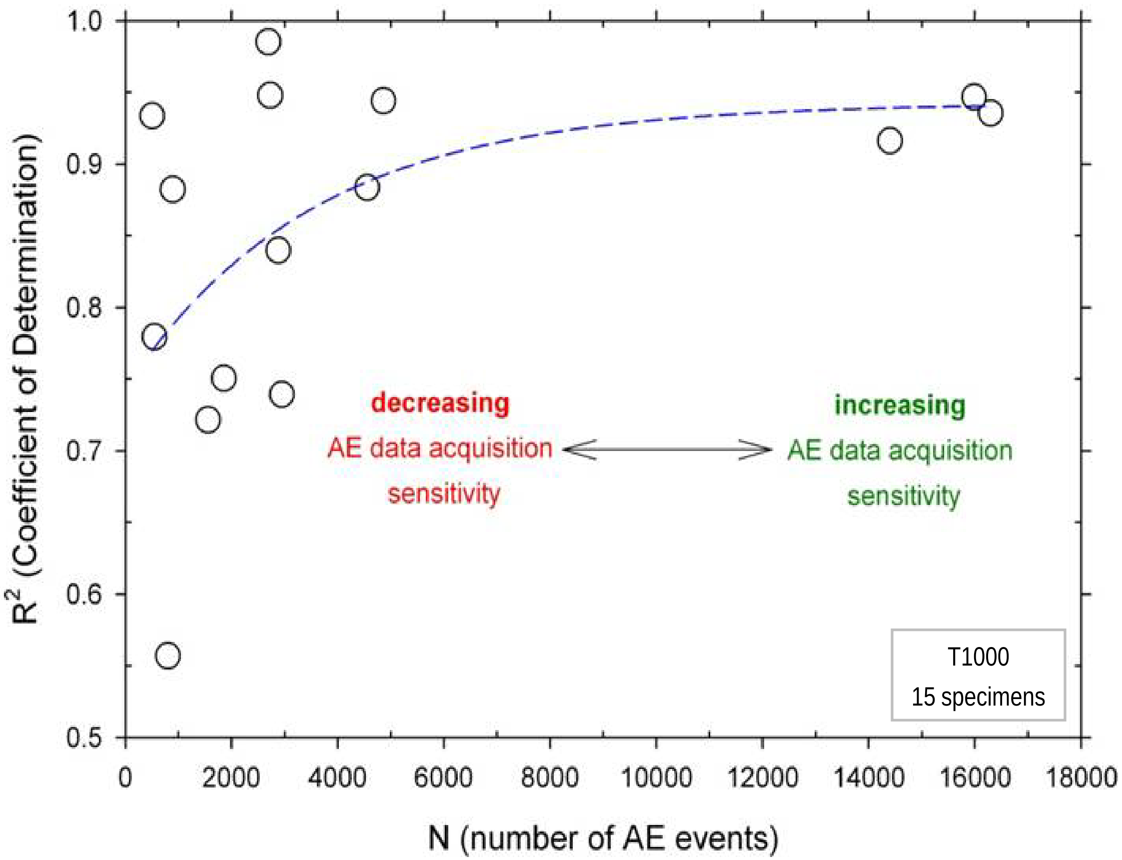


- Filtering Criteria
  - -1 arrival channel events were plotted against the load profile
  - -1 events primarily occurred on loading & upper load holds
  - No grounds for rejecting lower energy events

Results & Discussion

Data Reduction Enhancements

- Effect of data richness on FR trend analysis linearity showing that more sensitive AE DACS setting produce better linearity:

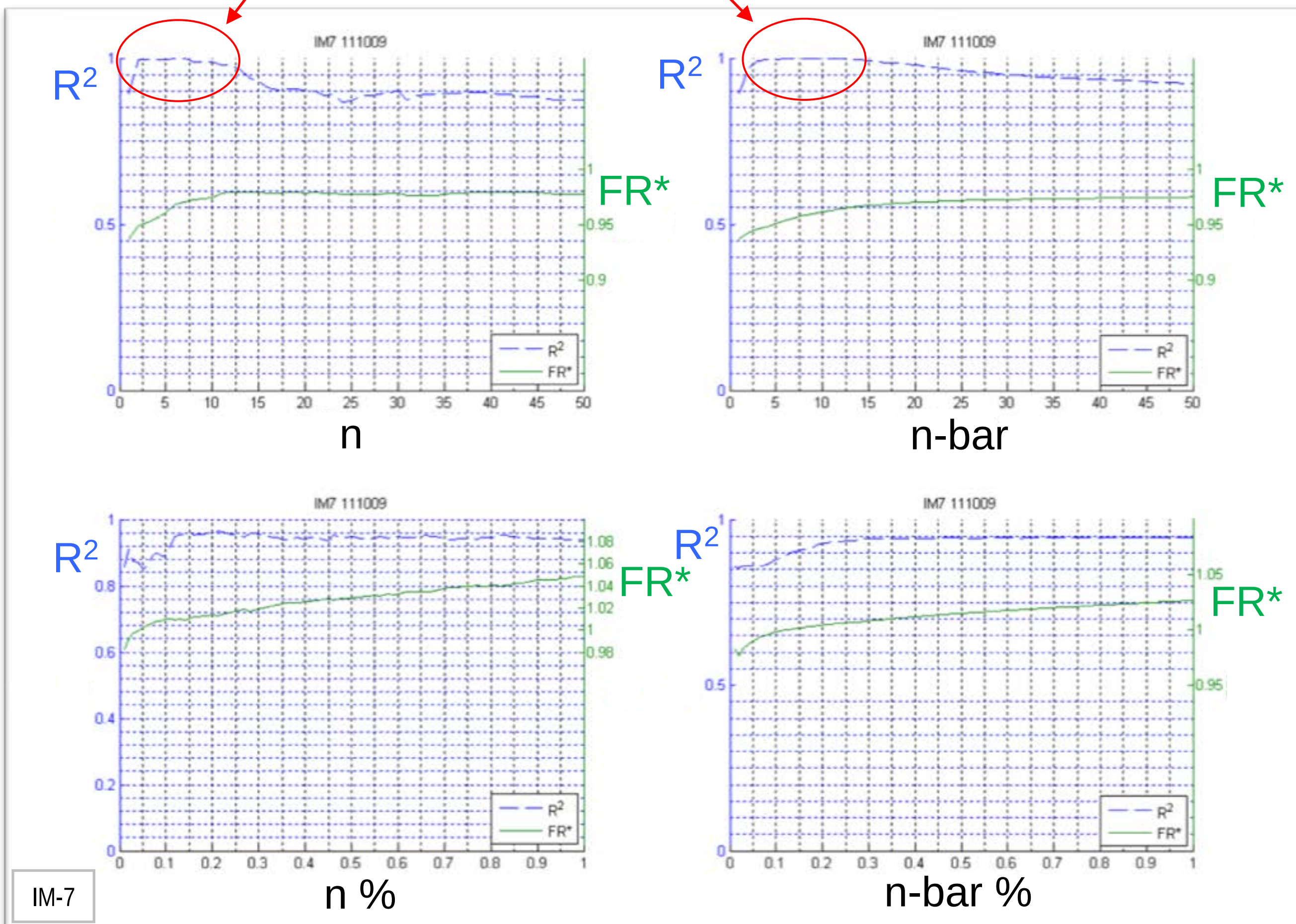


For example, 30-dB sensitivity is better than 50 to 60-dB sensitivity for FR analysis or quantification of fiber breakage events

Results & Discussion
Data Reduction Enhancements

- Can optimize the linear fit for different methods for determining the onset of significant AE used to calculate the FR:

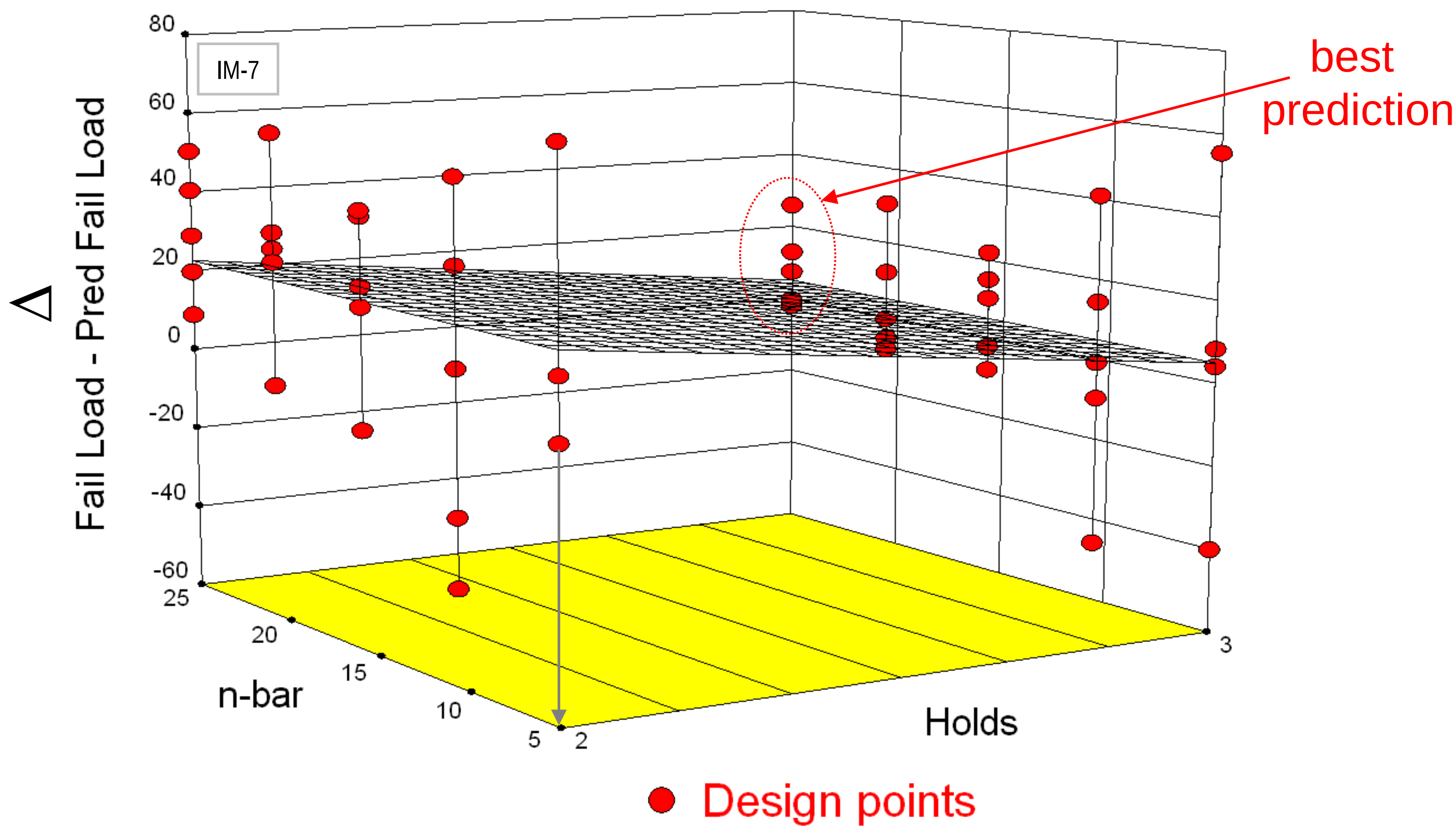
best linear fits



Results & Discussion

Data Reduction Enhancements

- Use the failure behavior of a known population to predict the failure of an unknown specimen using a rotating mean method
- Generate an $\Re^3$ response surface to identify where in the damage cycle the best failure prediction can be made:



. *Note:* two extreme data points removed from n-bar=5, Holds=2 to improve scale and Δ is measured in lb_f

Results & Discussion

composite tow

Date	Material & Spool #	Filter[1]	*F* @ *FR*=1 (lb_f)	F_{max} (lb_f)	σ @ *FR*=1 (ksi)	UTS (ksi)	*FR**	Failure Type[2]
83109	IM7 #95	32%	135	210	342	532	0.95	XGB
90109	IM7 #95	27%	151	234	383	591	0.945	XGM
90809	IM7 #95	58%	171	210	433	530	0.971	XGM
111009	IM7 #117	9%[3]	193	252	488	637	0.961	XGM
32610	IM7 #61	19%	183	228	464	578	0.97	XGM
82509	T1000 #74	32%	240	355	658	972	0.972	XGT
82609	T1000 #74	46%	231	369	633	1010	0.953	XGT
82809	T1000 #74	37%	226	362	[illegible]	992	0.977	XGT
112409	T1000 #155	4%[3]	181	379	[illegible]	1037	0.945	SGM
112509	T1000 #74	6%[3]	206	325	[illegible]	890	0.966	LGM
40910	T1000 #155	6%[3]	181	374	493	1024	0.95	XGM
Mean	**IM7**	**29%**	**167**	**227**	**422**	**575**	**0.959**	
	Std. Dev.	**18%**	**24**	**18**	**60**	**45**	**0.012**	
Mean	**T1000**	**22%**	**211**	**361**	**577**	**988**	**0.961**	
	Std. Dev.	**18%**	**26**	**19**	**71**	**53**	**0.013**	

UTS
5.3-7.9 % scatter

FR*
1.2-1.4 % scatter

- **Let *FR** = extrapolated *FR* at rupture predicted by the least squares fit**
- ***FR** behaves like a universal parameter that varies less than the UTS**

[1] Data filter reflects percentage of events removed from the raw AE data
[2] Failure abbreviations per ASTM D 3039, *Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials*, American Society for Testing and Materials, West Conshohocken, PA (2007)
[3] Improved tabbing method

Conclusions
composite tow

- Consistent *FR** values noted for T1000 and IM-7
  - Same matrix resin, cure history, and fiber loading
- Suggests that the FR can be used as an analytical PASS/FAIL criterion for C/Ep composite materials
- Precedent: ASTM suggests using *FR* < 0.95 as failure criteria in fiberglass reinforced pressure vessels §
  - Experimental C/Ep failure criteria from strand tests
    - » IM7: FR < 0.959
    - » T1000: FR < 0.961
- Opens up the possibility that C/Ep composite materials can be subjected to ILH profiles to assess in- or out-of-family response
  - Need to verify that test specimens or articles with low initial *FR*, or steep '*FR* vs. load' slopes in fact fail prematurely, or in the case in COPVs, fail at lower burst pressure

§ ASTM E1067, *Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels*, American Society for Testing and Materials, West Conshohocken, PA, 19428 (2011).

Waveform and FFT Analysis

and

Development of Pass/Fail Criteria

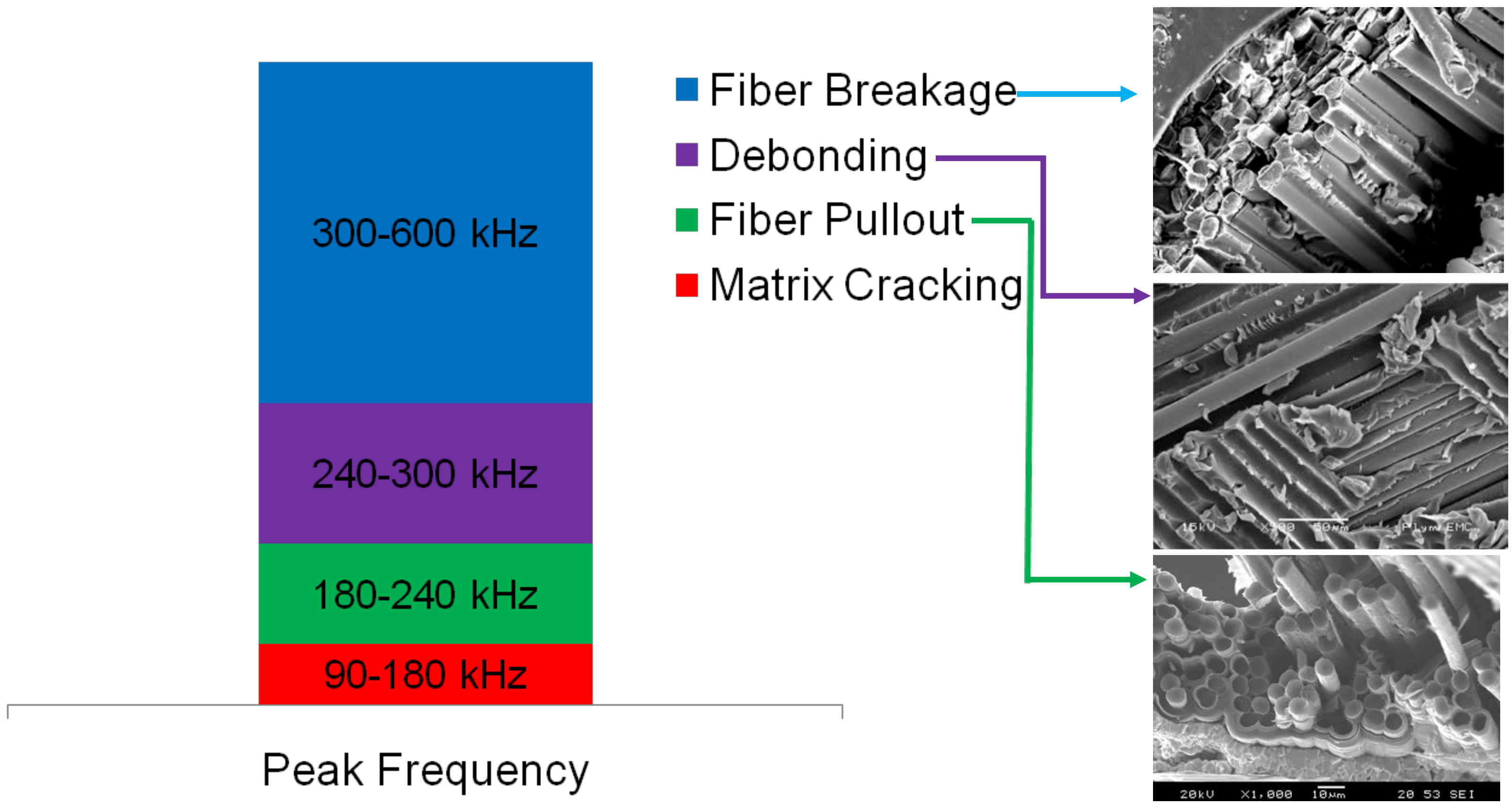
Based on AE

(IM7 & T1000 composite tow and COPVs)

Results & Discussion

Waveform and FFT Analysis

AE frequency ranges have been correlated with micromechanical damage mechanisms in C/Ep §

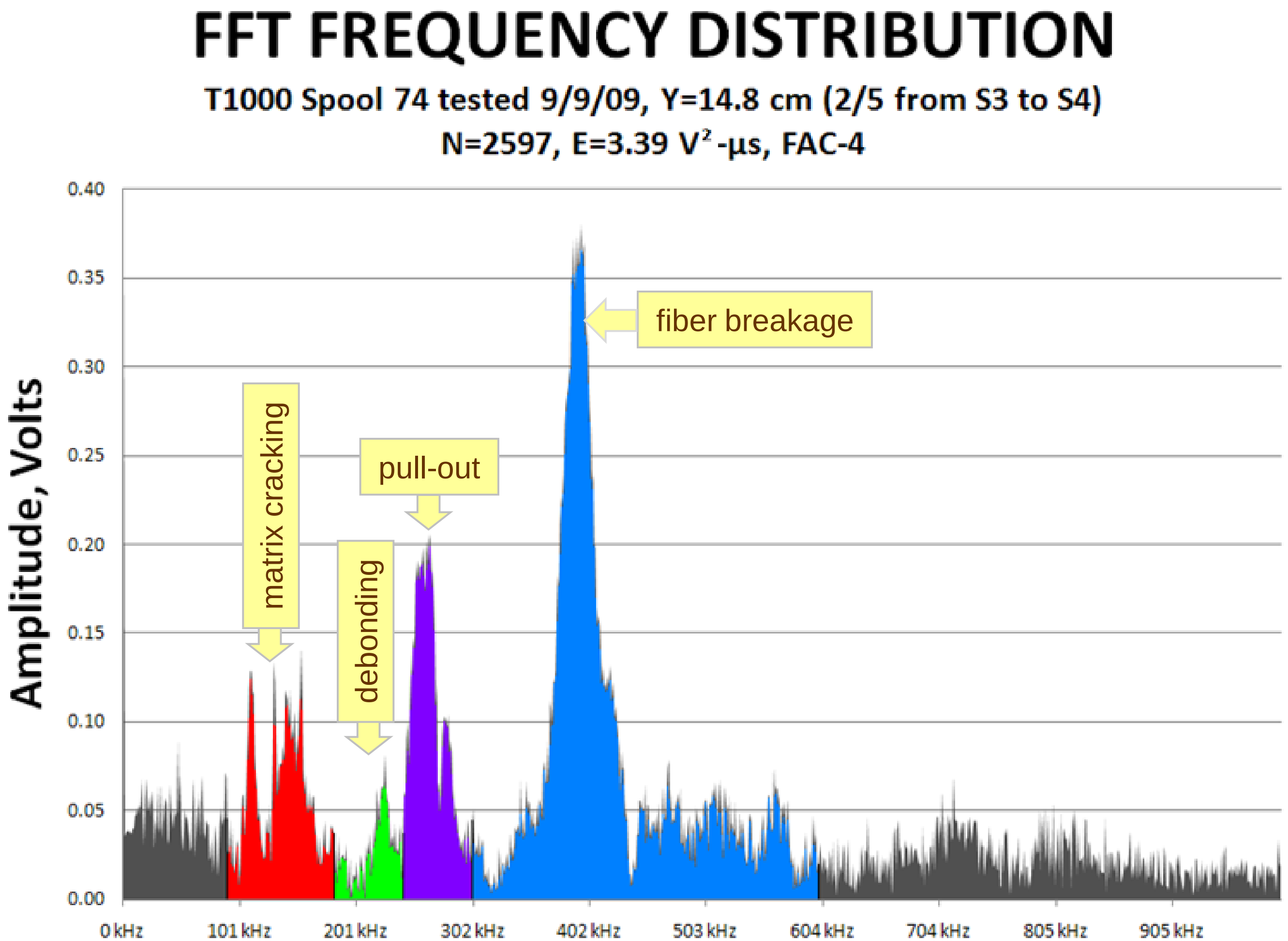


§ De Groot, P., P. Wijnen, and R. Janssen, "Real-time Frequency Determination of Acoustic Emission for Different Fracture Mechanisms in

Results & Discussion

Waveform and FFT Analysis

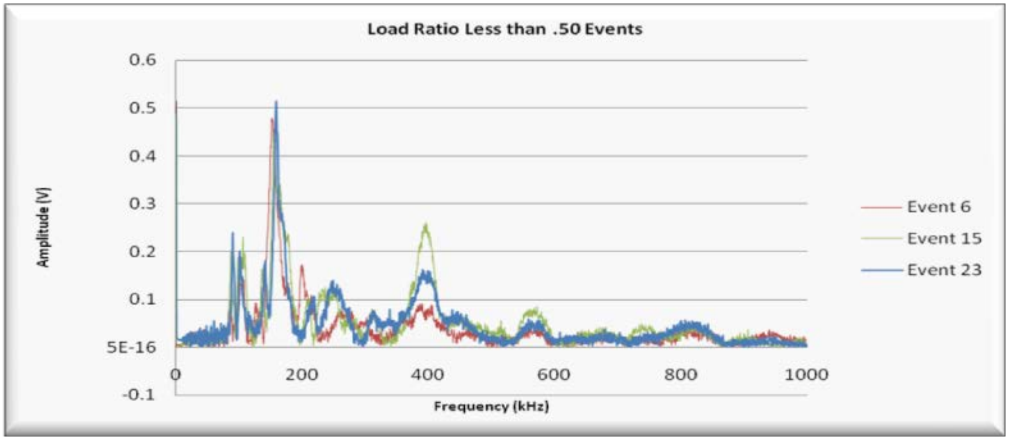
FFT (unfiltered) showing concerted failure using De Groot's frequency ranges



Results & Discussion
Waveform and FFT Analysis

- IM-7 early *vs*. late life events

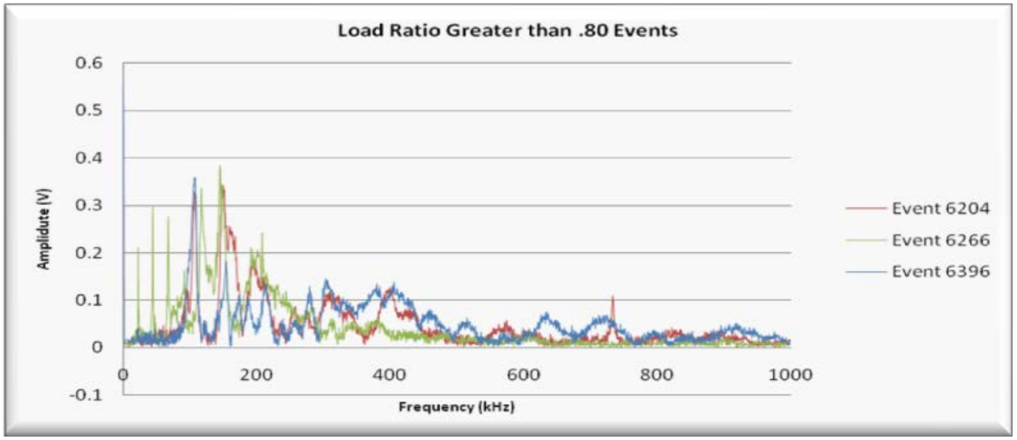
Early Life



LR < 0.5

first ILH ramp up

Late Life



LR > 0.8

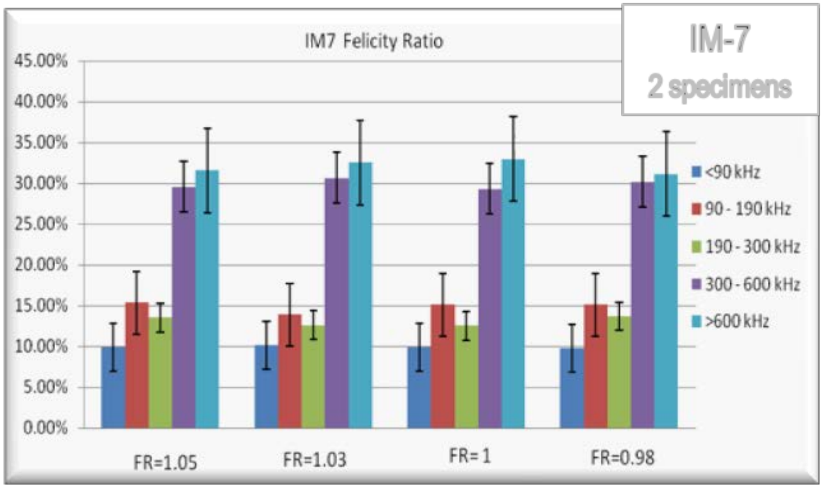
last ILH ramp up

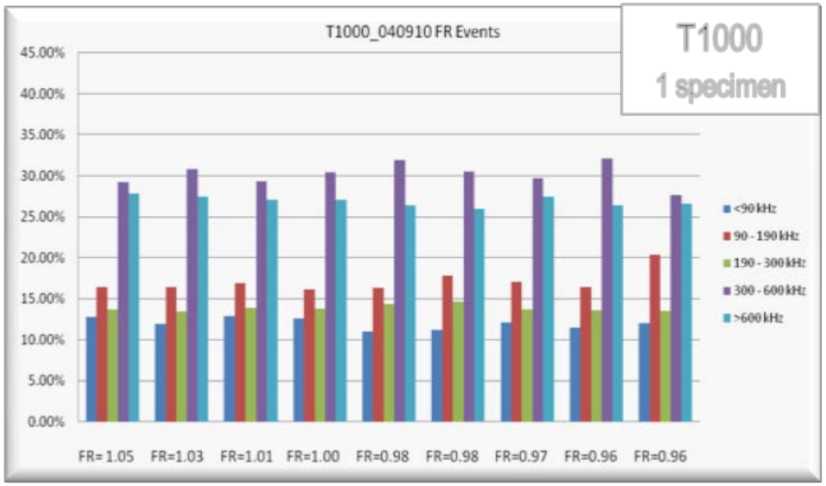
- Notice change from ordered (early) to unordered peaks (late life)

Results & Discussion

Waveform and FFT Analysis

- The FFTs of IM-7 and T1000 Felicity ratio events (first ten events) were then compared to see if they had a characteristic damage mode, or if the damage mode changed with load





- Fiber breakage dominates FR events
  - otherwise FR events involve concerted failure for both types of C/Ep
- Some differences, but same overall trend noted for T1000 & IM-7:

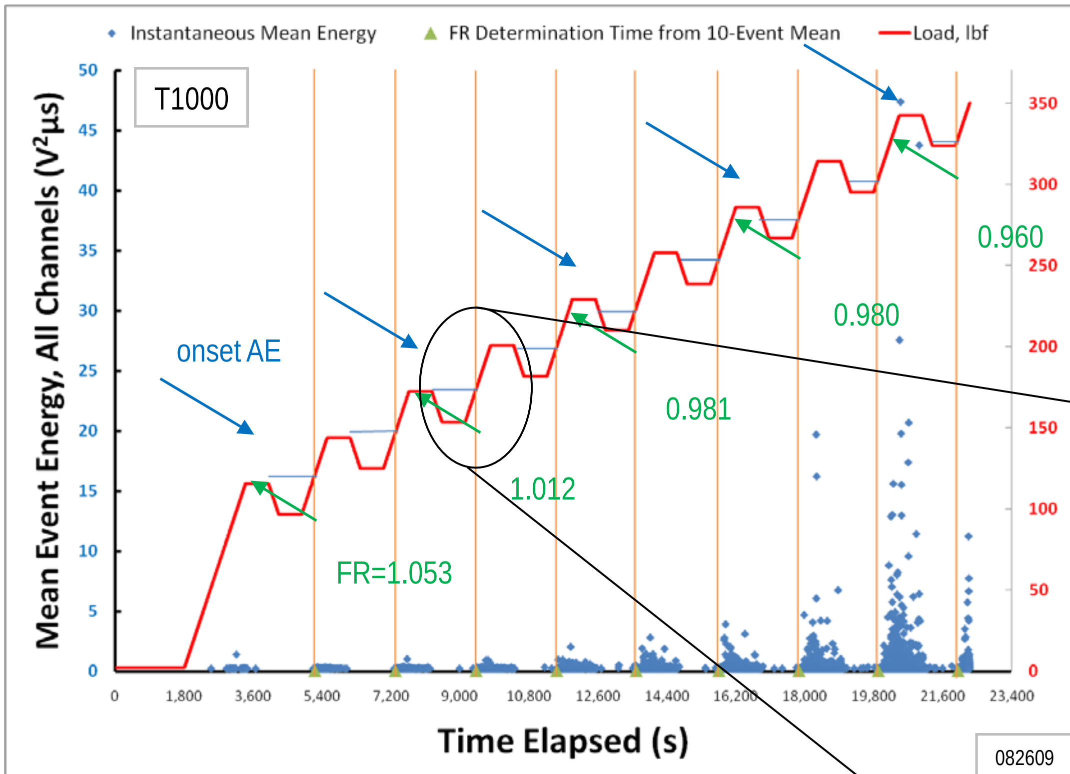
300-1000 kHz > 90-190 kHz > 190-300 kHz

(*fiber breakage > matrix cracking > debonding/pull-out*)

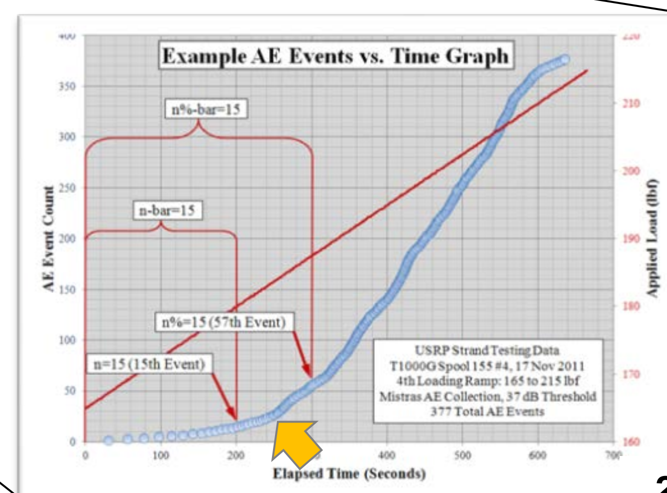
Results & Discussion

Data Reduction Enhancements

- Analytical identification of the ‘knee’ § in the AE events vs. time curve using an exponentially weighted moving average (EWMA) method:



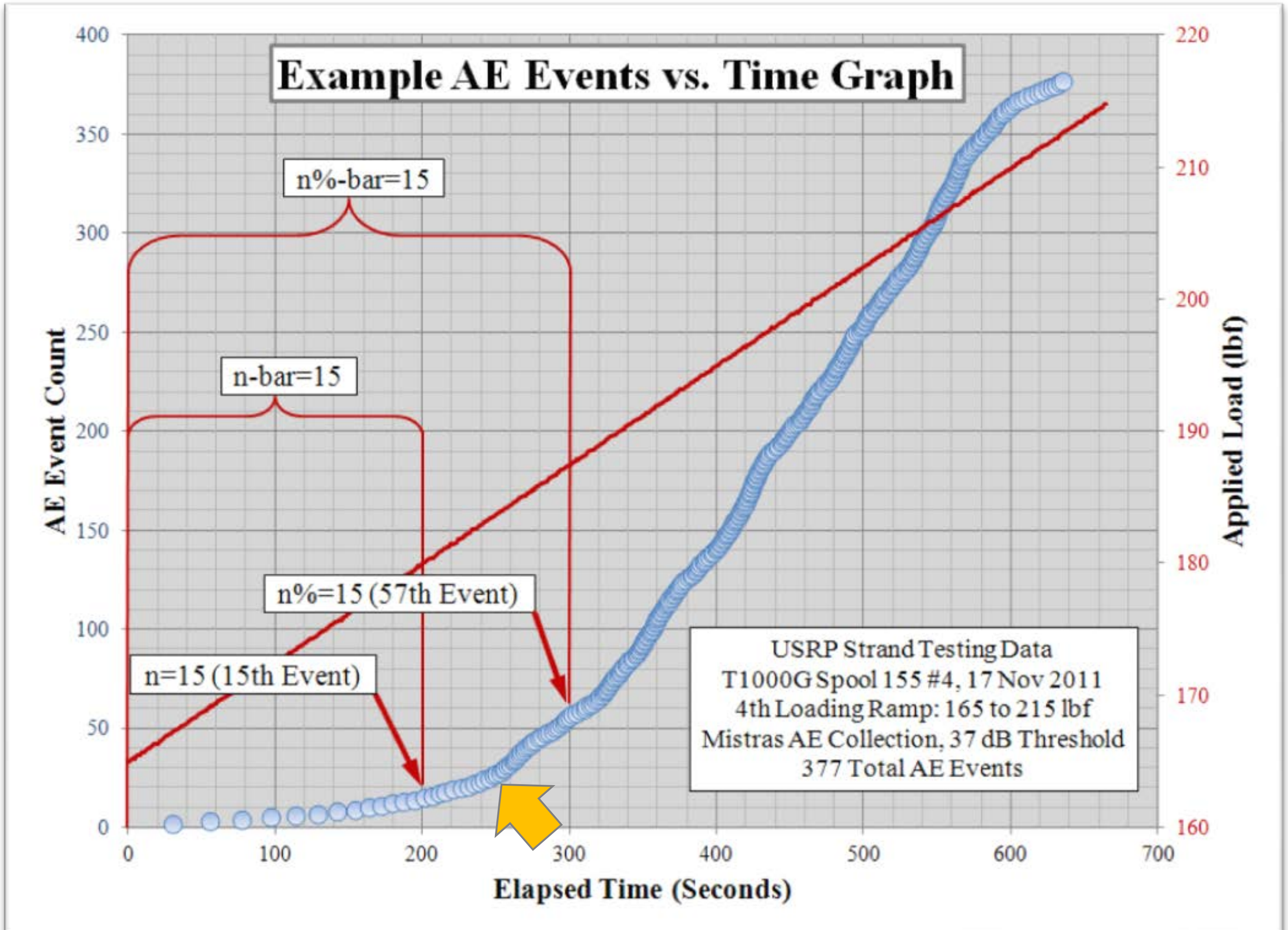
3rd Felicity ramp



§ *knee in the curve* — a dramatic change in the slope of the cumulative AE (MARSE or Signal Strength) versus time curve (ASTM E2478).

Results & Discussion
Data Reduction Enhancements

- Analytical identification of the 'knee' § in the AE events vs. time curve using an exponentially weighted moving average (EWMA) method:



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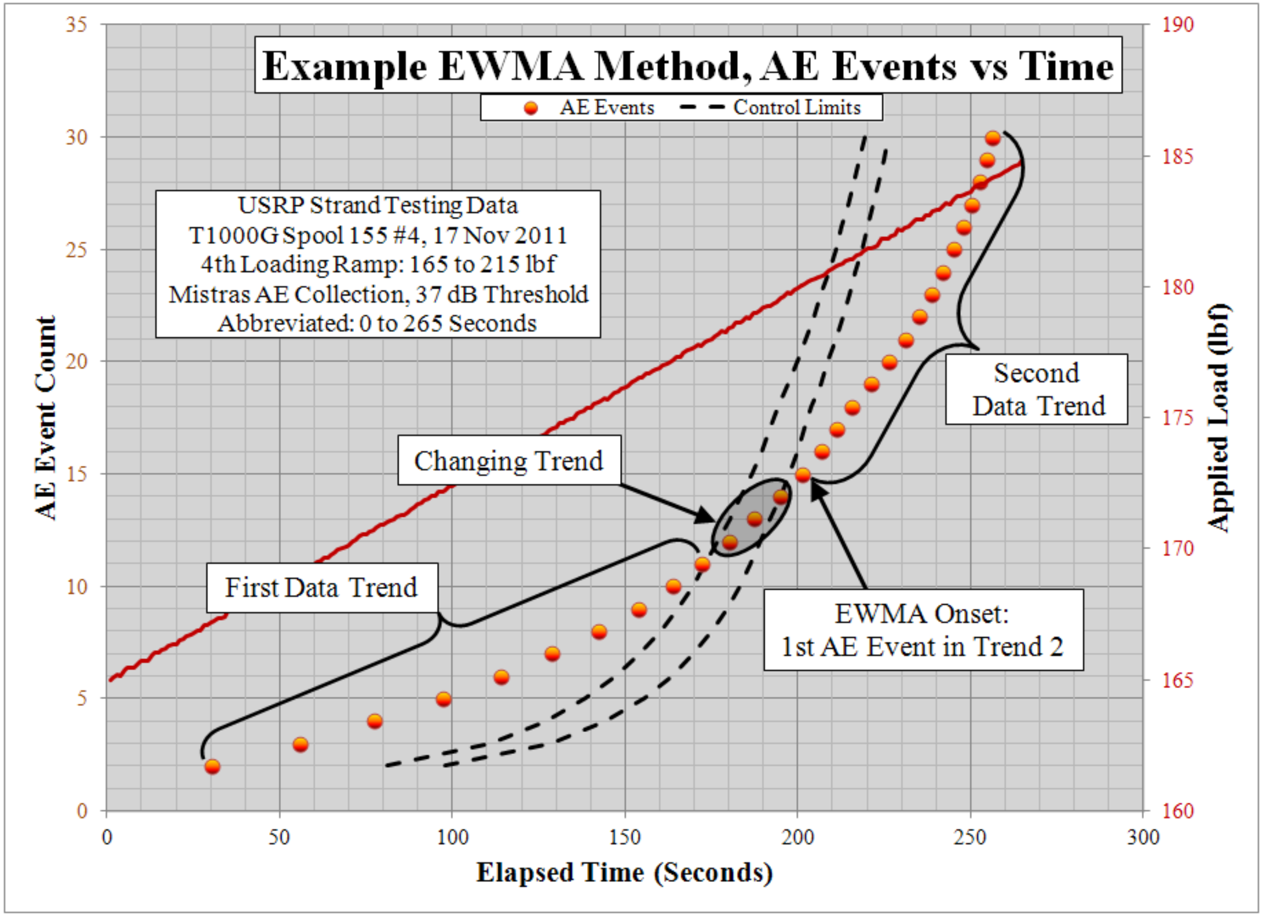
Results & Discussion

Data Reduction Enhancements

- Exponentially weighted moving average (EWMA) method:



plotted statistic:

$$z_i = \lambda x_i + (1-\lambda)z_{i-1}$$

control limits:

$$Limits = T \pm L\frac{S}{\sqrt{n}}\sqrt{\frac{\lambda}{2-\lambda}[1-(1-\lambda)^{2i}]}$$

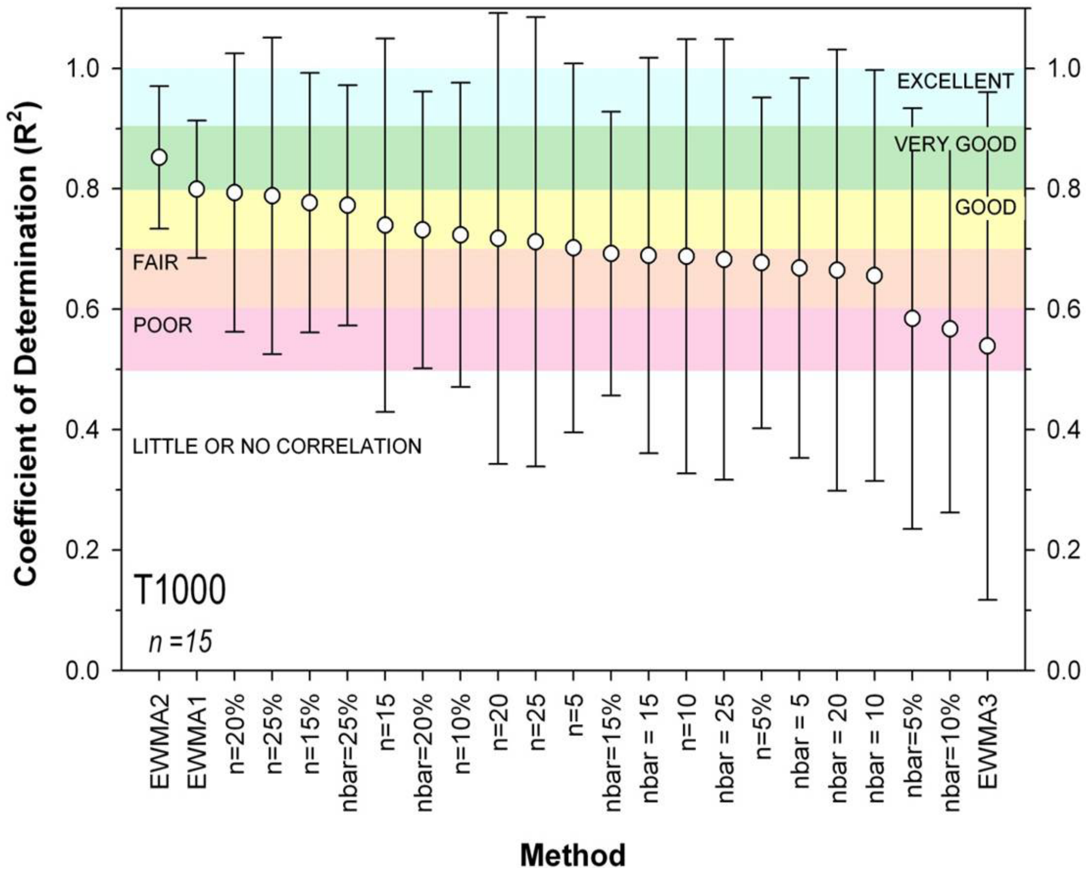
standard deviation:

$$\hat{\sigma} = \frac{\sum_{i=0}^{i} MR_i}{(i-1)d_2(2)}$$

Results & Discussion

Data Reduction Enhancements

- EWMA method found to yield better (more linear) results than other methods <u>for</u> T1000 tow:



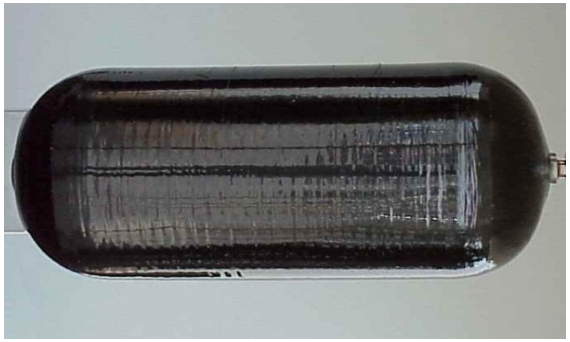
better linear fit

Application to
Composite Overwrapped Pressure Vessels
(COPVs)

Results & Discussion

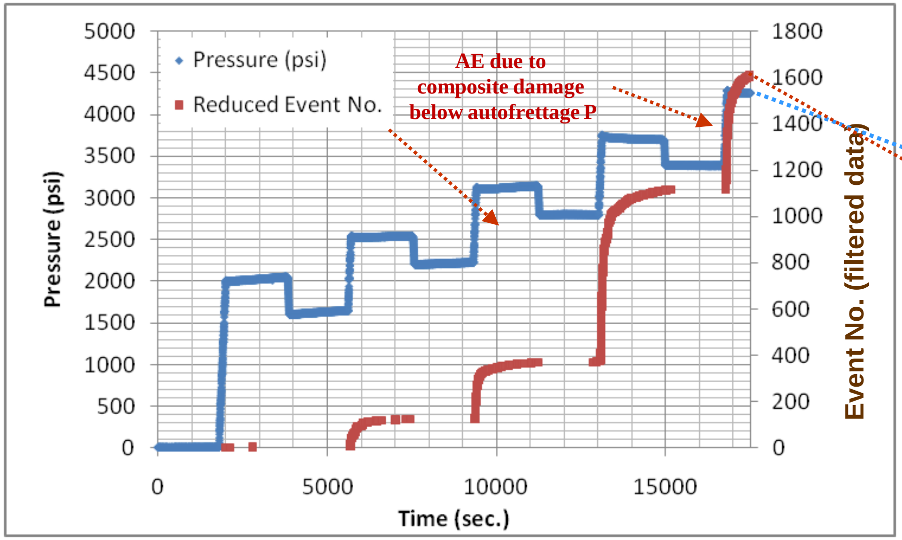
IM-7 COPV Case

A 6.3-in. diameter IM-7 COPV was subjected to an ILH pressure schedule up to LR ≈ 0.9

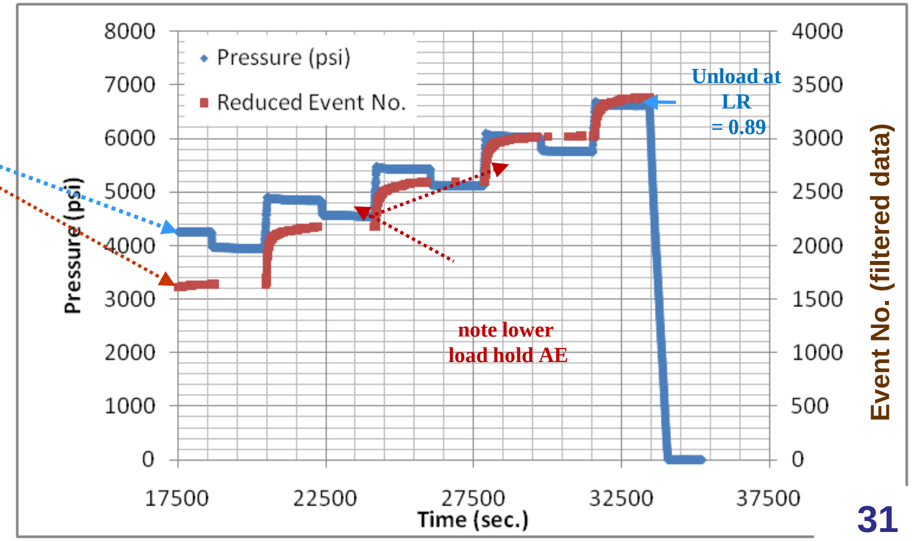


Pressure & Events vs. Time

0 to 17500 s



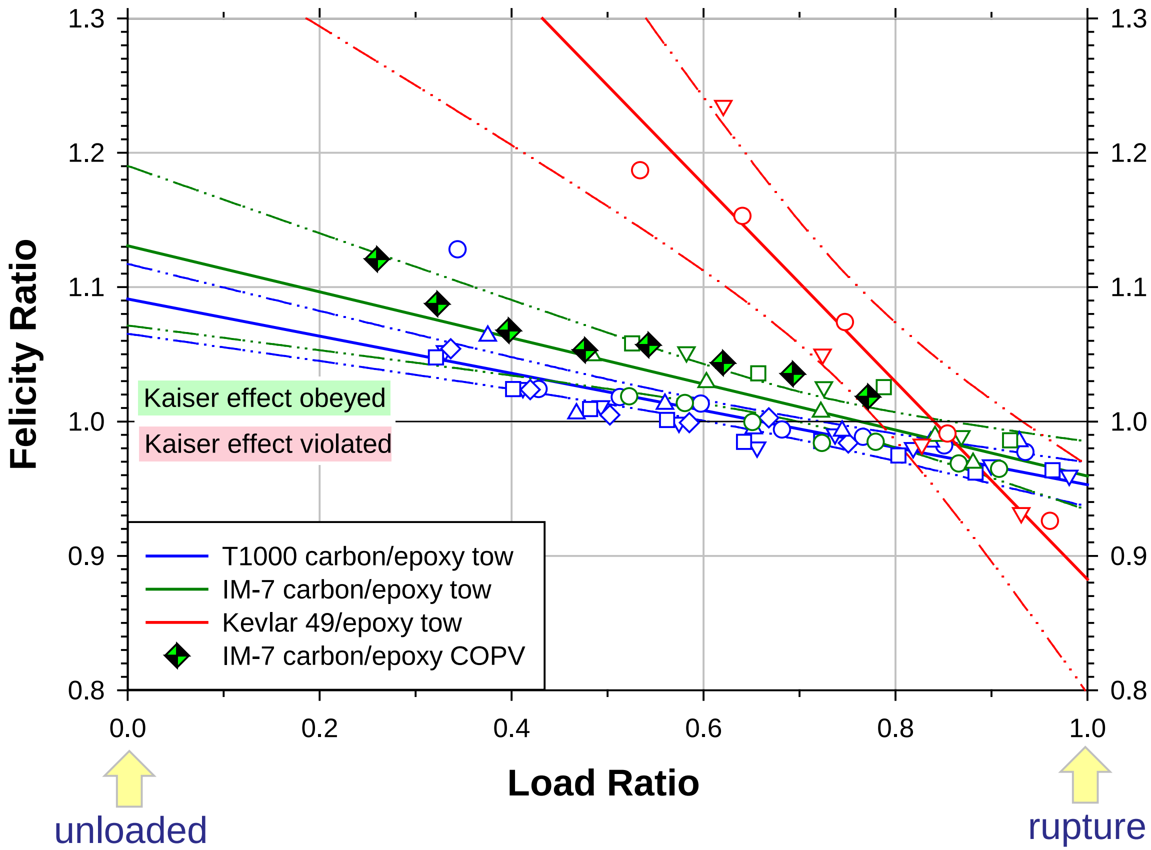
17500 to 37500 s (cont.)



Results & Discussion

COPV versus composite tow

IM-7 COPV data (◆ symbols) overlap IM-7 tow data (open green symbols)

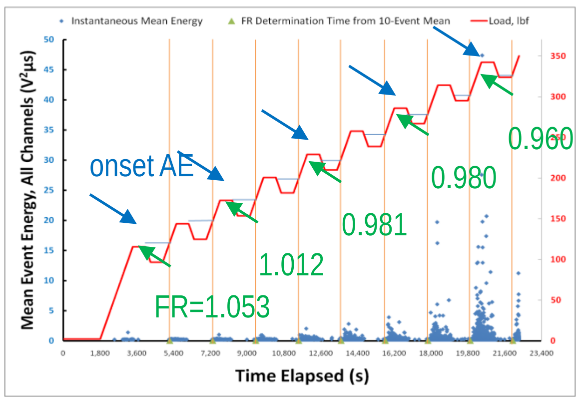


Least squares fits (solid lines) and 99 % confidence intervals (dash-dot-dot lines) also shown for T1000 and Kevlar® 49

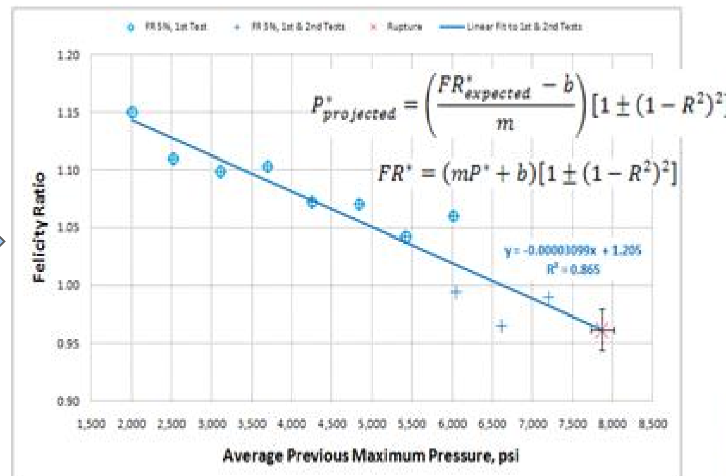
Results & Discussion
Prediction of COPV Burst Pressure

- Burst pressure prediction of a COPV using the Felicity ratio §

Subject C/Ep composite to intermittent load hold pressure schedule (red)



Measure cumulative composite damage by monitoring approach of *FR* to *FR**



First 8 Data Points:

$FR^* = 1.000 \pm 0.010$

$P^*_{projected} = 7{,}540 \pm 75$ psi in agreement with hydroburst data (below)

$P^*_{observed} = 7{,}529$ psi based on hydroburst data on 2 identical COPVs

All Data:

$FR^* = 0.961 \pm 0.018$

$P^*_{projected} = 7{,}870 \pm 144$ psi higher than initially projected 7,540 psi value

$P^*_{observed} = 7{,}869$ psi higher than 7,529 psi value based on hydroburst data on 2 identical COPVs

§

1. Nichols, C., J. Waller, and R. Saulsberry, "Acoustic Emission Lifetime Estimation for Carbon Fiber/Epoxy Composite Overwrapped Pressure Vessels," *USRP Final Report*, NASA-JSC Whites Sands Test Facility, Las Cruces, NM, August 2010.

2. Waller, J., C. T. Nichols, D. J. Wentzel, and R. L. Saulsberry, *Use of Modal Acoustic Emission to Monitor Damage Progression in Carbon*

Results & Discussion
COPVs

AE event decay rate analysis on load holds using ASME Section X, Appendix 8 §

$$y = A\, e^{-B\,t} + C$$

Acceptance criteria from ASME Section X Mandatory Appendix 8 and NB10-0601 Supplement 9 :

Acceptable Event Stability:

$-0.1 < B < -0.0001$ & $R^2 \geq 0.80$

Observed acceptance criteria in WSTF IR&D IM7 COPV tests (more stringent):

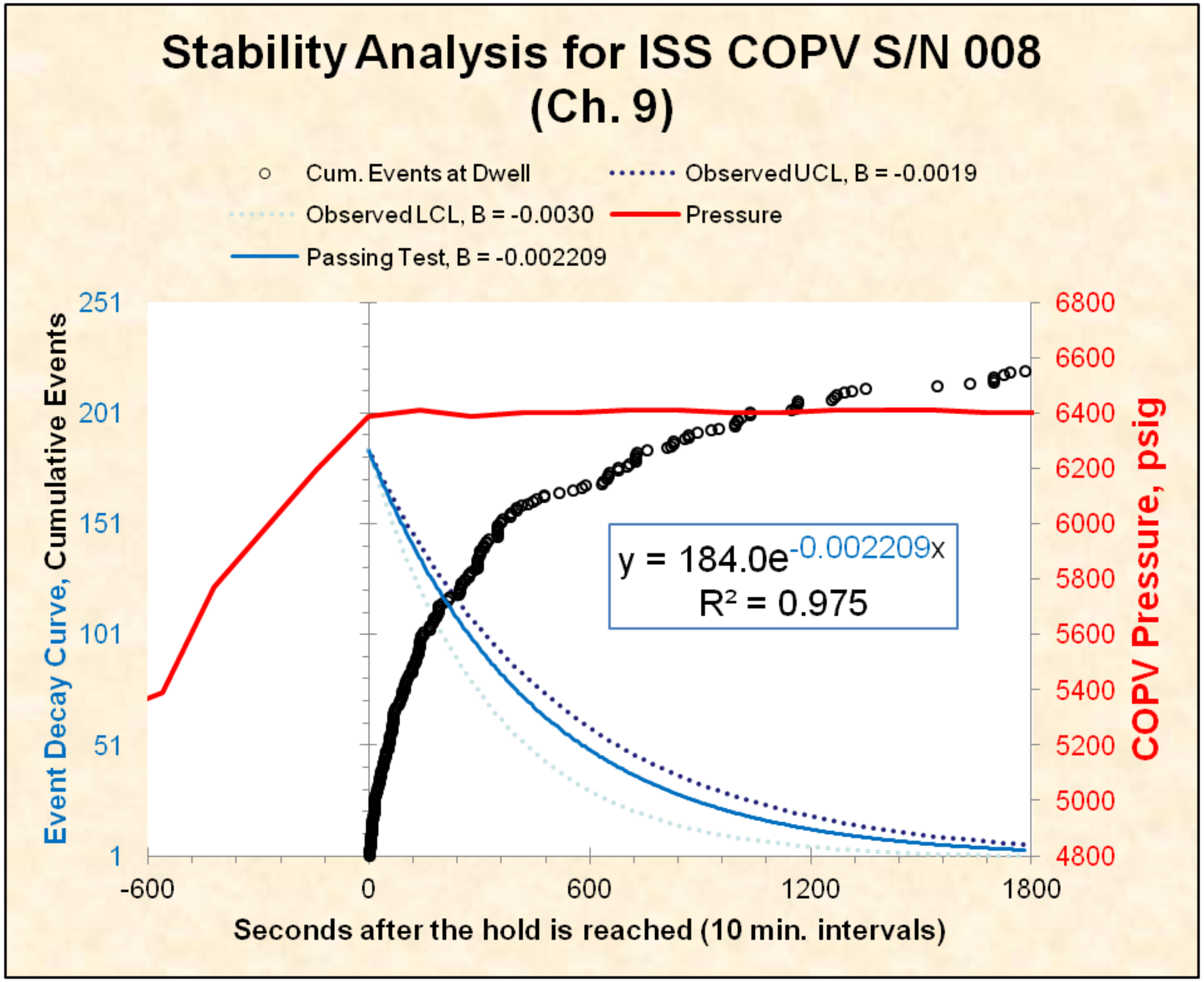
Acceptable Event Stability:

$-0.0030 < B < -0.0019$ & $R^2 \geq 0.90$

Shape factor B can also be expressed as the time required for the structure to emit 99% of events on a dwell.

$$t_{99\%} = \frac{\ln(0.01)}{B}$$

25 to 40 minutes *(1535 to 2424 sec)*



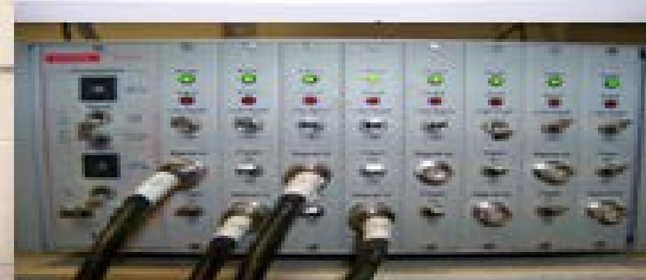
§ ASME Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels, Section X, Appendix 8-620 Supplementary Examination Requirements (latest revision).

Additional Conclusions
Strands and COPVs

- ASTM-based ILH methods using AE data collected on Felicity ramps were found to give a reproducible, quantitative estimate of the threshold at which significant accumulated damage began to occur
- Application of ILH or related stress profiles could lead to robust pass/fail acceptance criteria based on the *FR*
- Application of *FR* analysis to COPVs subjected to ILH pressure schedules is promising
- EWMA knee methods for determining the ‘knee’ look very promising
- ASME-based “composite stability” methods using AE data collected on load holds looks very promising as an additional pass/fail acceptance criterion

Back-Ups

Experimental

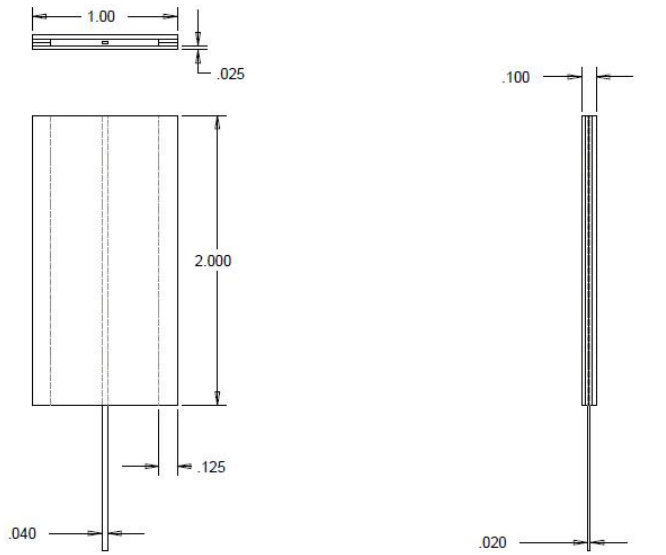


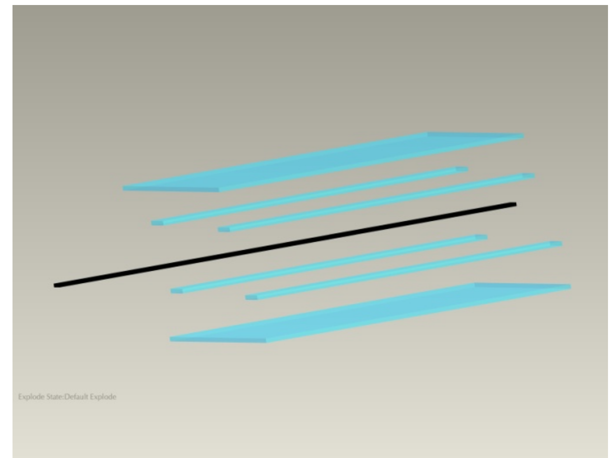
Load control and AE data acquisition system (DACS) consisted of:

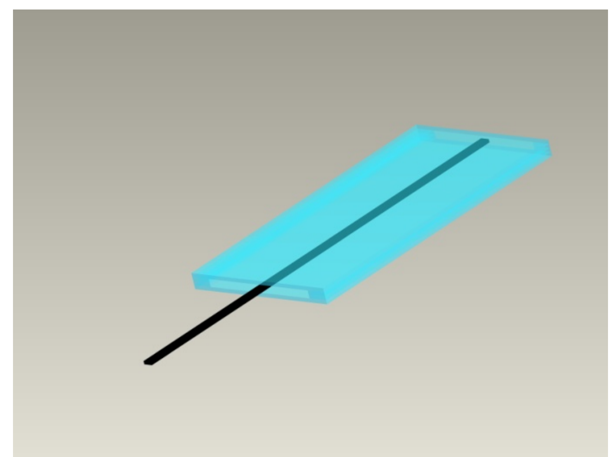
- Instron® 5569 Series Electromechanical Test Instrument (left)
- DigitalWave Corp. FM-1 8-channel DACS (lower right)
- AE and tensile test CPU controllers (upper right)

Experimental

Tabbing: shear strength of epoxy and bonded grip length important variables §







$$L_{min} = F^{tu}h/2F^{su}$$

where:

L_{min} = minimum required bonded tab length, mm [in.];

F^{tu} = ultimate tensile strength of coupon material, MPa [psi];

h = coupon thickness, mm [in.]; and

F^{su} = ultimate shear strength of adhesive, coupon material, or tab material (whichever is lowest), MPa [psi].

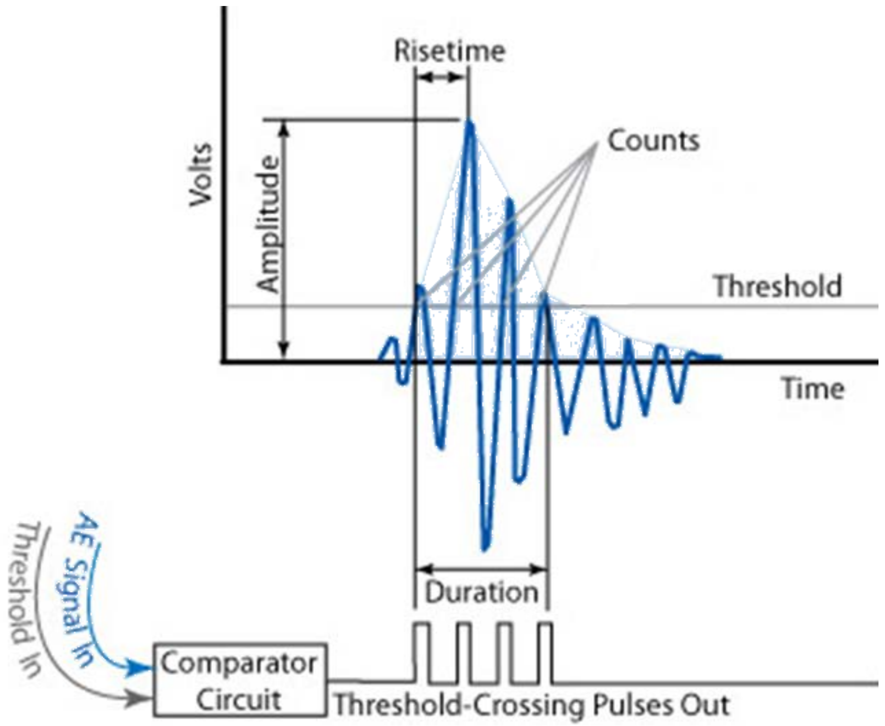
§ ASTM D 2343, *Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics*, American Society for Testing and Materials, West Conshohocken, PA (2008).

ASTM D 3039, *Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials*, American Society for Testing and Materials, West Conshohocken, PA (2007).

Acoustic Emission Testing

Acoustic Emission refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material. When a structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy, in the form of stress waves, which propagate to the surface and are recorded by sensors.

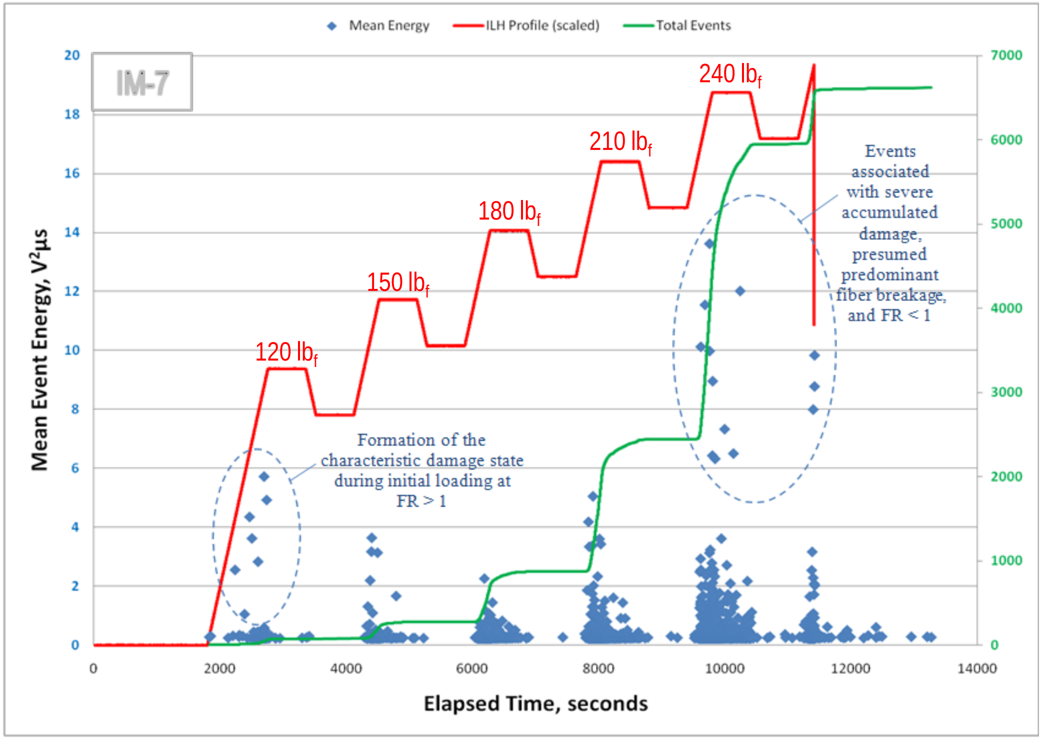
(http://www.ndt-ed.org/)



•100 mV

Results & Discussion
composite tow

- Formation of characteristic damage state very evident at load ratio (LR) < 0.6 for IM-7

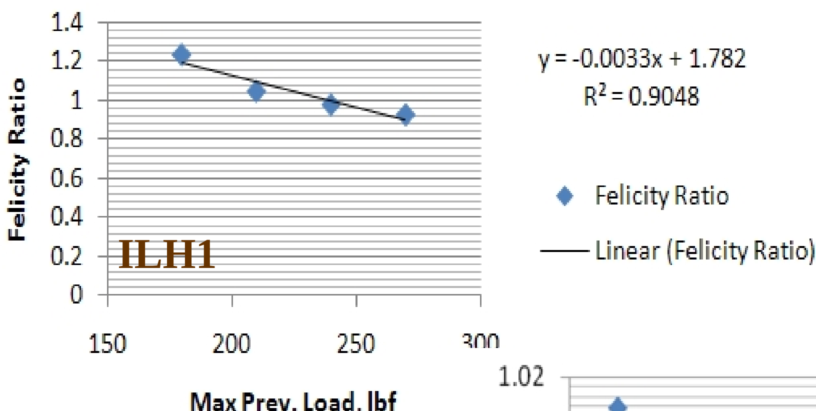


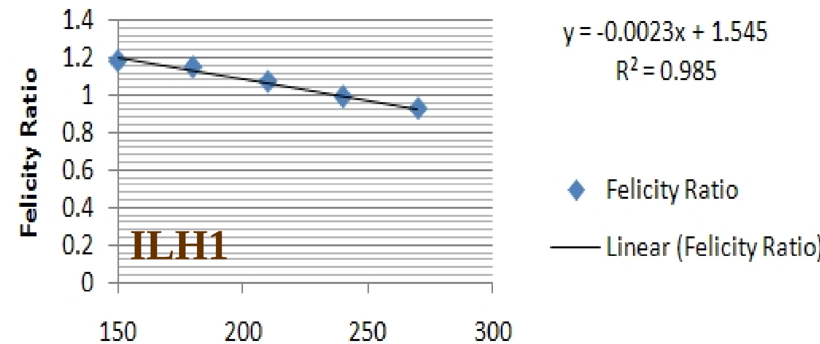
  - In quasi-isotropic composite lay-ups, for example, characteristic damage state formation thought to involve predominant matrix cracking
  - For uniaxial tow, FFTs revealed the characteristic damage state formation involves mixed mode failure mechanism (cooperative matrix cracking, fiber/matrix debonding, fiber pull-out, fiber breakage, with fiber breakage predominating)

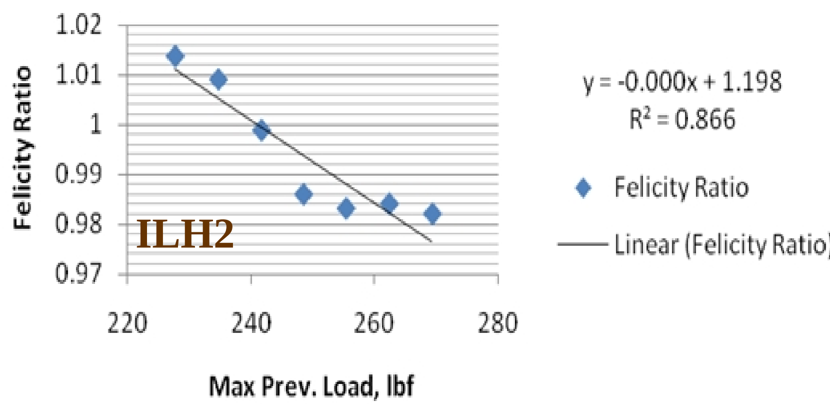
Results & Discussion

- For Kevlar-epoxy 4650 denier tow, correlation coefficients for ILH1 & 2 methods indicated good (R^2 = 0.866) to excellent (R^2 = 0.985) agreement:

Kevlar® 49-epoxy

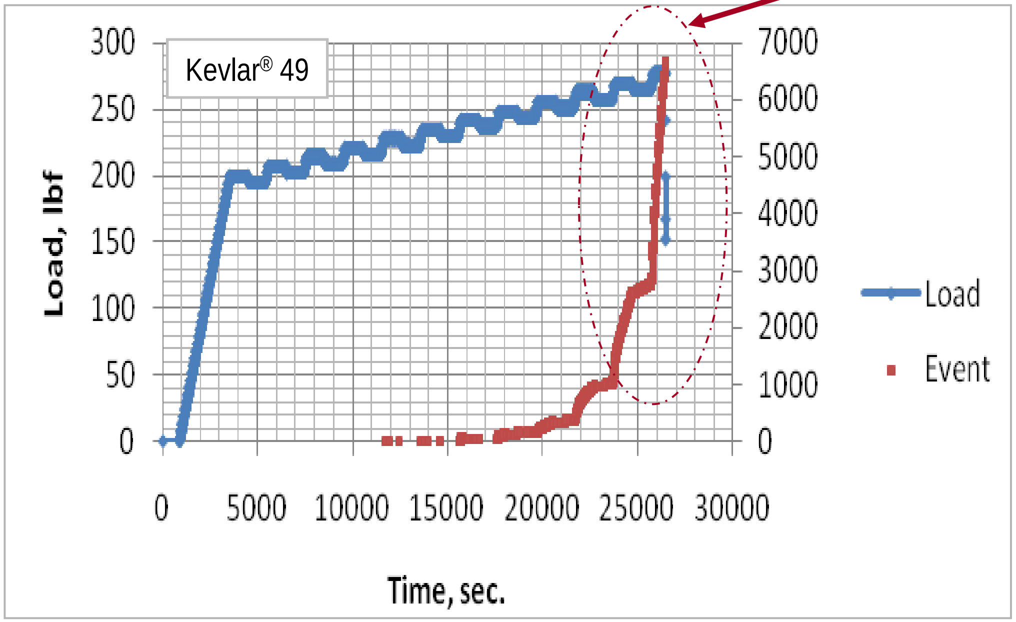






Results & Discussion

- Characteristics of significant AE:
  - For Kevlar-epoxy, and T1000 and IM-7 carbon-epoxy, nonlinear increases in AE event rate were observed immediately before rupture, indicative of '*critically intense*' AE activity per ASTM E 1067 and E 1118:

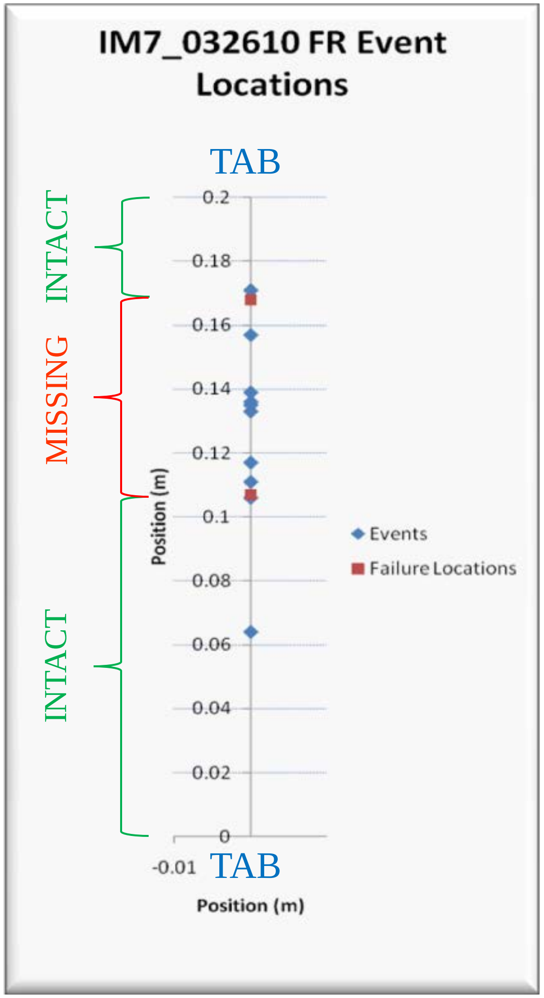


  - Areas of critically intense AE activity also showed greatest violation of Kaiser effect, hence, the lowest FR values

Results & Discussion

composite tow

Source location of FR events show they occur at or near locus of failure



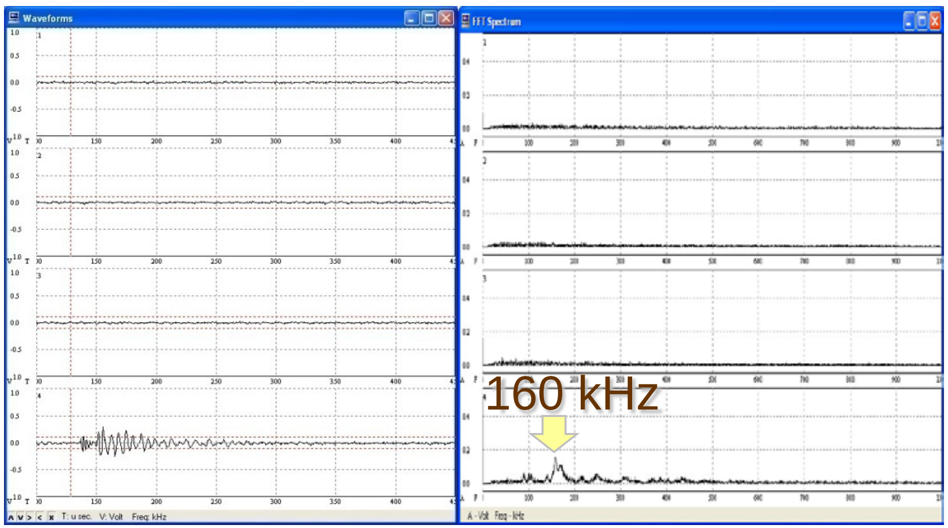
- IM7_032610 specimen had intact tow between and 0 (lower tab) and 0.115 m 0.17 and 0.20 m (upper tab)
- Tow region between 0.115 and 0.17 m obliterated (explosive failure)
- Most FR events were source located in the missing region that failed explosively

Results & Discussion

Waveform and FFT Analysis

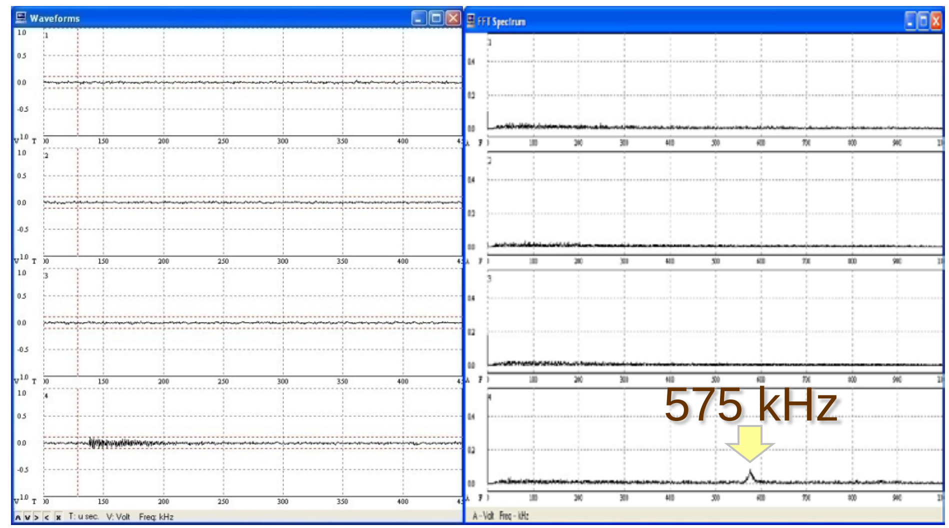
- In general, three different waveforms were observed for C/Ep

1. Matrix Cracking



waveform FFT

2. Fiber Breakage

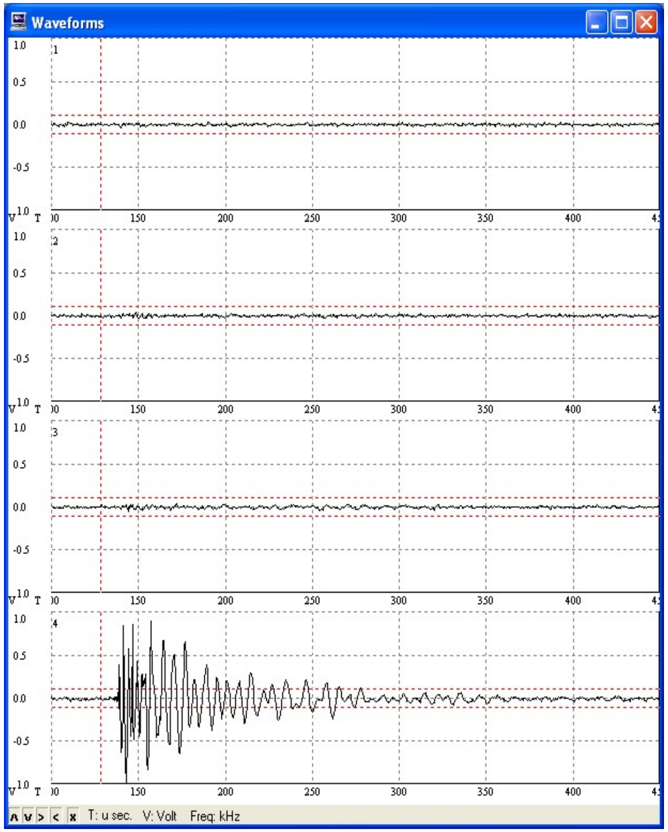


waveform FFT

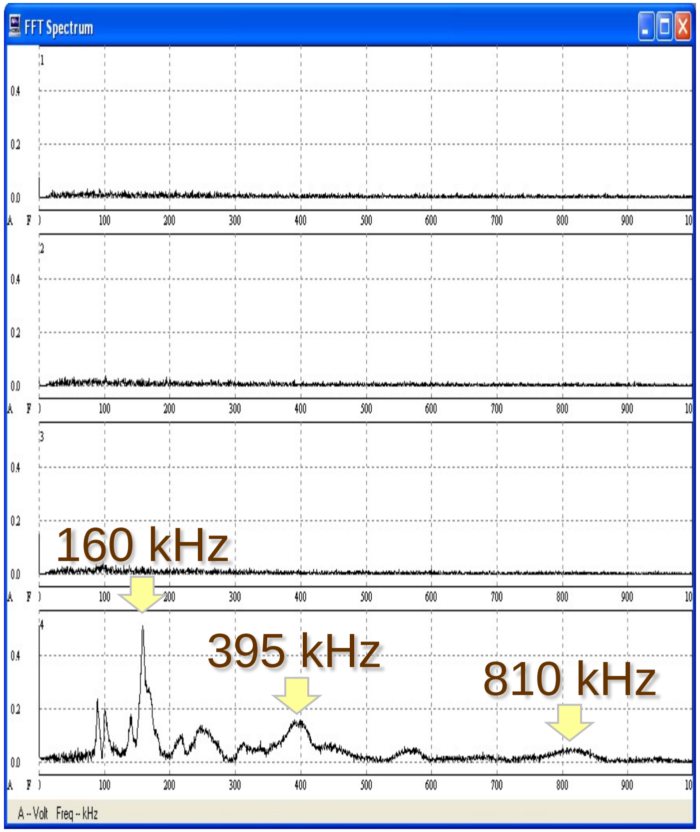
Results & Discussion
Waveform and FFT Analysis

- Three different waveforms were observed for C/Ep (cont.)

3. Concerted, mixed mode failure



waveform

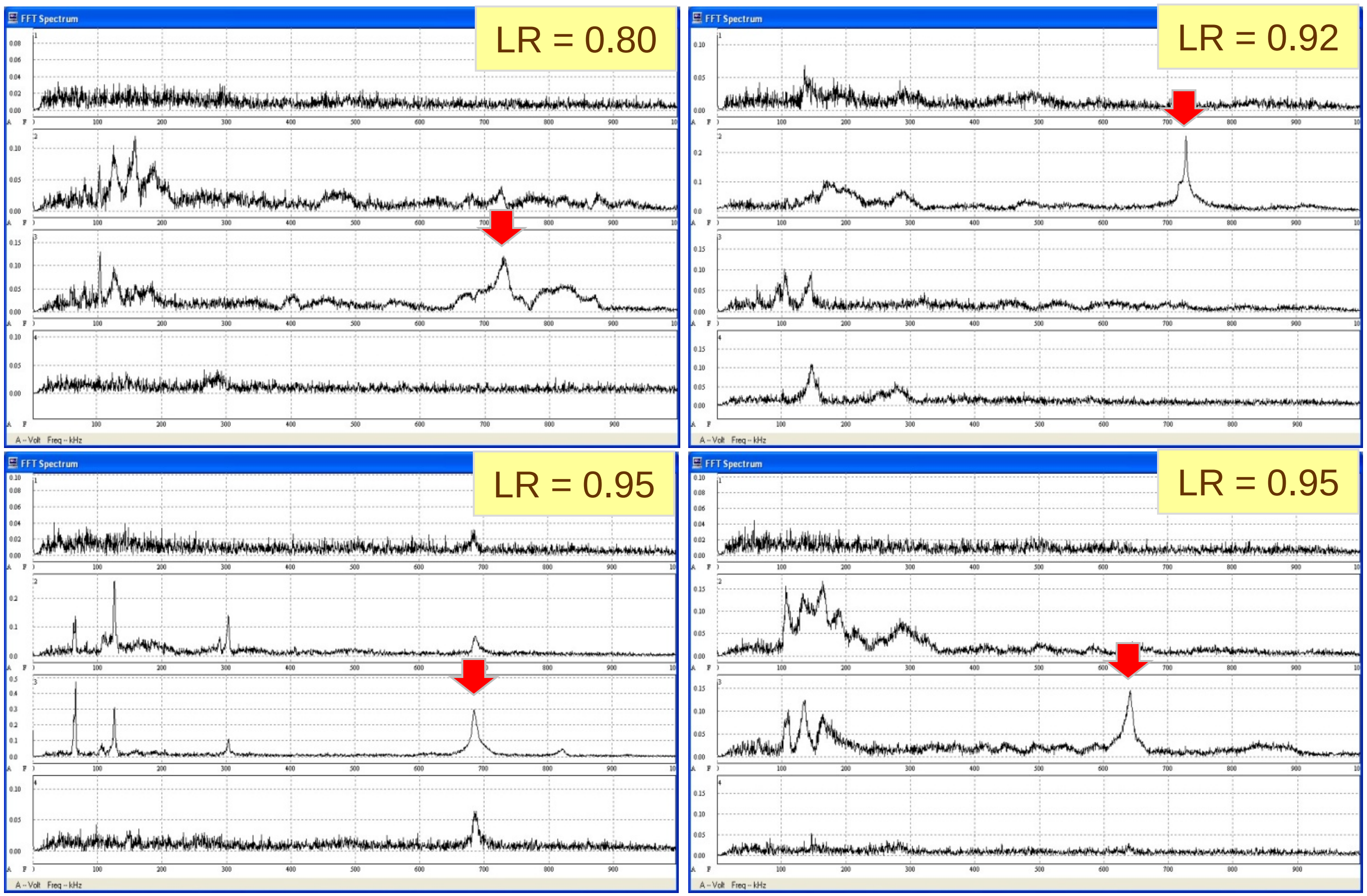


FFT

Results & Discussion

Waveform and FFT Analysis

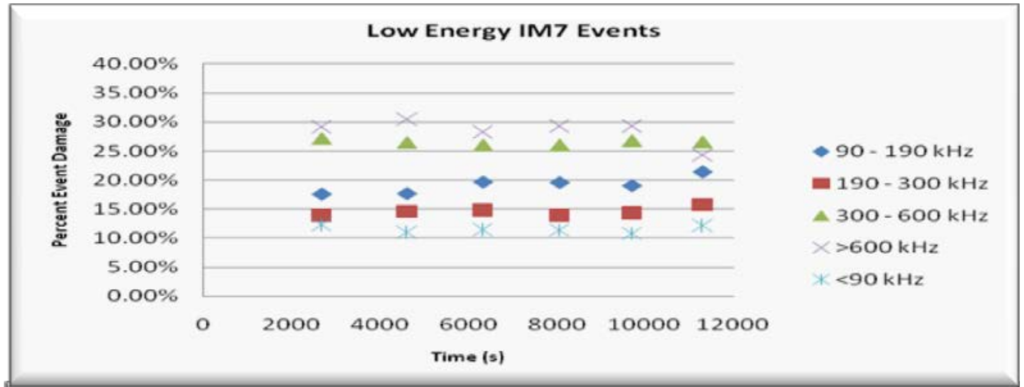
- High frequency peaks shifted downward with increasing load ratio:
  731 kHz ⇒ 728 kHz ⇒ 685 kHz ⇒ 640 kHz
- Attributed to increasing accumulated damage, hence lower modulus, causing slower stress wave propagation



Results & Discussion

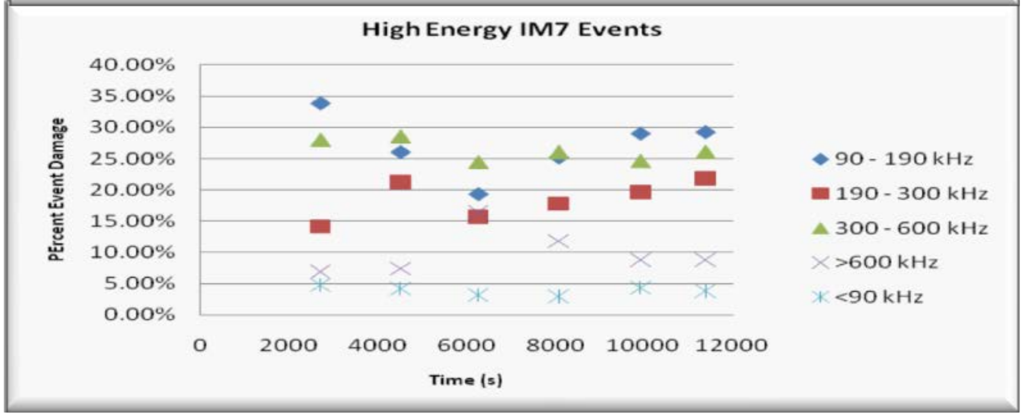
- IM-7 low *vs.* high energy events

Low Energy



E < 2 V²-µsec

High Energy



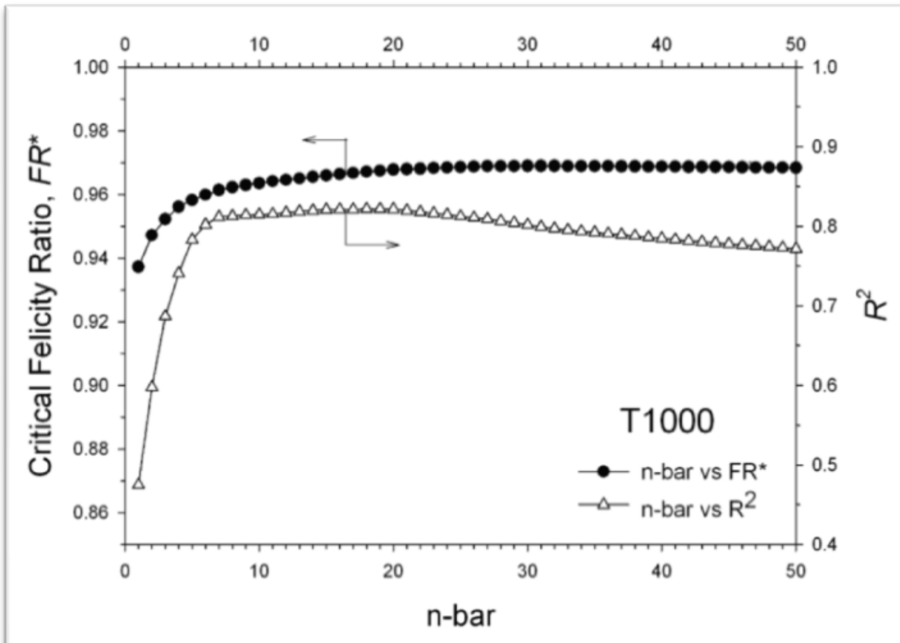
E > 2 V²-µsec

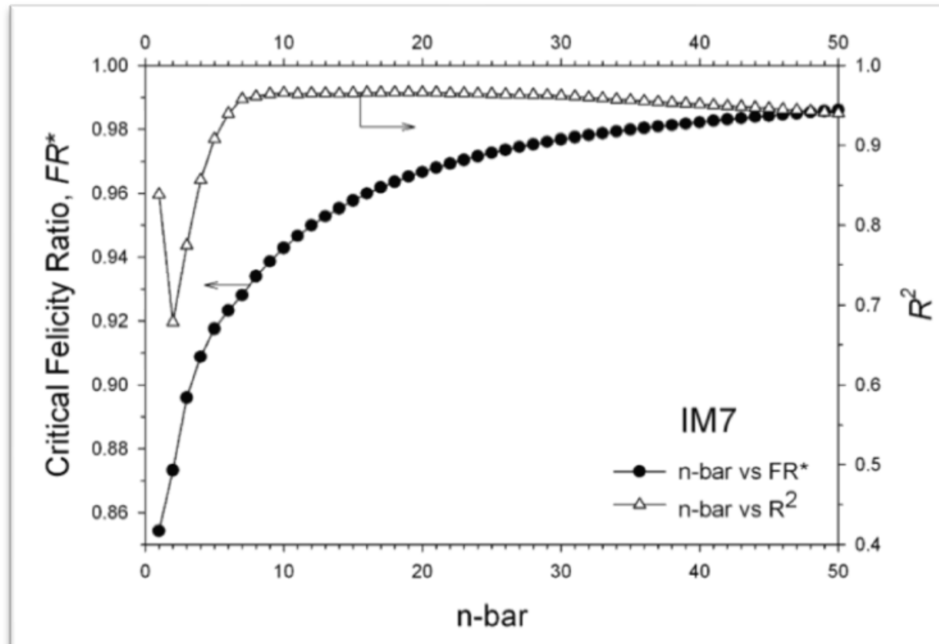
- Low energy events have similar damage ‘footprint’ (top), while high energy events have a more variable damage ‘footprint’ (bottom)
- Similar observation of a of a fiber breakage dominated “footprint” for FR events

Results & Discussion

Data Reduction Enhancements

- Comparison of IM7 and T1000 tow showing the variation of the R^2 (coefficient of determination) and FR* with *n*:



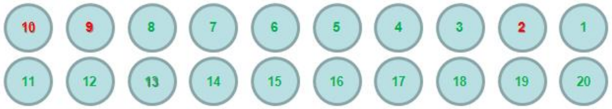


Note: lower values of R^2 for T1000 as compared to IM7

Results & Discussion

COPVs

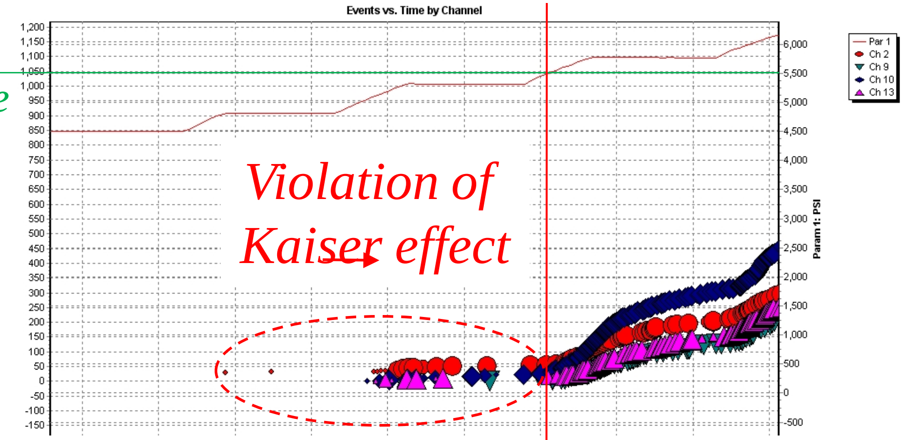
WSTF Area 270 Test, Week 1, T1000 COPVs (General Dynamics)



ca. 5500 psi

autofrettage pressure

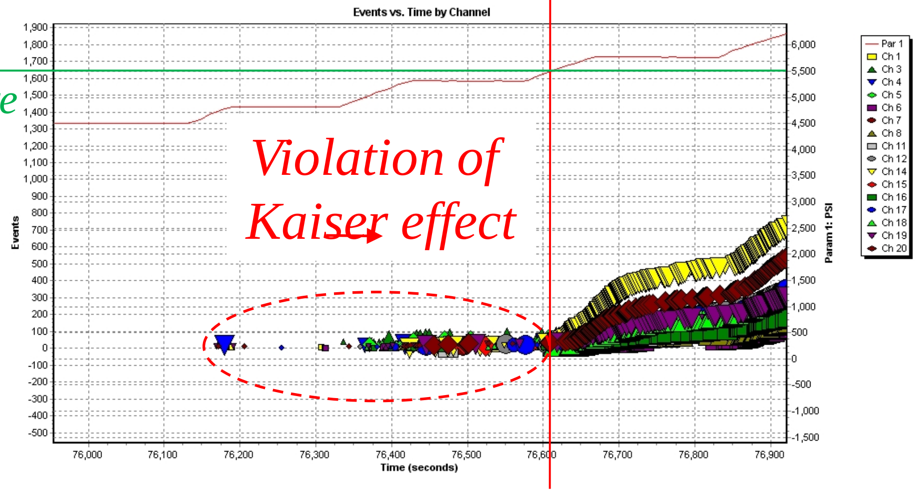
burst or impending burst vessel



ca. 5500 psi

autofrettage pressure

survivors



Acknowledgments

Shawn Arnette (TRI, Austin, TX)

Supplying K/Ep test specimens & tabbing suggestions

S. Leigh Phoenix (Cornell University, Ithaca, NY)

Supplying C/Ep test specimens & tabbing suggestions

Paul Spencer, Brooks Wolle and Ben Gonzalez (WSTF-JSC)

Universal tensile tester set-up & tabbing

Ralph Lucero and Anthony Carden (WSTF-JSC)

COPV-level tests and AE data acquisition

Office of Safety and Mission Assurance (NASA, Washington, DC)

Support to develop AE methods specific to K/Ep and C/Ep

(NDE of composite micromechanics)

Nondestructive Residual Stress Analysis in Pipes and Pressure Vessels

Joshua E. Jackson
Generation 2 Materials Technology LLC
www.g2mt.com

Composite Conference 2012

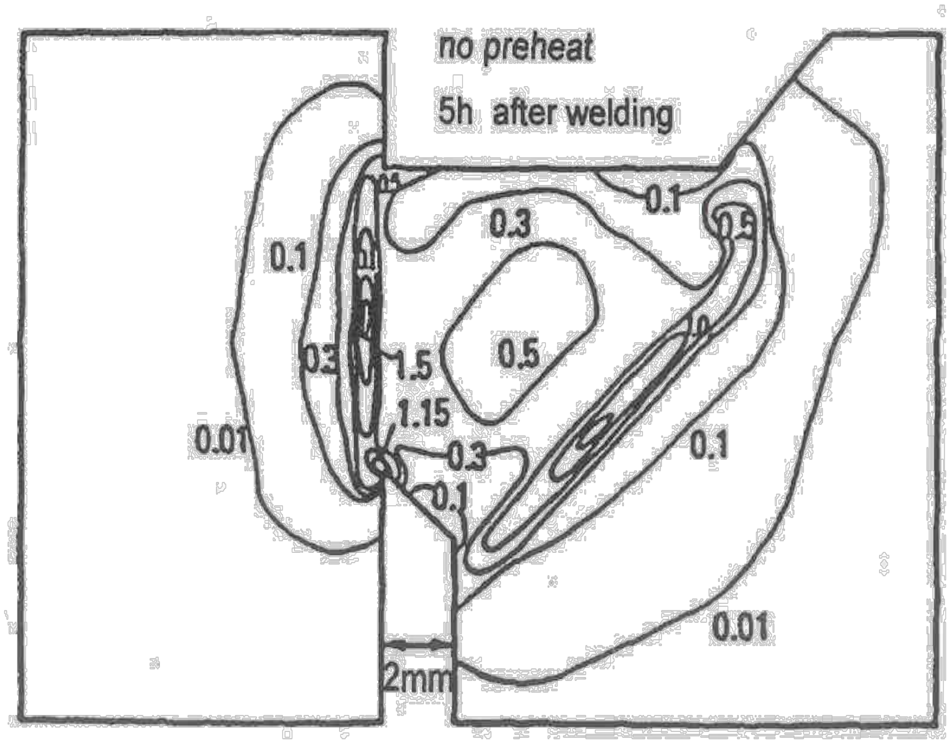
August 15, 2012

Outline

- Overview of Past Work
- Background
- R&D
- Residual Stress Characterization
- Future Plans
- Near Term and Future Tasks

Overview of Past Work

- In-Situ Hydrogen Analysis in Weldments: Novel NDE for Weld Inspection
- Direct Correlation Between Hydrogen Sensor and Residual Stress Sensor



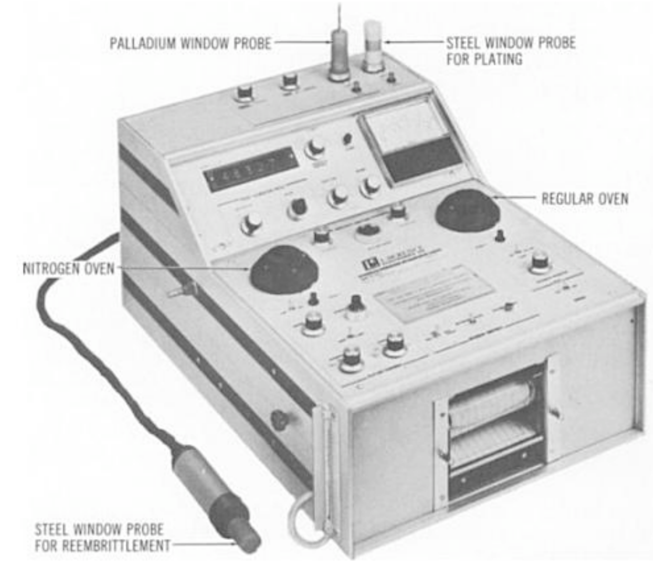
The power of hydrogen

Hydrogen has an immense effect on materials:

Field Hydrogen Sensors

- Types of Hydrogen Sensors
  - Hydrogen Permeation Sensors (Electrochemical, Vacuum, Pressure)
  - Hydrogen Damage Sensors

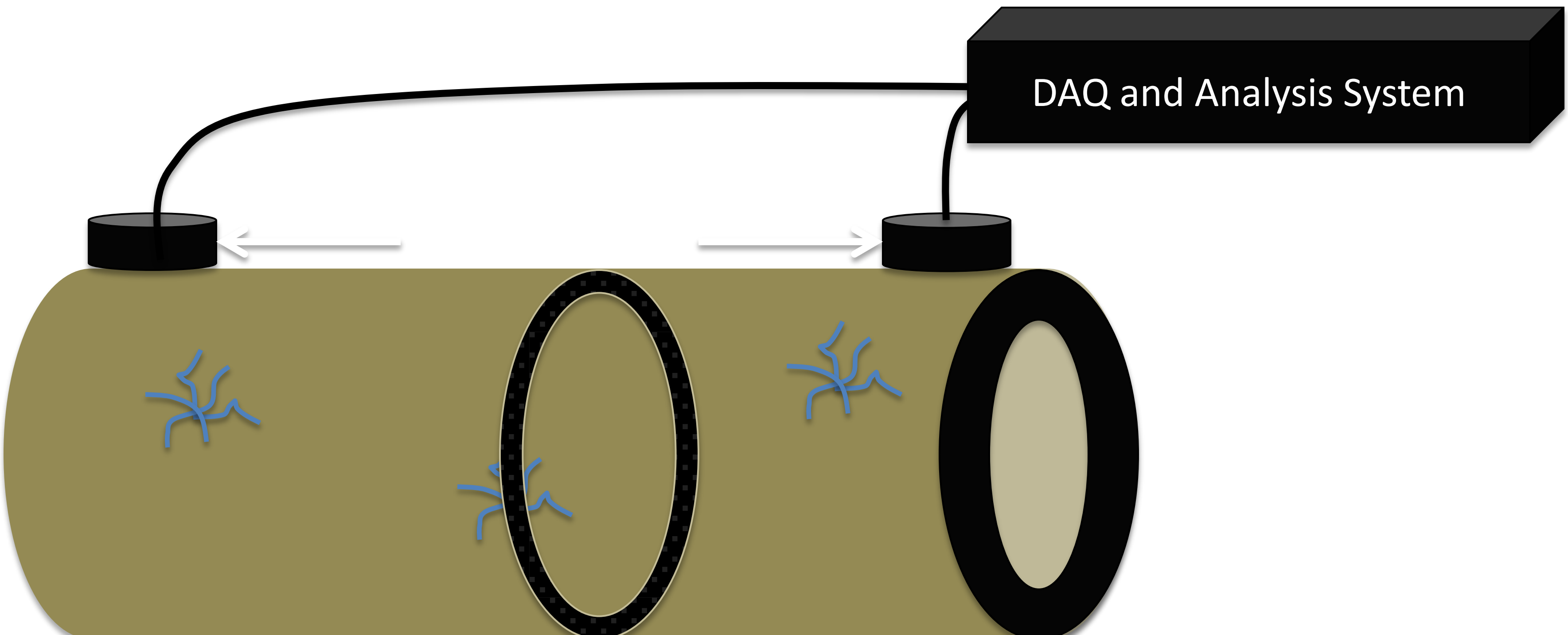
Left: MIS sensor chip containing four individual hydrogen sensors. The sensing areas are the pie-shaped segments. Right: The MIS sensor chip shown alongside a dime for scale. https://share.sandia.gov/8700/projects/content.ph



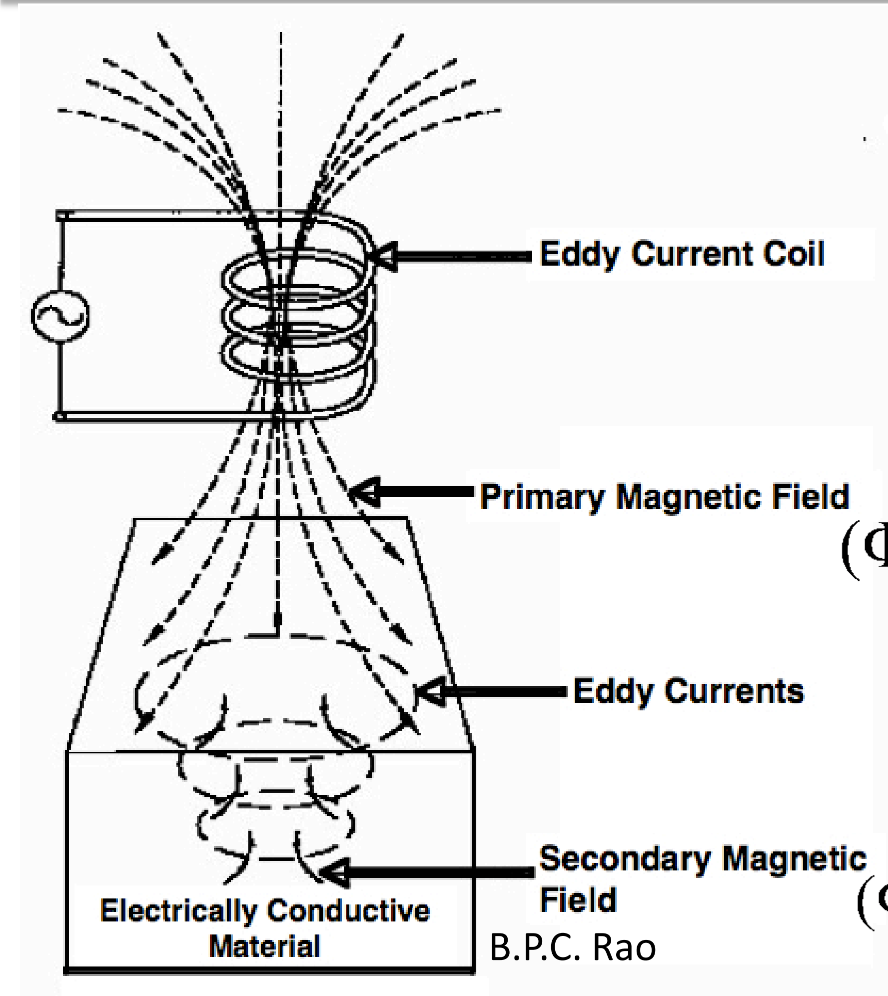
REFERENCE: Lawrence, S. C., Jr., "**Hydrogen Detection Gage**," *Hydrogen Embrittlement Testing, ASTM STP 543*, American Society for Testing and Materials, 1974, pp. 83–105.

Hydrogen Damage Sensors

- Detect hydrogen damage in the form of cracks, blisters, deformities



Electromagnetic Hydrogen Sensors



(Φ_P)

(Φ_S)

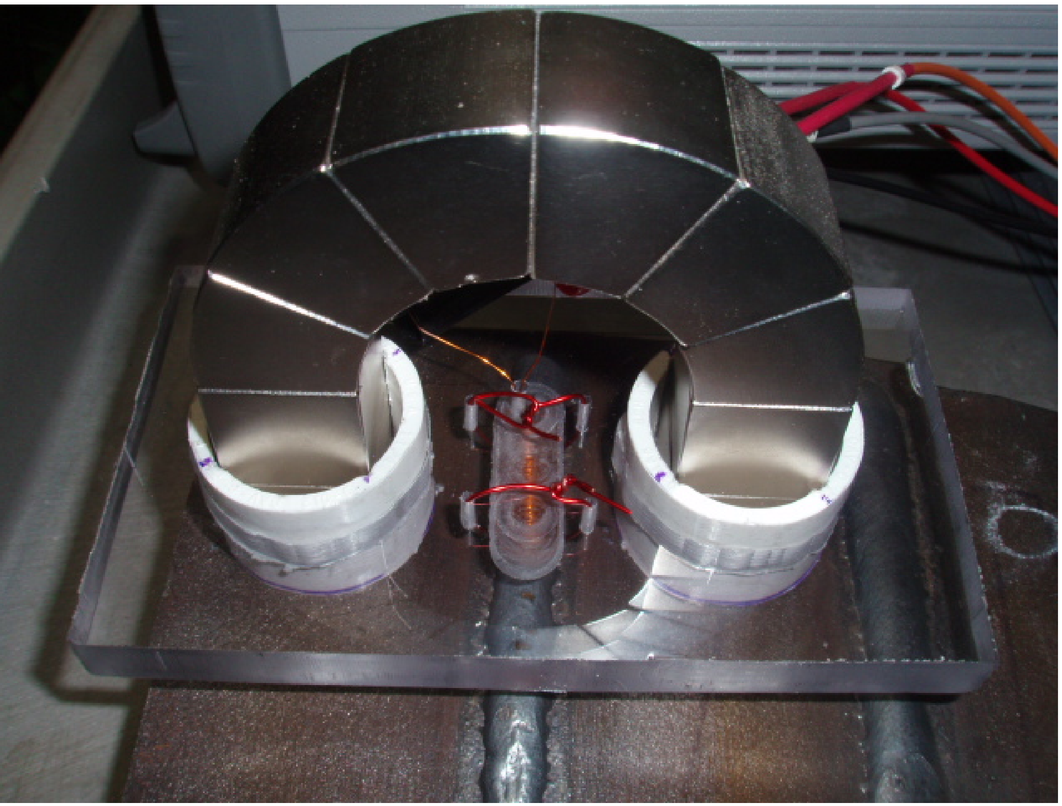
$$\underbrace{\int E \bullet dl}_{\textbf{EMF}} = - \underbrace{\frac{d\phi}{dt}}_{\textbf{Flux}}$$

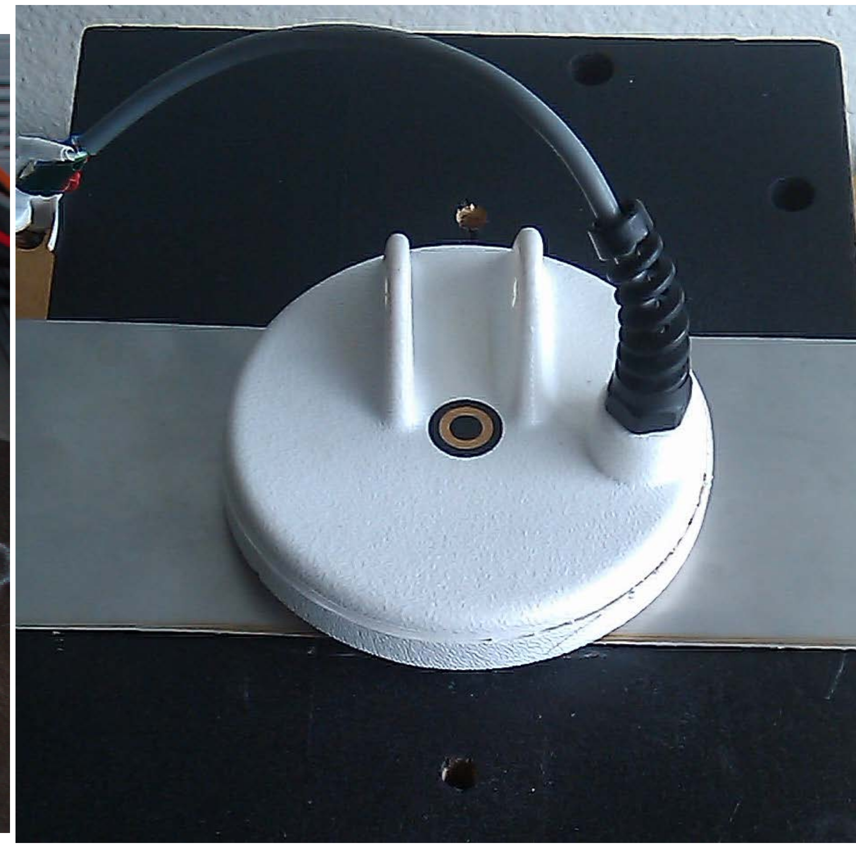
$$V_P = -N_P \left[\frac{d\Phi_E}{dt} \right]$$

$$\boxed{\Phi_E = \Phi_P - \Phi_S}$$

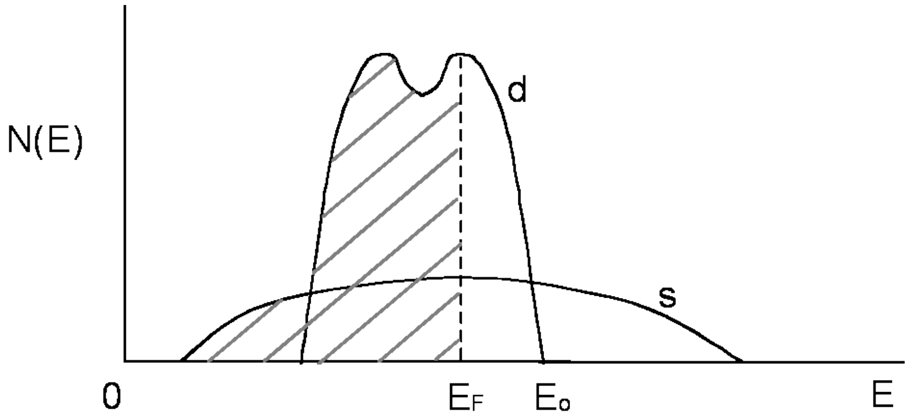
$$Z = \sqrt{\left(\omega L - \frac{1}{\omega C}\right)^2 + R^2}$$

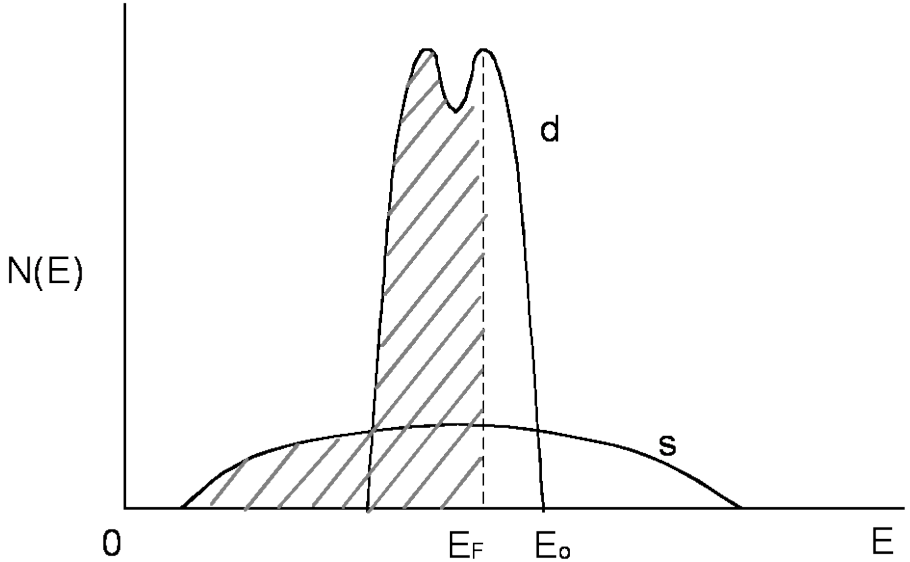
Electromagnetic Hydrogen Sensors



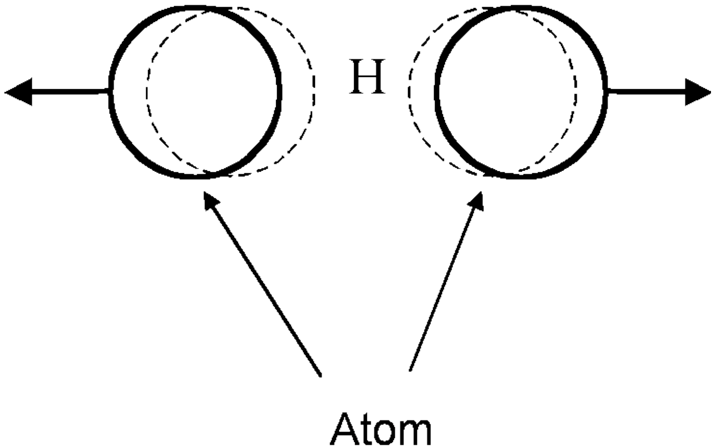


Electronic Nature of Hydrogen



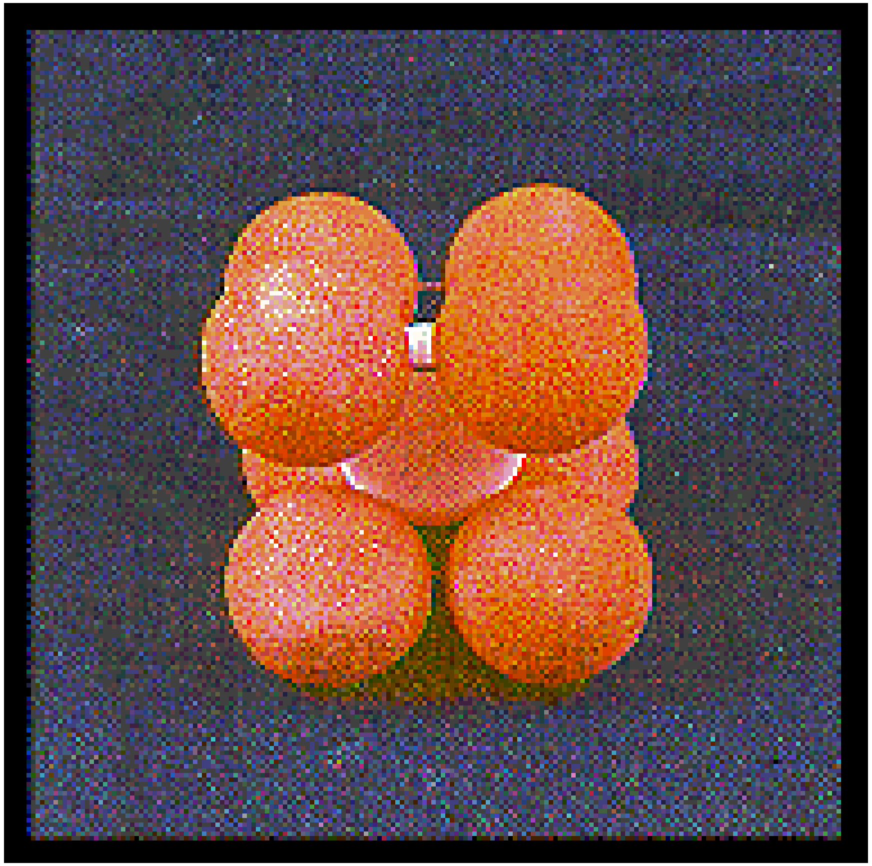


$$E_F = \frac{\hbar^2 k^2}{2m_e}$$



$$m_e \propto \frac{1}{(d^2E/dk^2)}$$

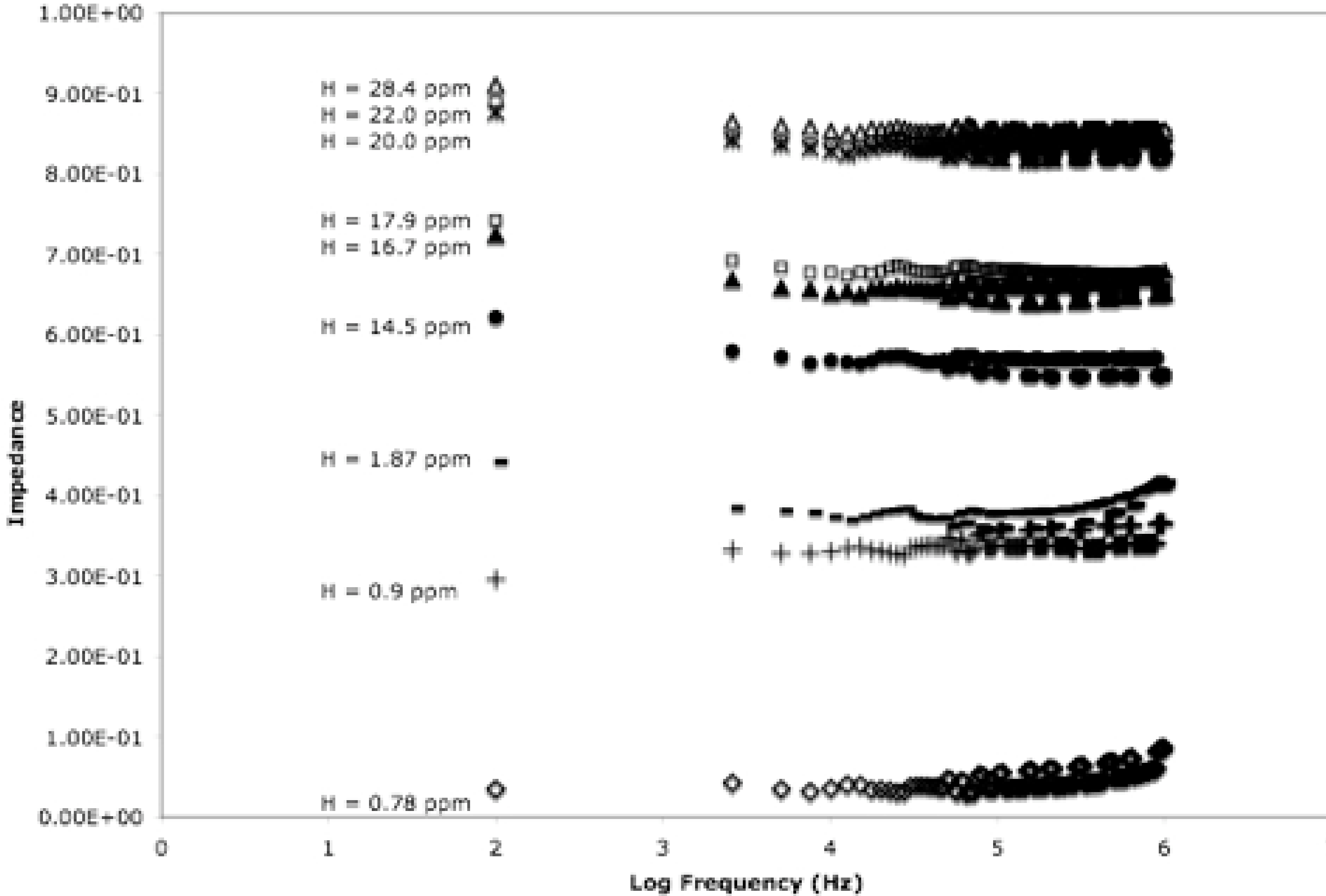
Electronic Nature of Hydrogen



	Tetra-hedral	Octa-hedral
BCC-Iron Interstitial Hole Size	0.36 Å	0.19 Å
H-Filled Interstitial Hole Size	0.87 Å	0.66 Å

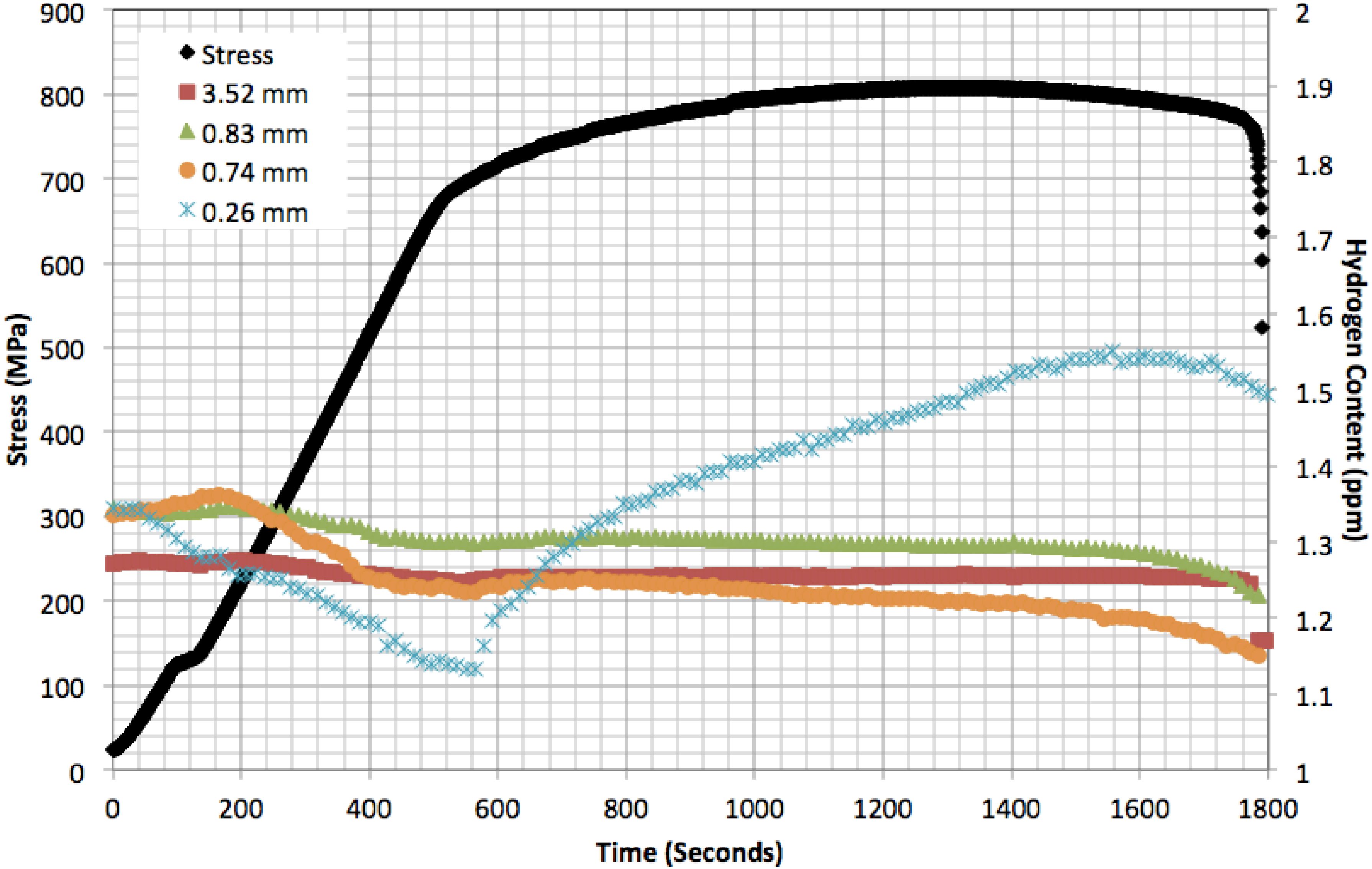
Ref:[Fukai, 1993]

Electromagnetic Hydrogen Measurements on Pipeline Steel



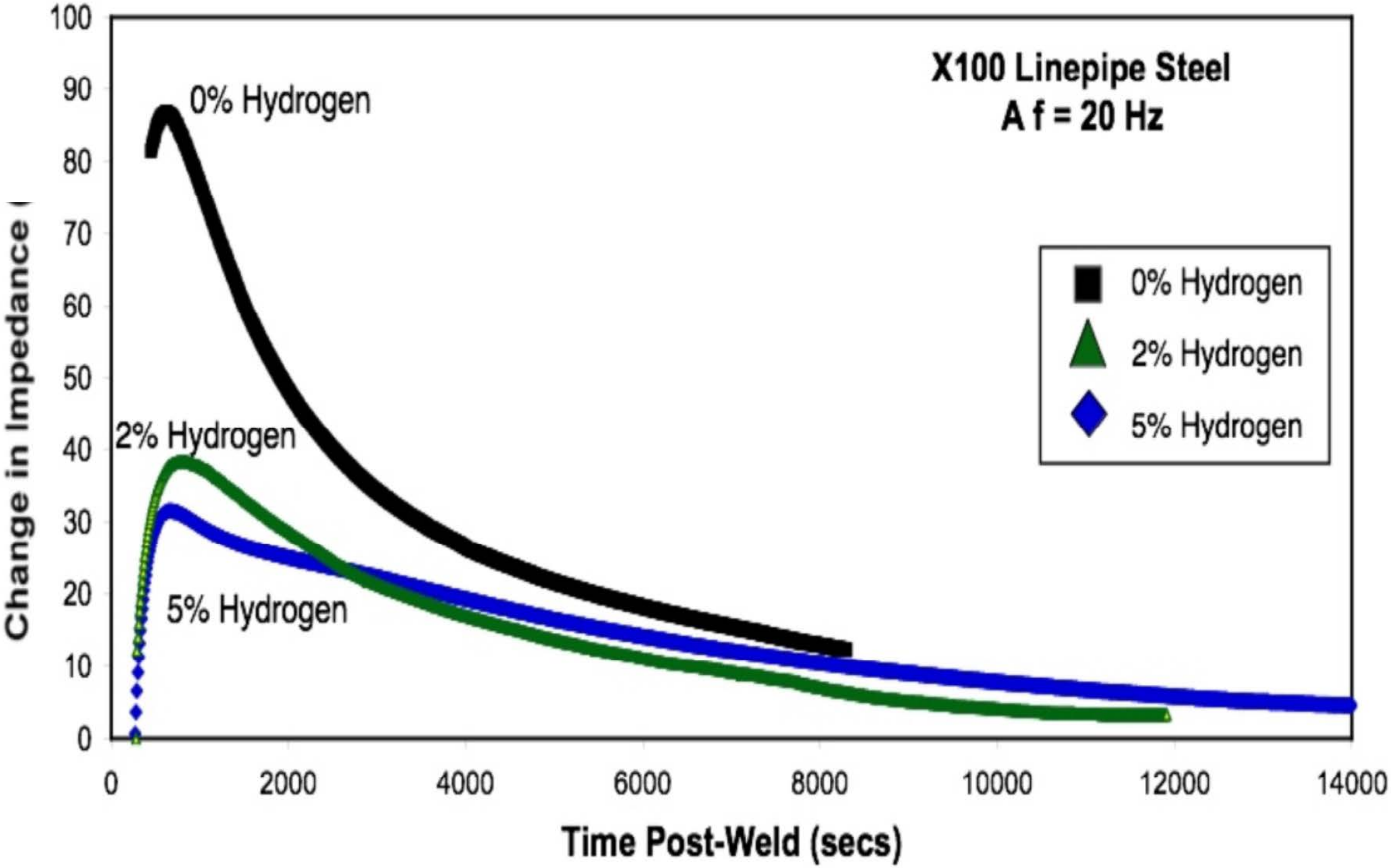
Lasseigne, 2006

Real-Time Electromagnetic Hydrogen Sensors

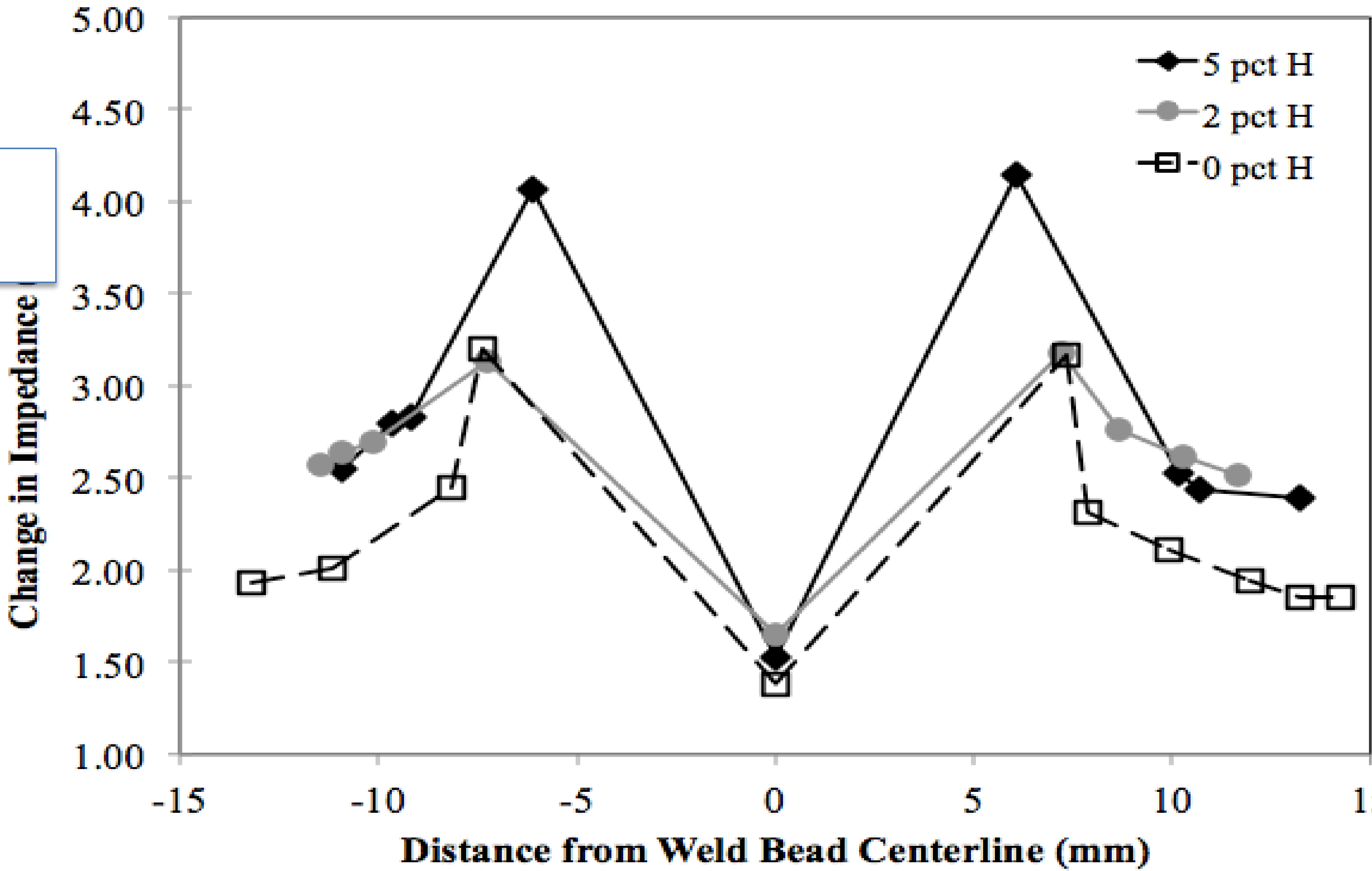


Lassaigne et al. 2011

Real-Time Electromagnetic Weld Hydrogen Evolution



Real-Time Electromagnetic Weld Hydrogen Sensor



Residual Stress Sensor Background

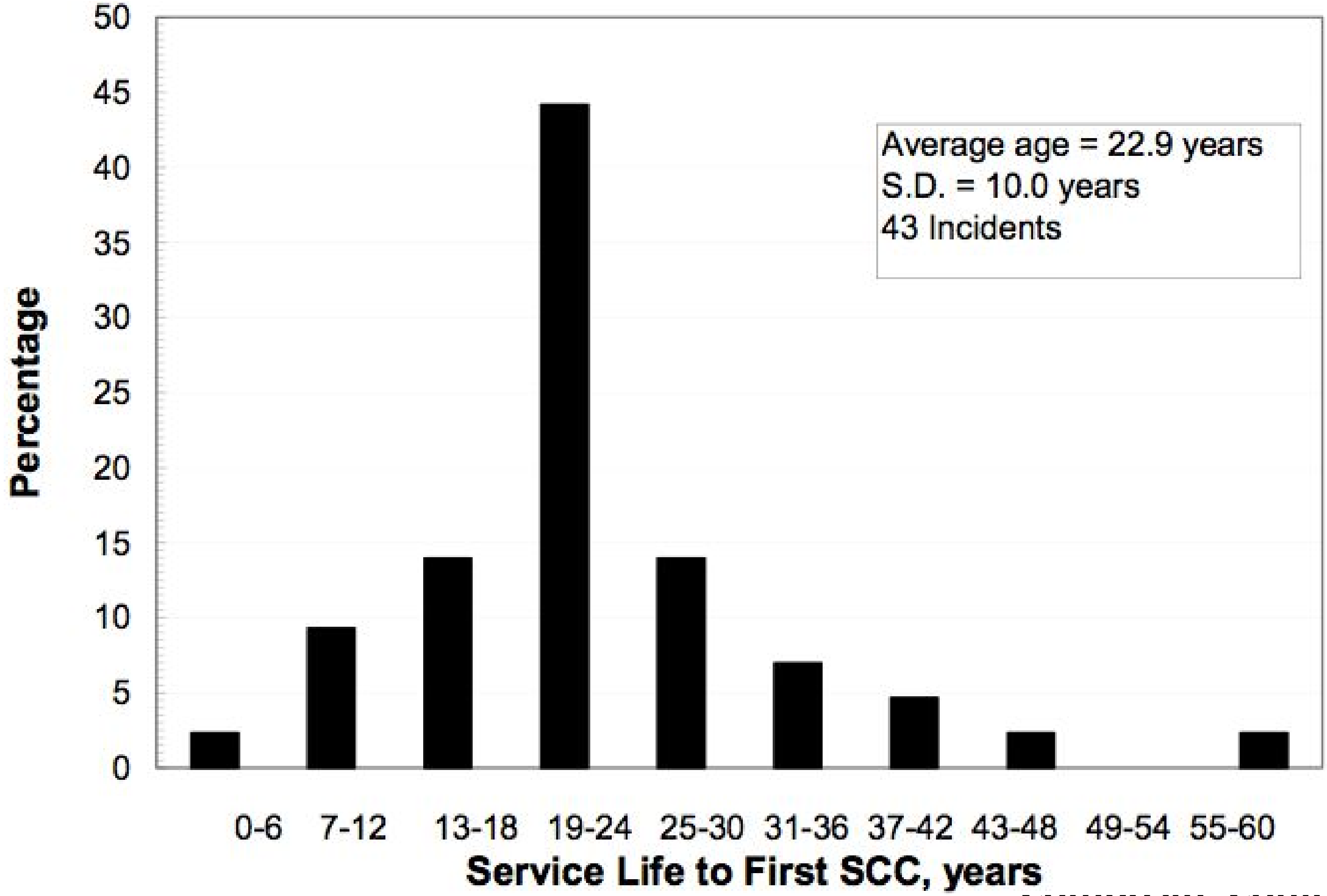
- Mechanical damage is the leading cause of pipeline failures.
- Mechanical damage exhibits a variety of features:
  - Denting
  - Removal of metal surface
  - Cold-work of the material below the surface
  - Cracking when the pipe is re-rounded by internal pressure
  - Residual stresses and strains due to plastic deformation
  - Coating damage

Background

- Mechanical damage occurs at different periods during construction of pipelines.
  - Wrinkles, ripples, or buckles commonly occur during laying and bending of the pipelines.
  - Dents, surface damage, and coating damage more often arise during removal and movement of third-party construction equipment [Maxey, 1986].

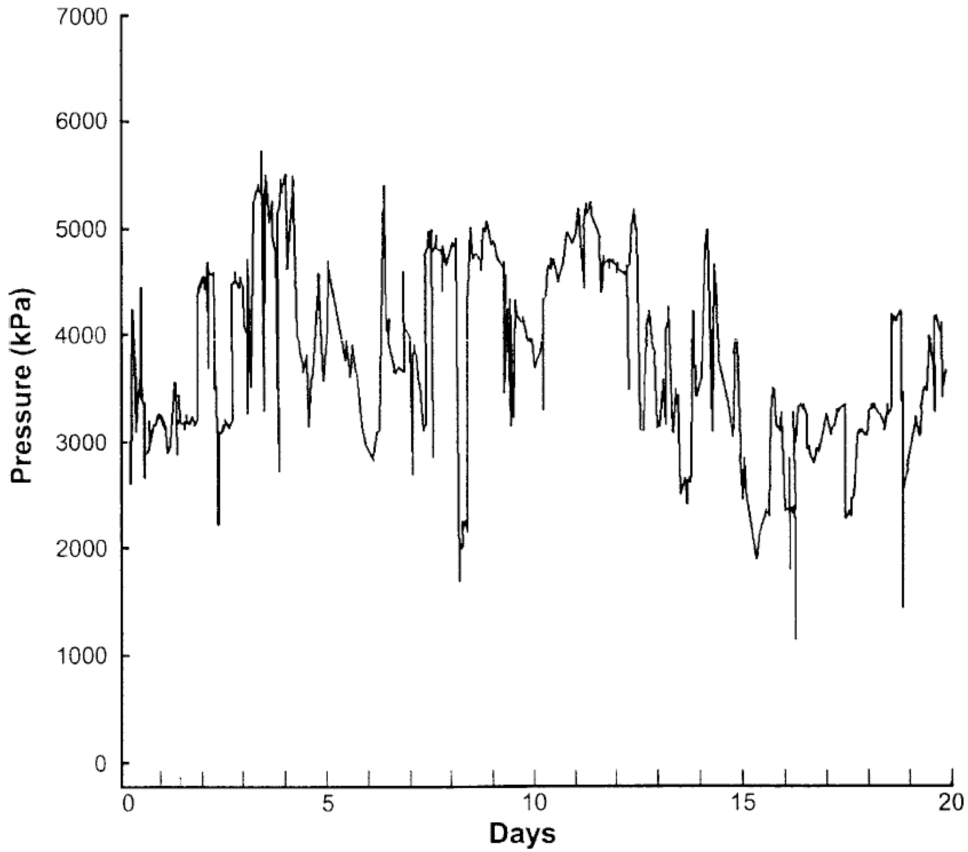
Pipelines Background

- Mechanical damage can lead to immediate failure, but otherwise results in a delayed or time-dependent failure.



Pipelines Background

- The mechanical damage and residual stresses lower the overall fatigue strength of the steel and weldments.
- The size and shape of the flaw determines the level of stress necessary for crack initiation [Vuherer et al., 2007].



Magnetic Effects on Pipeline Corrosion

- MFL and other practices leave large magnetic fields on pipelines (often up to 1 Tesla)
- Magnetocorrosion is the increase in corrosion observed under high magnetic fields

Existing Damage Inspection Practices

- The current practices for inspection of mechanical damage typically involves the use of inline inspection data from caliper tools followed by exterior inspection with UT and caliper tools to measure the angle of the dent – ***NOT EFFECTIVE!***

	Plain dents		Dents at welds	Dents with cracks or gouges	Dents with corrosion
	Constrained	Unconstrained			
ASME B31.8	Up to 6% OD or 6% strain		Up to 2% OD or 4% max strain for ductile welds. No safe limit for brittle welds	No safe limit	Up to 6% OD for dent and metal loss, as per corrosion criterion
API 1156	No limit provided rock remains in place	Up to 6% OD. >2% requires a fatigue assessment	Up to 2% OD	Not allowed	Not considered
EPRG	Up to 7% at a hoop stress of 72% SMYS		Not allowed	Not allowed	Not allowed
PDAM	Up to 7% of pipe diameter		Not allowed	Assess as dent and defect combination	
Z662	Up to 6 mm for <102 mm OD Up to 6% for >102 mm OD		Not allowed	Not allowed	Not allowed

Electromagnetic Residual Stress Sensor

- Quantitative non-destructive technology to measure through-thickness residual stress (strain) associated with dent damage.
- Without removal of structural coatings.
- Data will be combined with computer models and databases to **provide improved life prediction** for pipeline integrity assessment.
- Phase 3: development of a smart pig version.
- Can accurately and rapidly assess damage where existing tests miss it, and allow continued use in circumstances that would currently require replacement or repair.

Next Generation of Mechanical Damage Assessment

- G2MT is developing an electronic property electromagnetic sensor to measure residual stress

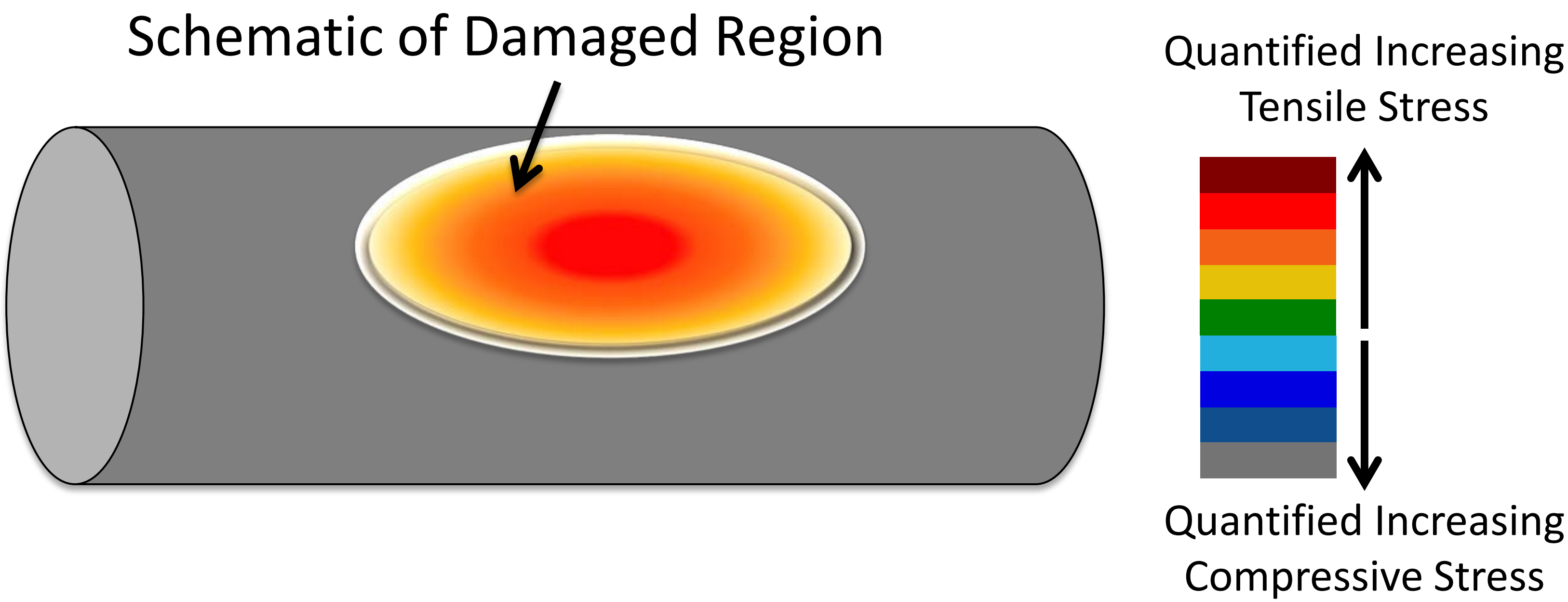
$$S = \left(\pm\frac{k}{e}\right)(27.1)\left(r+\frac{3}{2}\right)\left(\frac{m_e}{h^2}\right)\left(kTn^{\left(-\frac{2}{3}\right)}\right)$$

- S Electronic Property Measurement
- r Scattering parameter
- h Planck constant
- k Boltzmann's constant
- n Free electron concentration
- m_e Effective mass (m*)

$$m_e = \frac{\hbar^2}{\left(d^2E/dk^2\right)}$$

The Next Generation of Mechanical Damage Assessment

- Focus on overall residual stress in the steel pipeline to determine the severity of mechanical damage



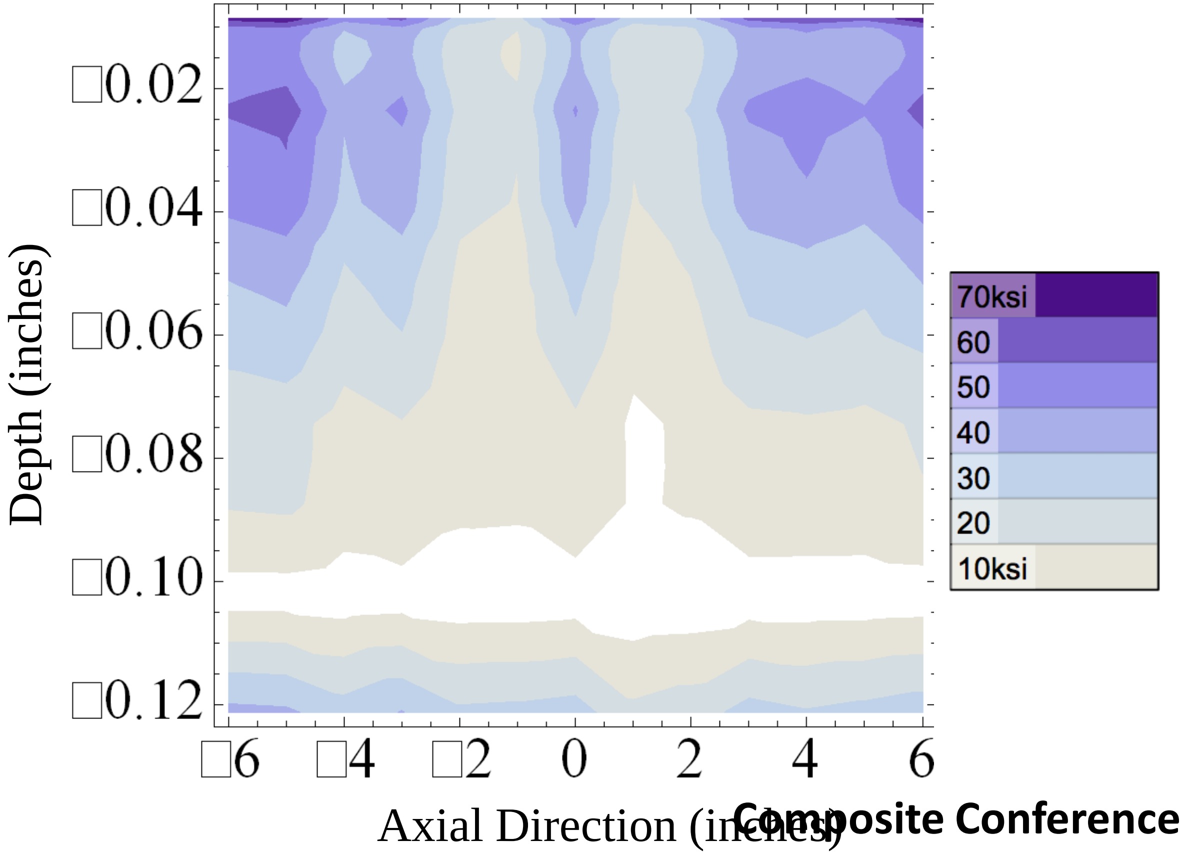
- These residual stresses form the basis for nucleation and growth of cracks.

Residual Stress Characterization

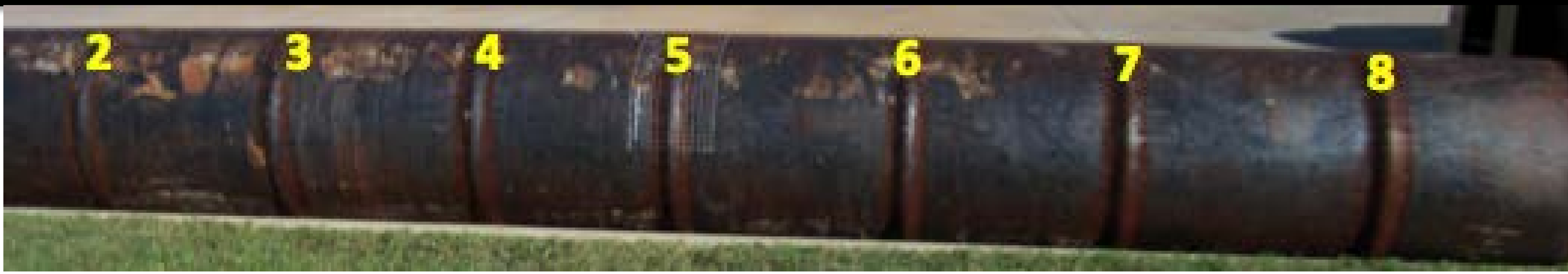
- Need to account for variables in trad. residual stress testing:
  - Variance in surface versus through thickness residual stress measurements and measurement techniques
  - Variance between results from different testing labs and techniques (e.g. XRD, neutron diffraction, rosettes, FEA)

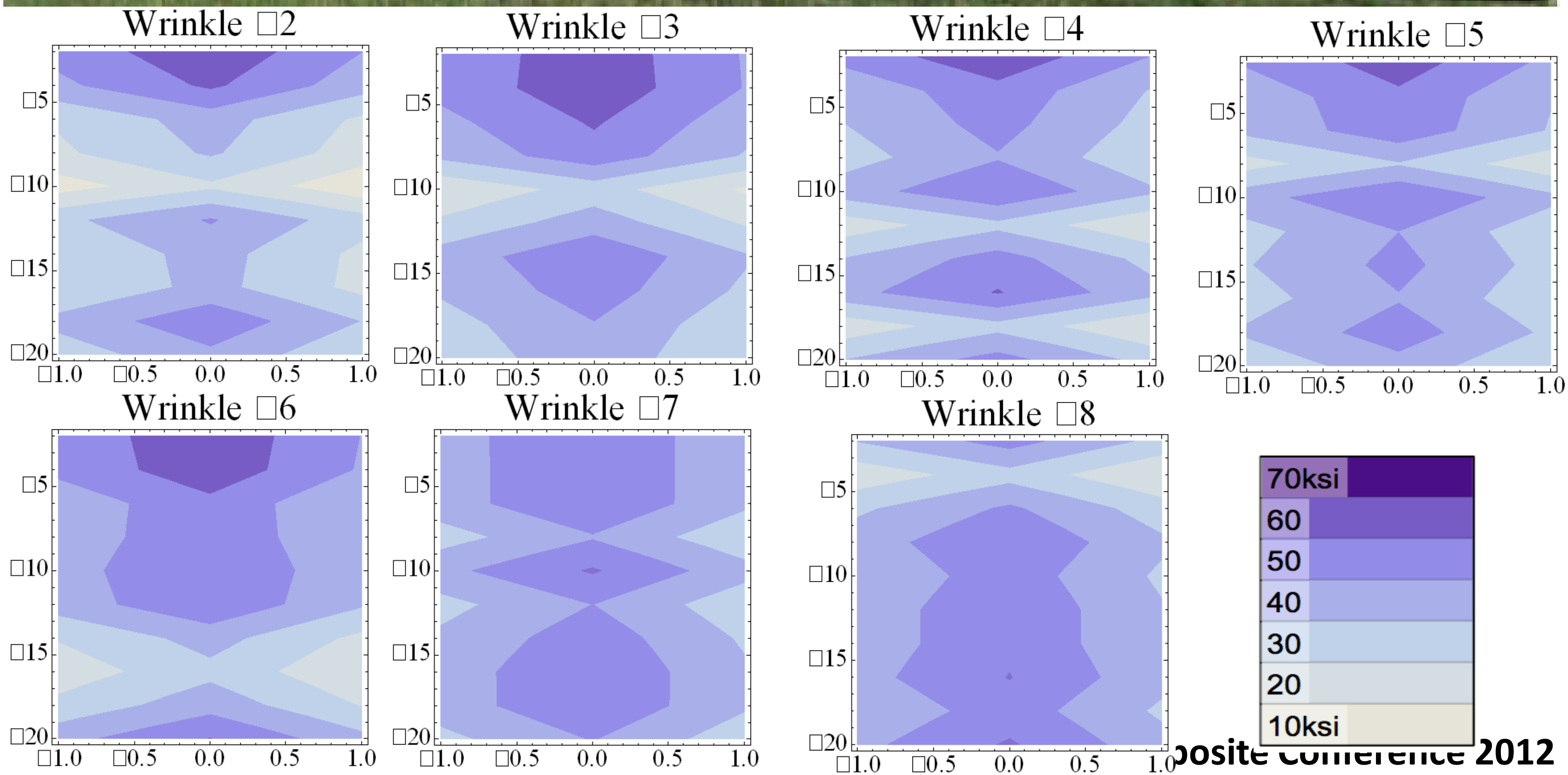
- G2MT is using multiple methods to characterize residual stresses

PIPELINE MECHANICAL DAMAGE ASSESSMENT



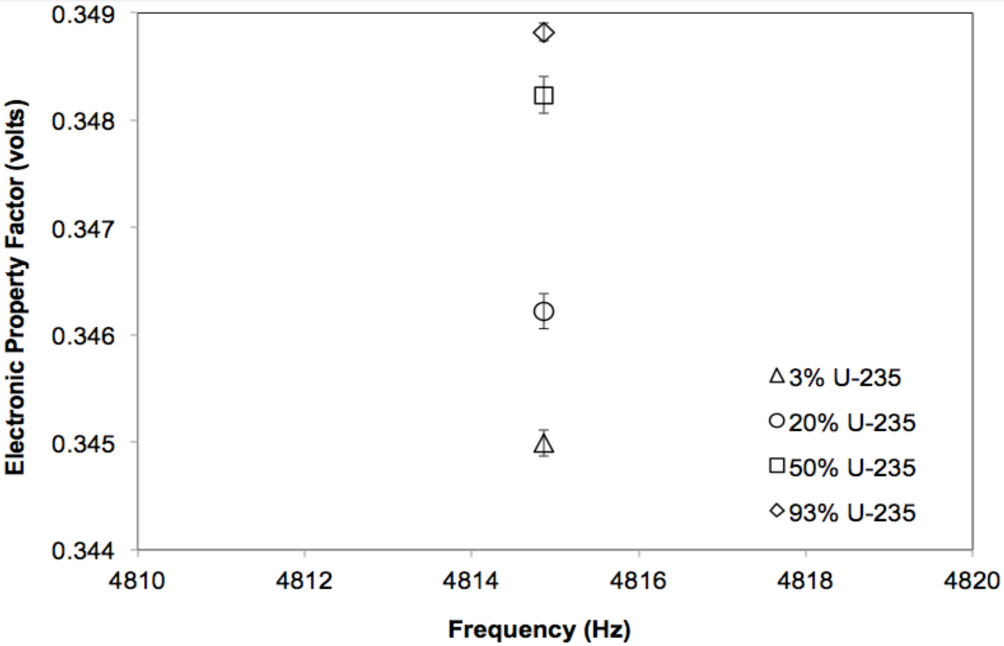
PIPELINE MECHANICAL DAMAGE ASSESSMENT



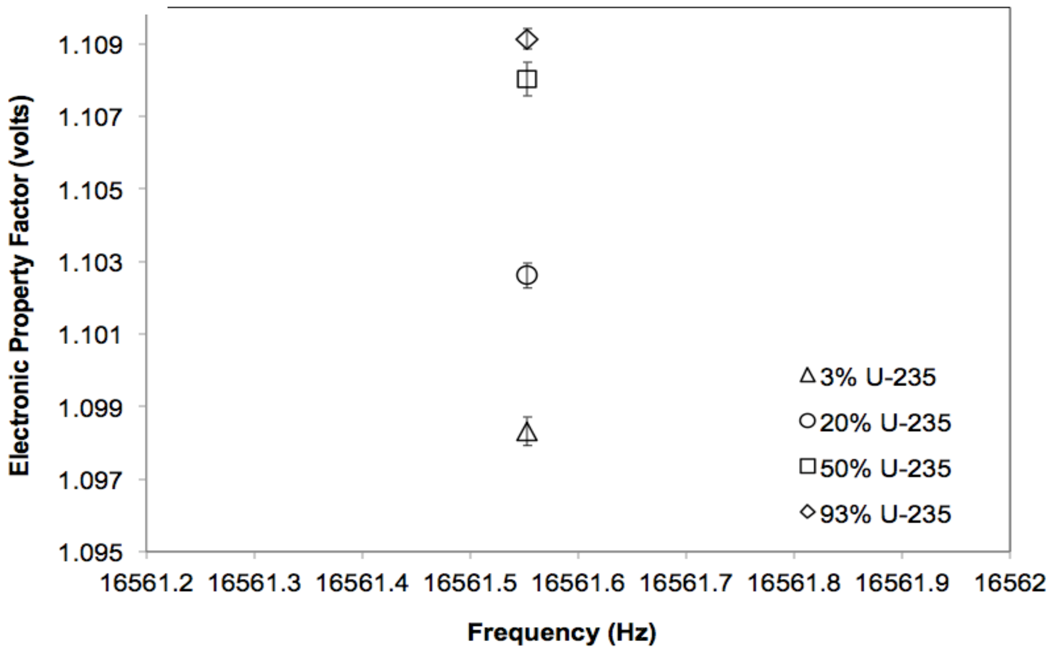


RESIDUAL STRESS SENSOR FOR CONCRETE AND REBAR

ISOTOPE SENSOR



Distinguishing between 'identical' isotope samples



High Temperature Hydrogen Attack

SA204 Grade B, C-0.5Mo

No Cracking

Surface Decarburization

0.055 Inches

~10% Depth of Cracking

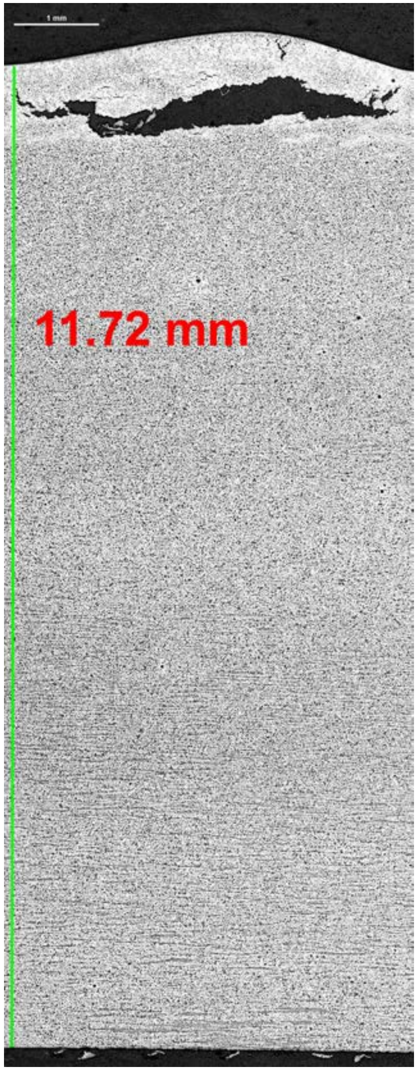
0.100 Inches

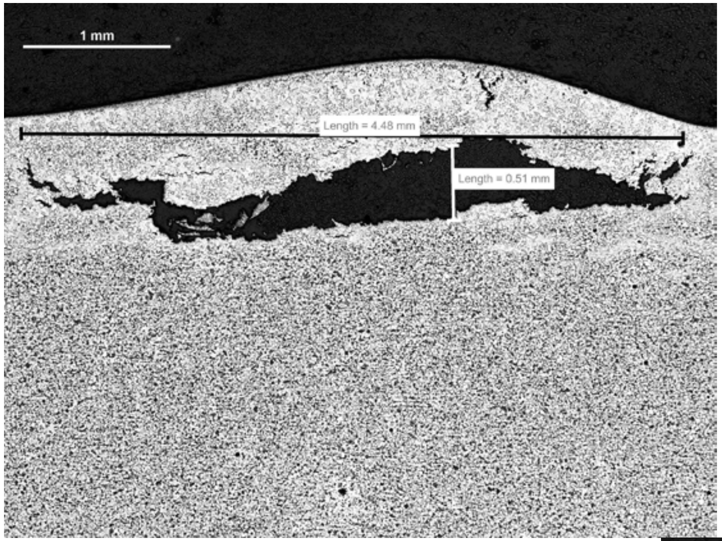
~20% Depth of Cracking

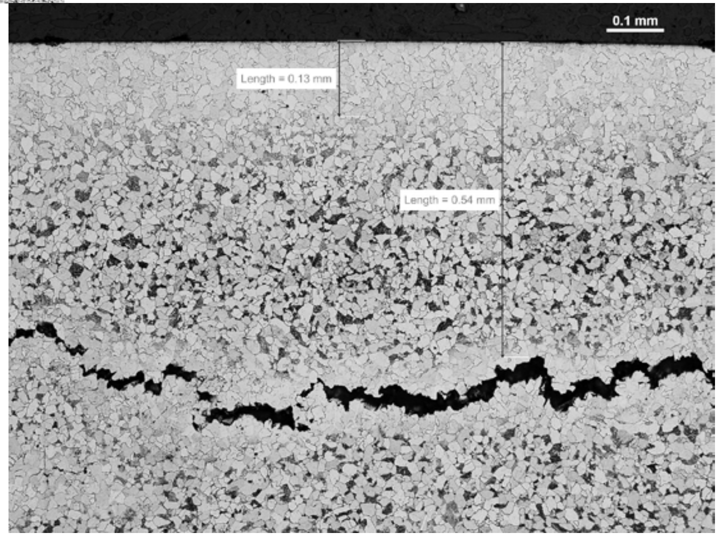
- **Sample thickness ~ 0.49 inches**

Samples provided by Lloyds Register

Depth of HTHA Damage 0.055 Inches

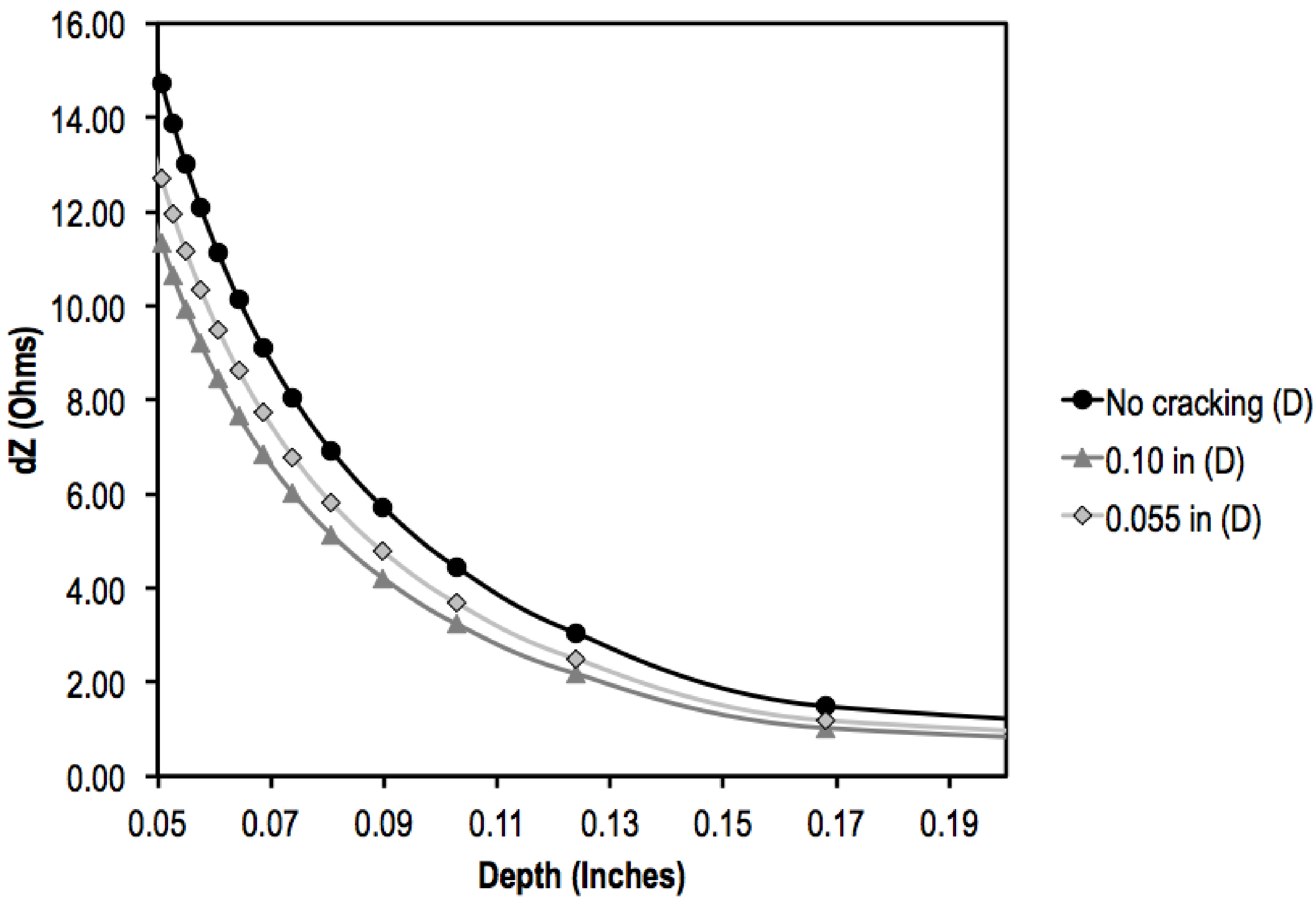




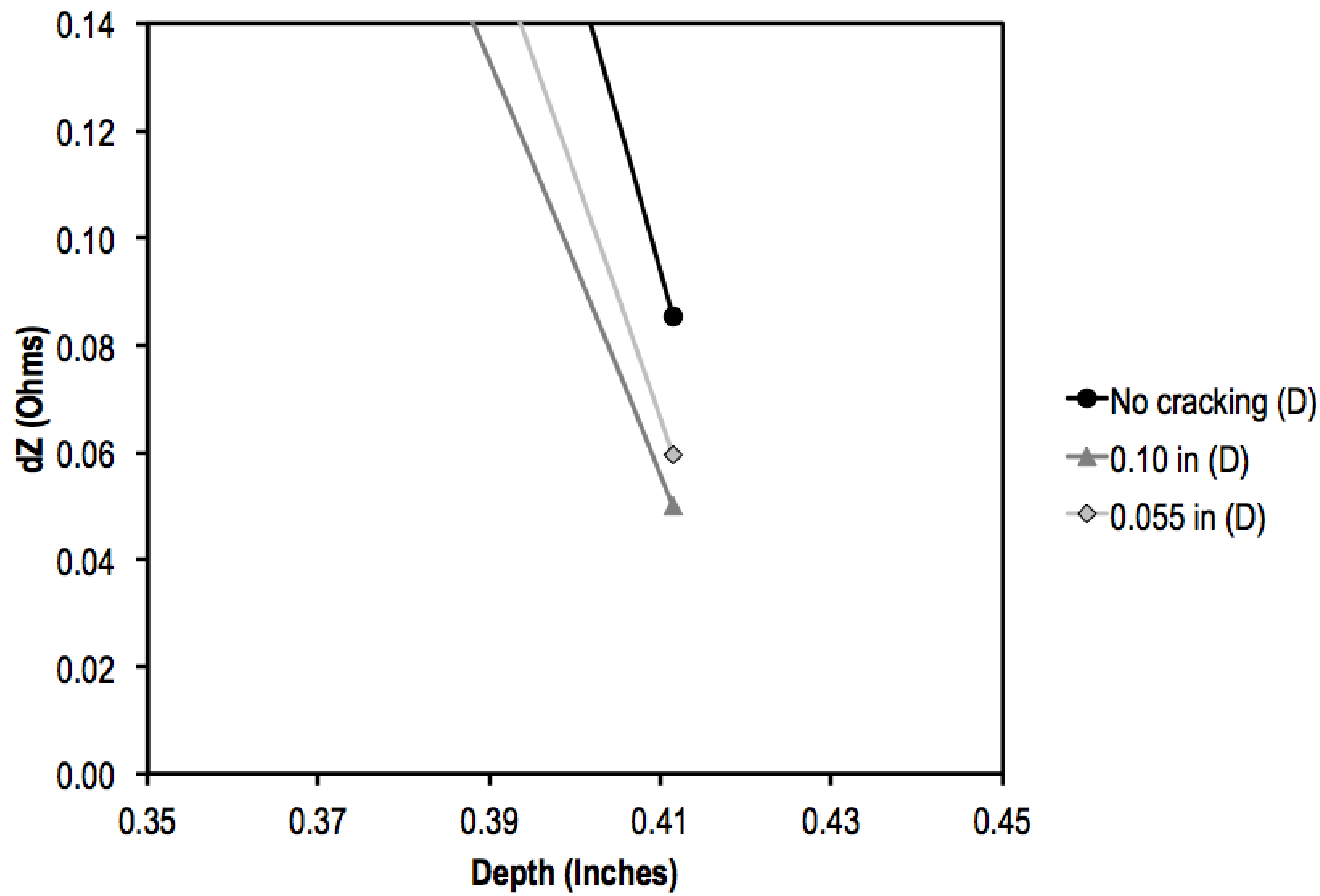


Composite Conference 2012

Electromagnetic HTHA Measurements

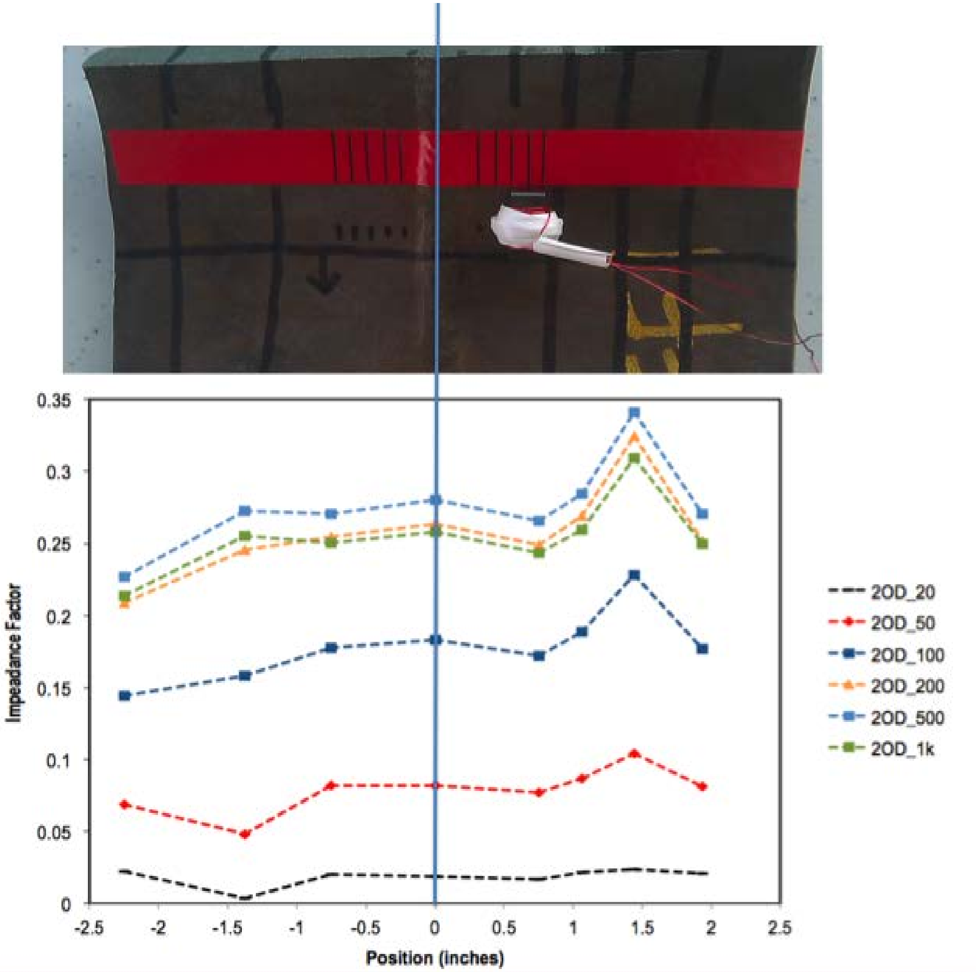


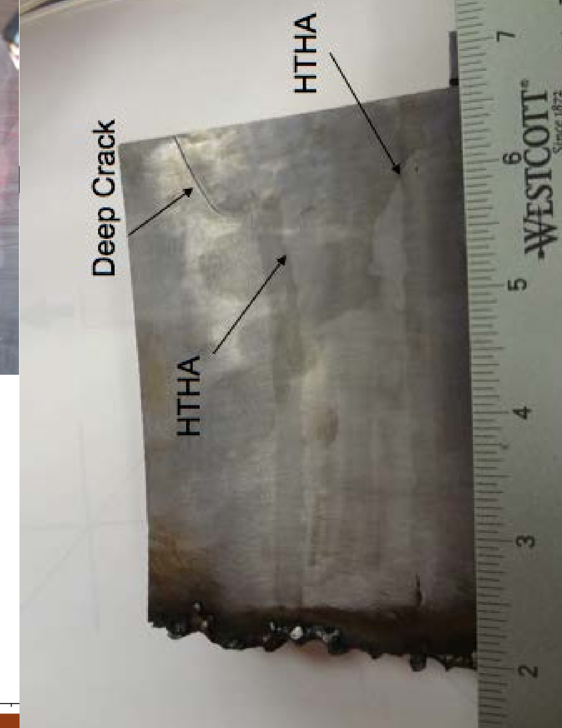
Electromagnetic HTHA Measurements



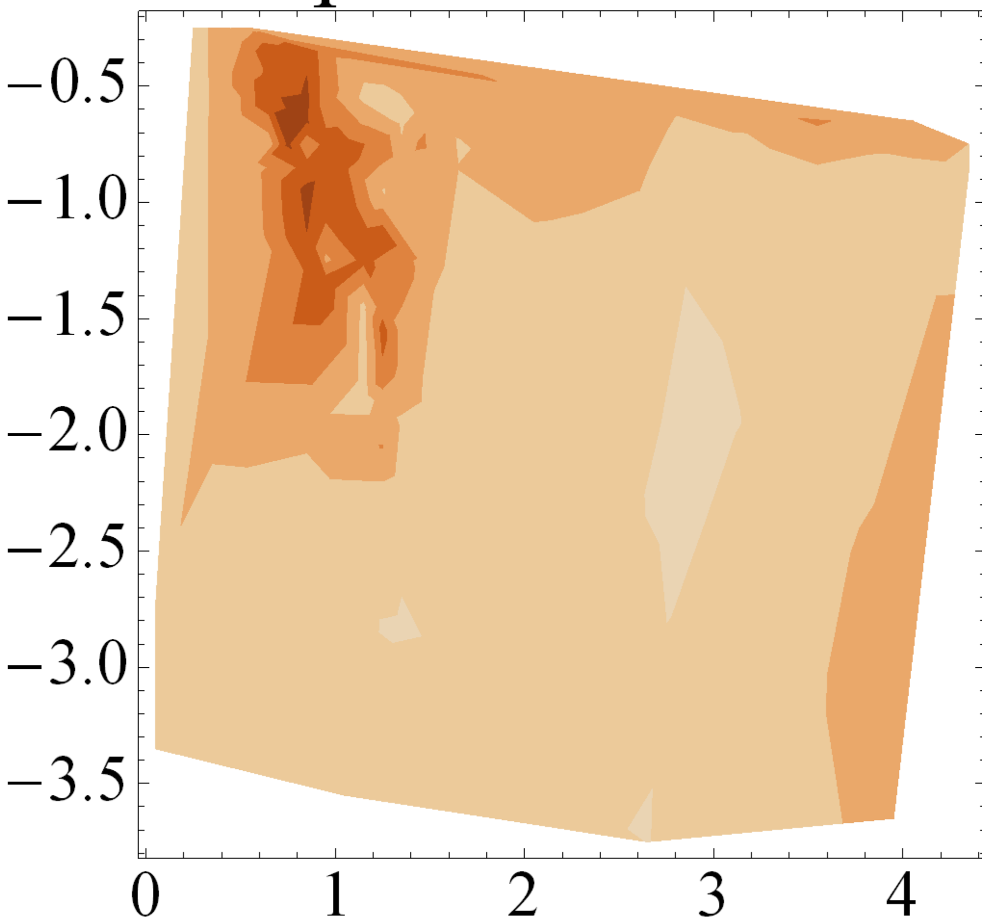
HIGH TEMPERATURE HYDROGEN ATTACK

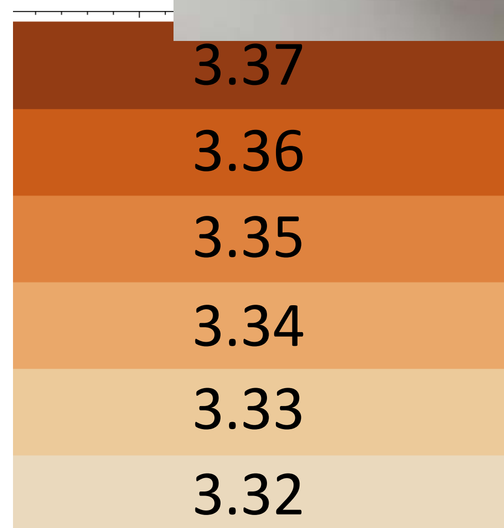
http://webwormcpt.blogspot.com/2007/09/high-temperature-hydrogen-attack-in.html





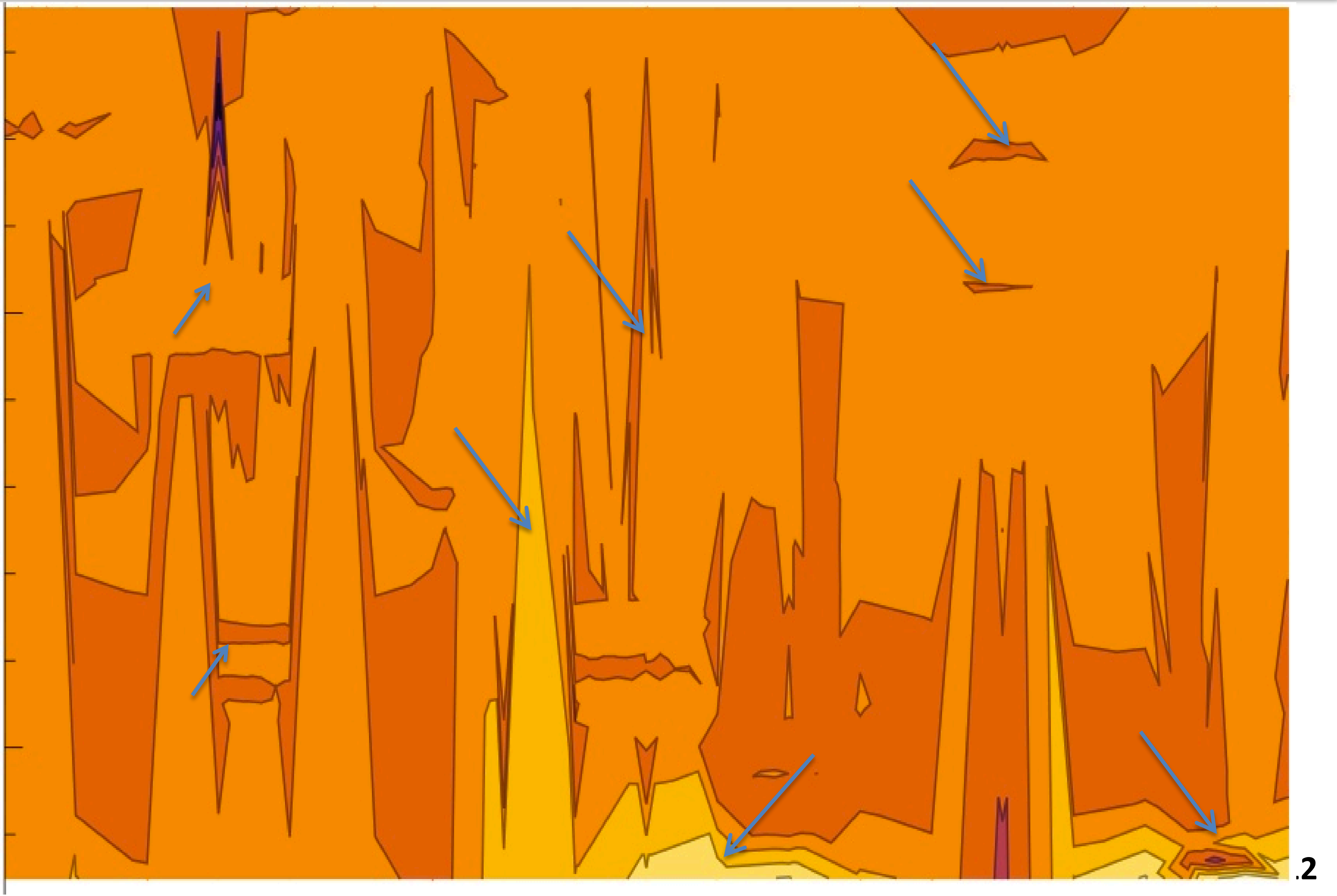
depth = 0.27 mm





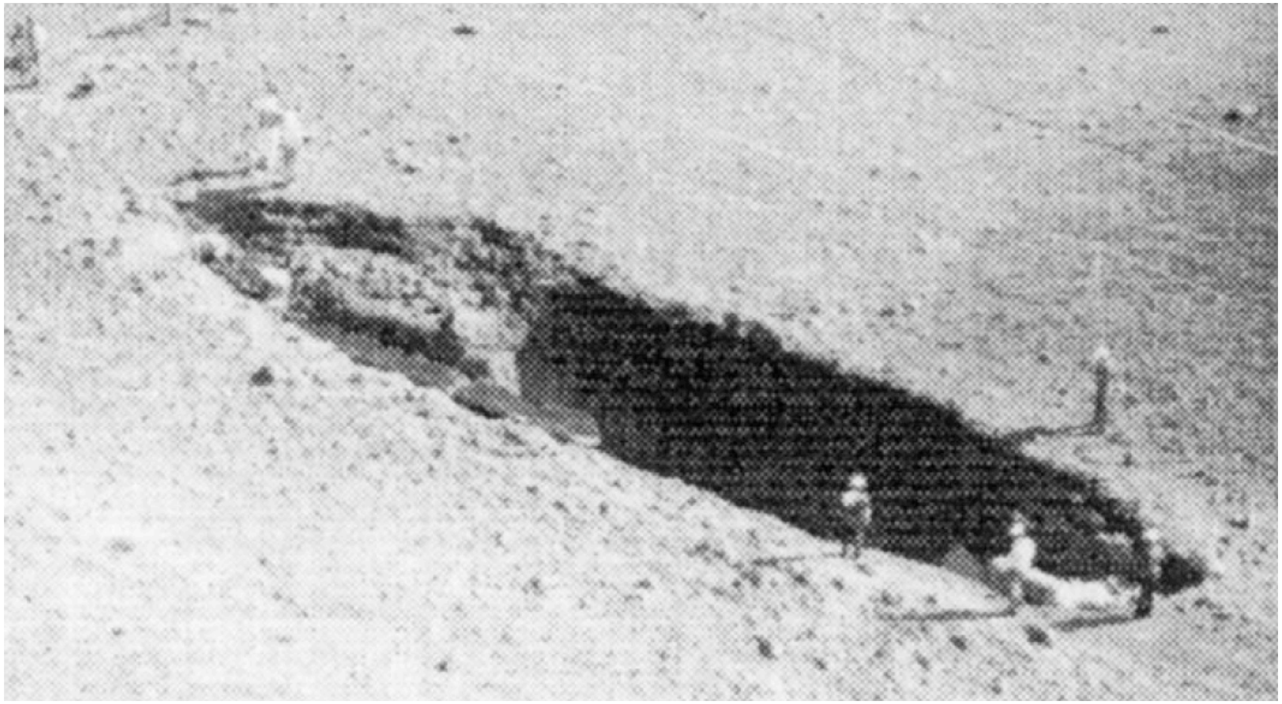
Measurement uncertainty is ± 0.00107

COPV Residual Stress Analysis



Conclusions

- G2MT is moving forward rapidly with development of the electromagnetic residual stress technology
- Collaboration and partnerships will further improve the effectiveness and reach of this technology



Performance of Composite Overwrapped Pressure Vessels (COPV) Commonly Used In Transportation

Application of Model Acoustic Emission (MAE) For Assessing Fiber Breakage & Structural Damage

Mark Toughiry
DOT/PHMSA/Engineering & Research

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration

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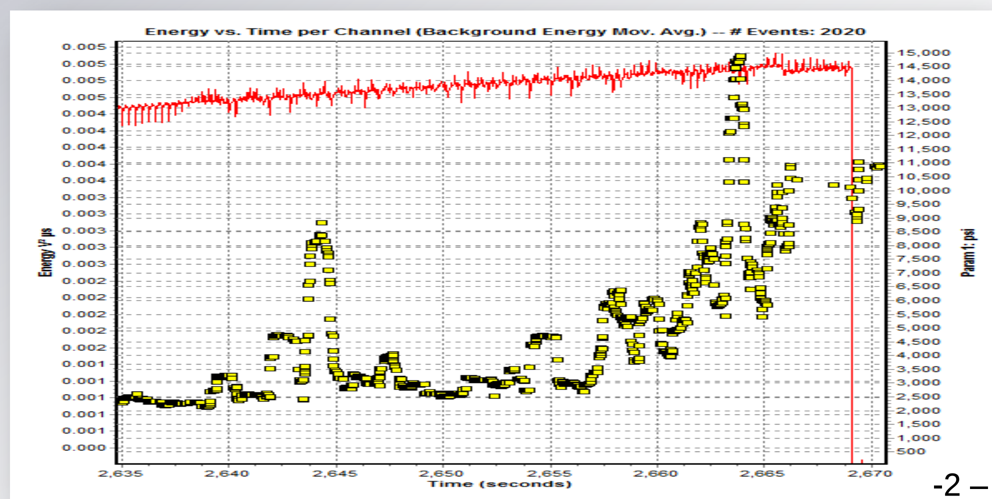


-Toughiry

COPV Usage Under DOT and UN Regulations

Background:

- The DOT composite cylinders or COPVs have been used in transportation of various compressed gases for over 25 years;
- DOT COPV are mainly authorized under special permits (SP) ;
- COPV are also authorized under United Nation Model Regulations.

COPV Standards Authorized by DOT

- DOT-FRP 1
- DOT-FRP 2
- DOT-CFFC
- ISO 11119-1
- ISO 11119-2
- ISO 11119-3
- ASME, Section X
- Special Permits – Similar design to above standards with larger volume and/or service pressure

COPV Standards Authorized Under UN Model Regulations & DOT

- ISO 11119-1
- ISO 11119-2
- ISO 11119-3
- New ISO Standards

In progress (e.g. ISO 11515)

Fiber Reinforced Plastic Fully Wrapped Composite Cylinder (FRP-1)

- Liner – Seamless Aluminum
- Shell – Glass Fiber
- Maximum water volume – 200 Lb (90 l)
- Maximum Service Pressure – 5,000 psi
- Limited service life – 15 years
- Safety factor (Min. burst/service pressure ratio) = 3.0

Fiber Reinforced Plastic Hopped Wrapped Composite Cylinder (DOT FRP-2)

- Liner – Seamless Aluminum
- Shell – Glass Fiber
- Maximum water volume – 200 Lb (90 l)
- Maximum Service Pressure – 5,000 psi
- Limited service life – 15 years
- Safety factor (Min. burst/service pressure ratio) = 3.0

Fully Wrapped Carbon-fiber Reinforced Aluminum Lined Cylinders (DOT-CFFC)

- Liner – Seamless Aluminum
- Shell – Carbon fiber and glass fiber reinforced plastic
- Maximum water volume – 200 Lb (90 l)
- Maximum Service Pressure – 5,000 psi
- Limited service life – 15 years
- Safety factor (Min. burst/service pressure ratio) = 3.4

Hooped Wrapped Metallic Liner-Composite Cylinder (ISO 11119-1)

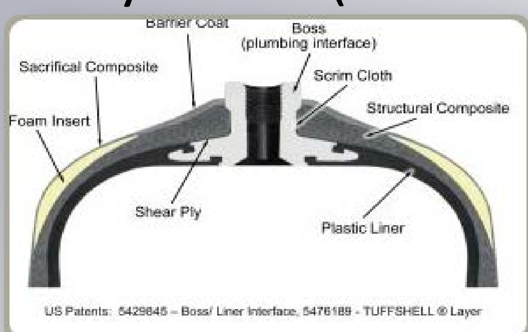
- Liner – Seamless metallic (Steel or Aluminum)
- Shell – Carbon fiber or aramid fiber or glass fiber
- Maximum water volume – 1,000 Lb (450 l)
- Maximum Service Pressure – 6,283 psi (433 bar)
- Limited service life – 15 years
- Safety factor (Min. burst/service pressure ratio) = 3

FULLY WRAPPED METALLIC LINER COMPOSITE CYLINDER (ISO 11119-2)

- Liner – Seamless metallic (Steel or Aluminum)
- Shell – Carbon fiber or aramid fiber or glass fiber
- Maximum water volume – 1,000 Lb (450 l)
- Maximum Service Pressure – 6,283 psi (433 bar)
- Limited service life – 15 years
- Safety factor (Min. burst/service pressure ratio) = 3

Fully Wrapped Polymer (Plastic) Liner-Composite Cylinder (ISO 11119-3)

- Liner – Non-load Bearing Polymer (plastic)
- Shell – Carbon fiber or aramid fiber or glass fiber
- Maximum water volume – 1,000 Lb (450 l)
- Maximum Service Pressure – 6,283 psi (433 bar)
- Limited service life – 15 years
- Safety factor (Min. burst/service pressure ratio) = 3



Large Composite
DOT Special Permits

Special Permit Number			
14951	14867	14266	11903
14402	14951	14867	12516
14275	14402	15334	15552
14779	14275	11565	14266
14277	14779	9166	9180
15552	14277	9180	
14266	15552	10878	

Large Fully Wrapped Plastic Liner Pressure Vessel

Recent DOT Special Permit (SP 14951)

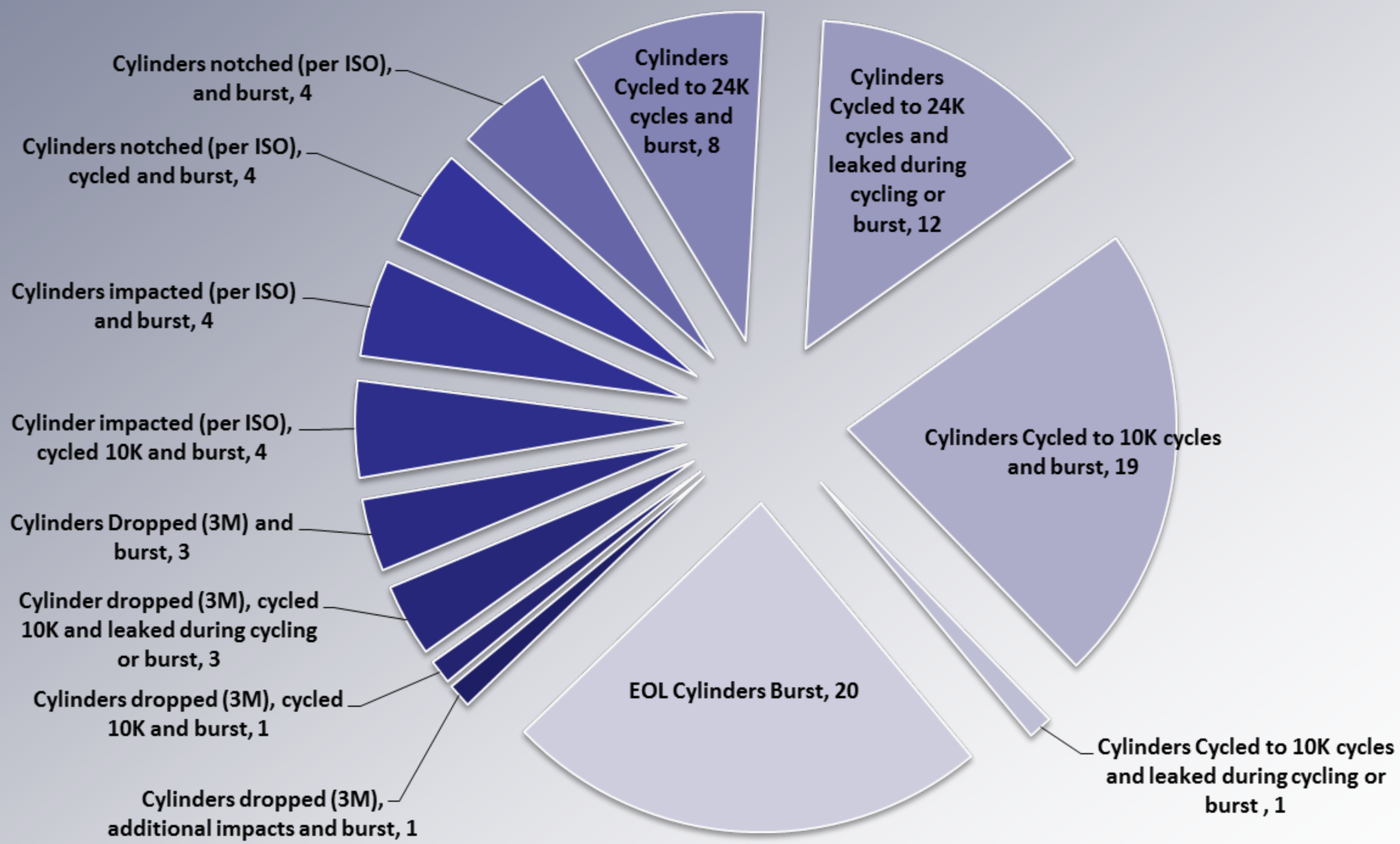
- Water volume = 8,500 Liter;
- Diameter = 42”
- Length = 458”
- Service Pressure = 3,500 psig
- Safety factor = 2.4

Performance of DOT FRP-1 and CFFC Cylinders Which Approached 15 Year Service Life

- 85 Cylinders were randomly selected from population of 50, 000 Cylinders which were approaching the end of their 15 year service life.

- Sample cylinders were subjected to design qualification testing such as burst, pressure cycling, flaw tolerance and impact (drop testing).

85 SCBA (DOT FPR-1 and CFFC) Cylinders Subjected to Performance Testing



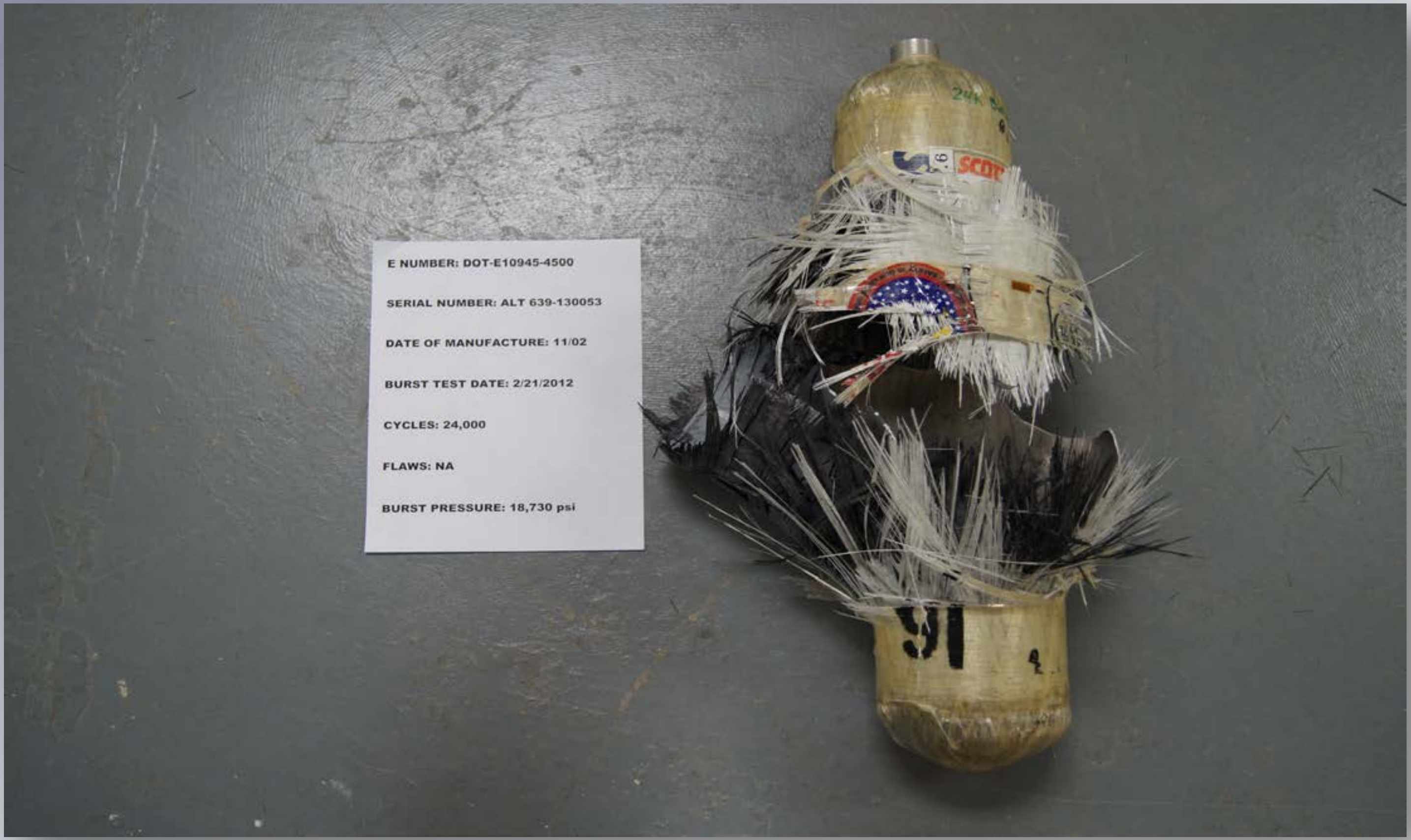
Number of SCBA Cylinders Used for Each Test

- Cylinder pressurized to Burst = 20
- Cylinders Cycled to 10K and then burst = 19
- Cylinders Cycled to 24 k and then burst = 8
- Cylinders Cycled to 24 k and leaked or burst = 12
- Cylinders Notched (per ISO) and burst = 4
- Cylinders Notched and cycled to failure = 4
- Cylinders impacted and burst = 4
- Cylinders Dropped (3M) and burst = 3
- Cylinders Dropped (3M) and cycled 10K and leaked during cycling or burst = 3
- Cylinders Dropped (3M) and then subjected to additional impact = 1

Burst Testing

- 20 cylinders were pressurized to burst;
- Results – All cylinders met or exceeded the original design burst pressure requirement

Typical DOT-FRP1 Burst Pressure Testing



Pressure Cycling Test

- Each cylinder was subjected to hydraulic pressure cycling;
- Min. cycling pressure = 0 psig
- Max Cycling pressure = 5, 200 psig (Service pressure of SCBA @ 65° C)
- Max number of pressure cycle = 24,000

Pressure Cycling and Post Burst Testing Results

Cylinder Type	Mfg Date	No. Cycles	Cycle Result	Failure During Cycling or Post Burst	Min Burst Pressure (psi)
FRP-1	06/00	12,096	Leaked	NA	13,500
FRP-1	10/00	14,837	Leaked	NA	13,500
FRP-1	09/00	19,613	Leaked	NA	13,500
FRP-1	10/00	13,148	Leaked	NA	13,500
FRP-1	06/00	24,000	ok	16,408	13,500
FRP-1	09/00	24,000	ok	15,552	13,500
FRP-1	12/99	24,000	ok	14,636	13,500
FRP-1	12/99	10,670	Leaked	NA	13,500
FRP-1	04/00	24,000	ok	Leaked	13,500
FRP-1	12/98	16,181	Leaked	NA	13,500
CFFC	11/02	24,000	ok	18,730	15,300
CFFC	02/03	13,255	Leaked	NA	15,300
CFFC	02/03	17,208	Leaked	NA	15,300
CFFC	02/03	24,000	ok	19,830	15,300
CFFC	06/02	24,000	ok	19,800	15,300
CFFC	07/03	24,000	ok	Leaked	15,300
CFFC	12/02	24,000	ok	20,044	15,300
CFFC	08/03	18,527	Leaked	NA	15,300
CFFC	01/03	21,536	Leaked	NA	15,300
CFFC	03/08	24,000	ok	17,508	15,300

Pressure Cycling Set-Up

Drop Testing/Impact Setup for DOT-FRP1 and CFFC Cylinders

First - Dropped from 10 feet, half filled with water

Second - Hit with the broad end of an axe

Third - Hit with a 2" stainless steel round stock 10-15 times

Finally - Pressurized to Burst

FRP-1 Cylinder After 10' Drop, Half Filled with Water

FRP-1 Cylinder After Hit With An Axe

FRP-1 Cylinder After Hit with a 2" Stainless Steel Round Stock 10-15 Times

Impacted FRP-1 Cylinder Subjected to Hydraulic Pressurization to Burst

Burst Pressure Test Result of DOT FRP-1 After All Three Impacts

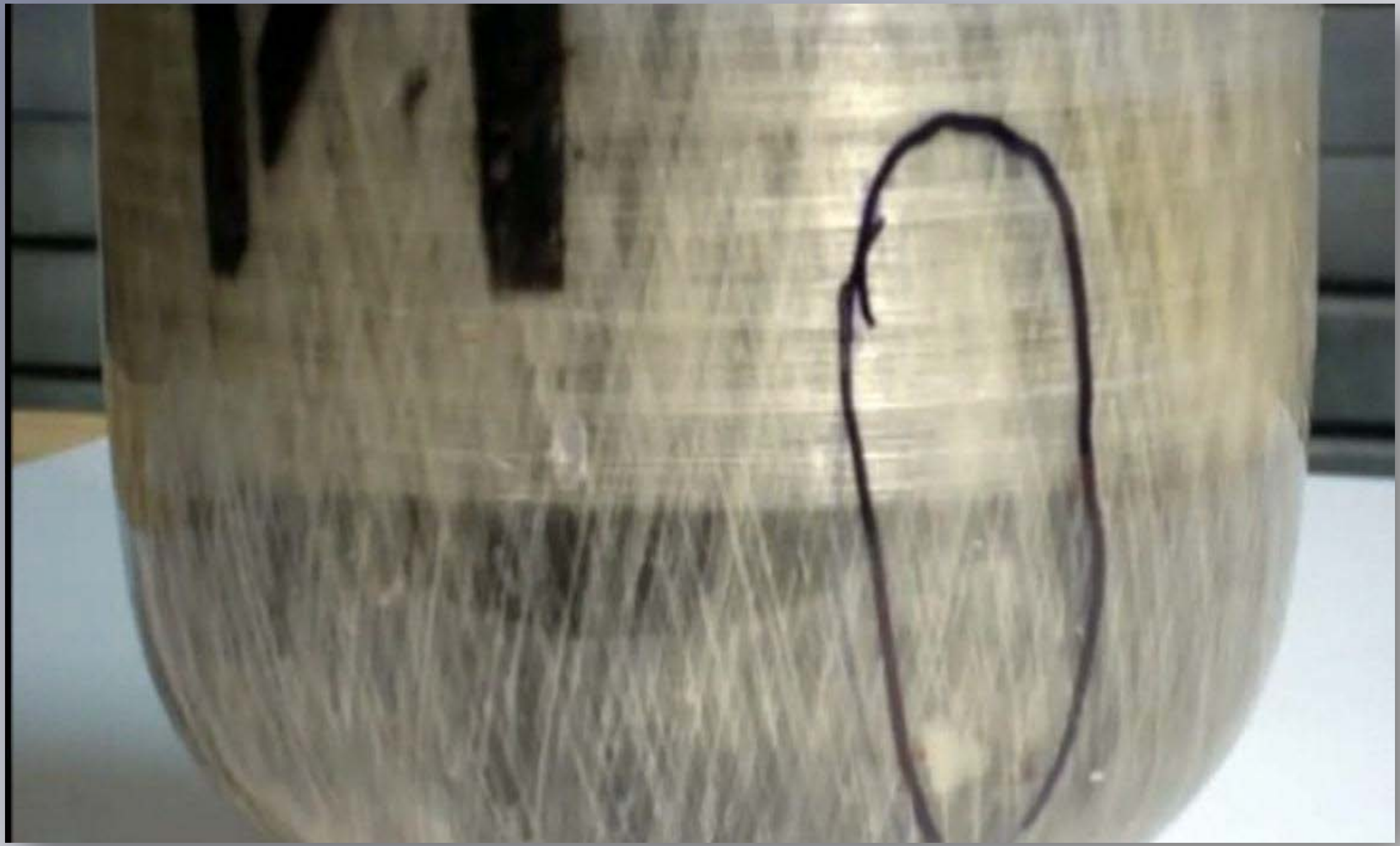
- Impacted FRP-1 Cylinder then subjected to a burst pressure testing and failed at 14,544 psi, well above the minimum design burst pressure of 13,500 psi.

Additional 15' Drop Test of DOT FRP-1 and CFFC

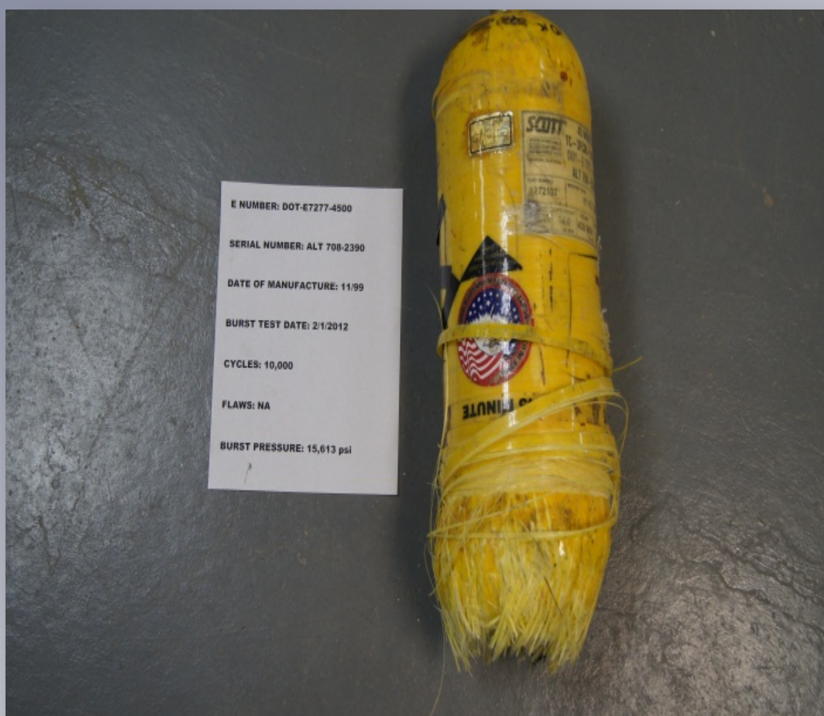
DOT CFFC Cylinder Pressure Cycling Test After 15’ Drop

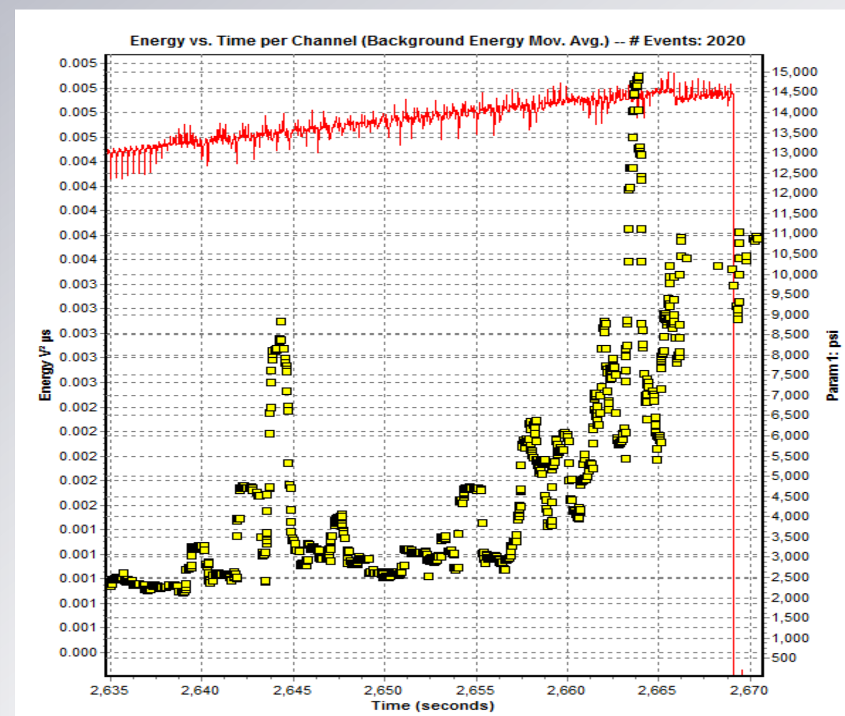
- DOT CFFC Cylinder was subjected to pressure cycling test (o to 5, 200 psig) which leaked after 3941 cycles.

DOT-CFFC Cylinder after 15’ Drop

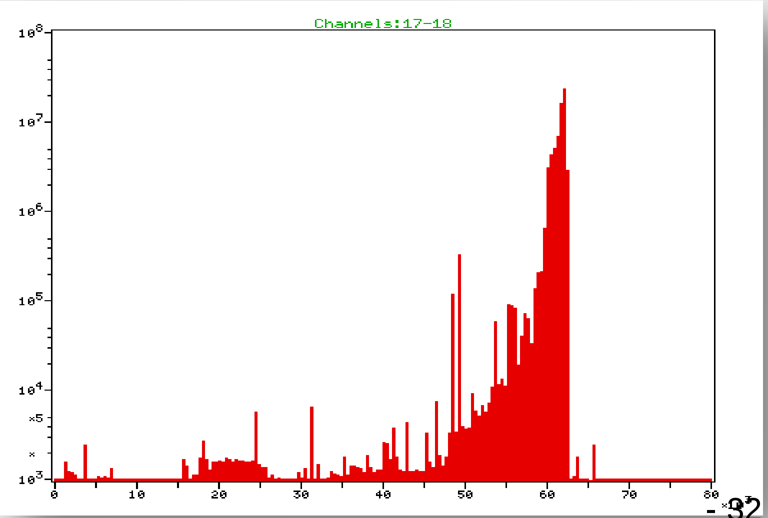


Application of Modal Acoustic Emission (MAE) for Assessing Composite Fiber Breakage and Structural Damage



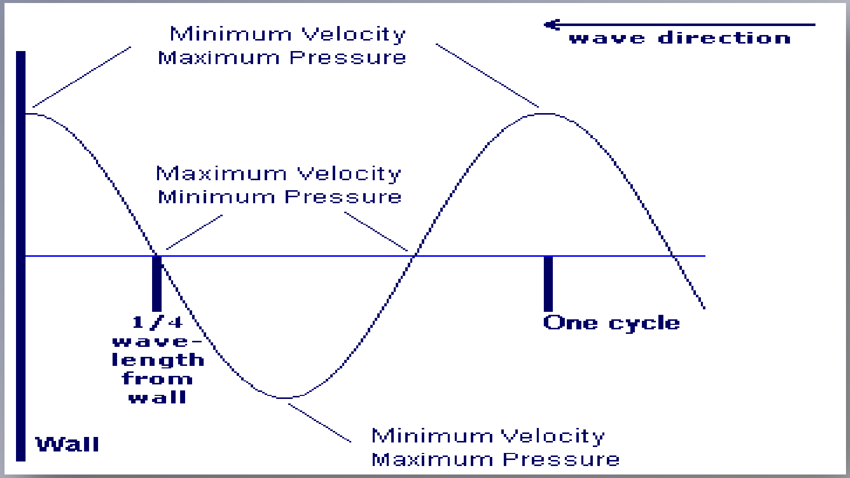


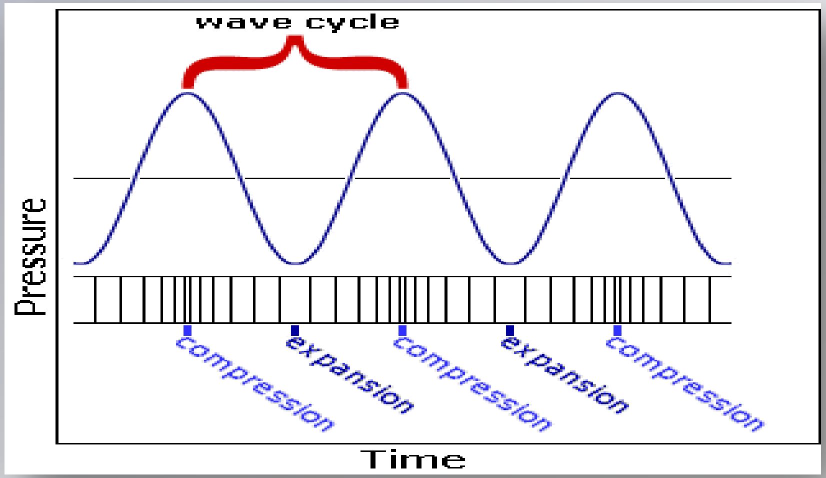
MAE System Set-Up



MAE Waveforms Used to Identify and Locate The Source of a Fiber Break

An AE waveform is distinguished by:

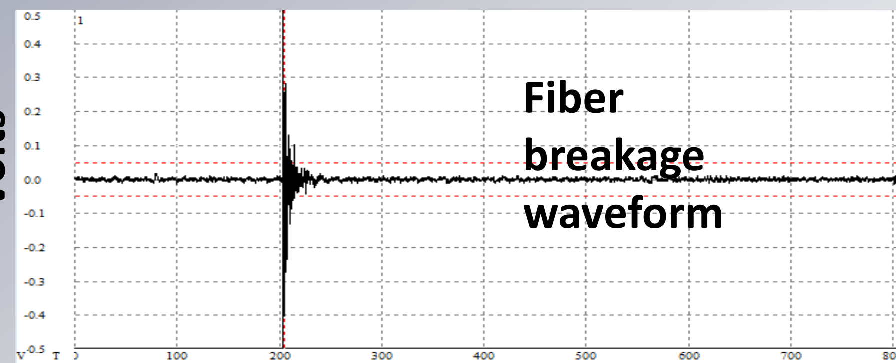


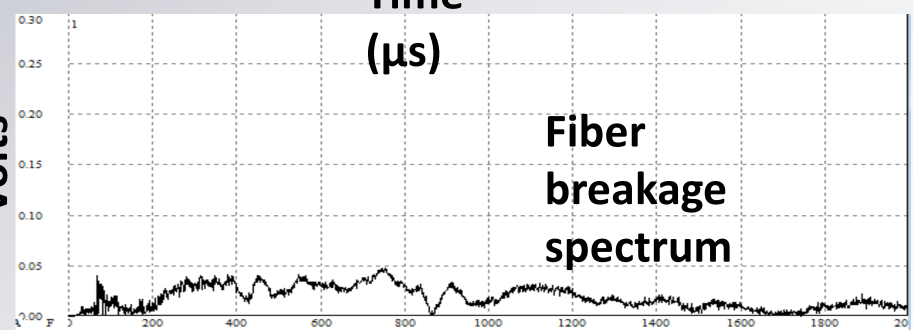


1. Wave (mode) shapes and velocities
2. Wave (mode) energies
3. Wave (mode) frequency spectrum

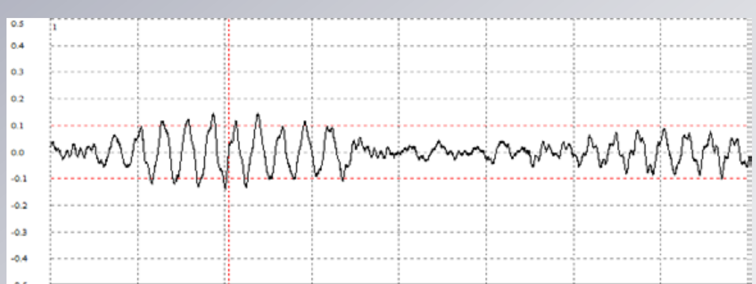
Fiber Breakage Waveform

- The waves are analyzed to determine whether the source is a delamination
- Small matrix crack event
- Fiber breakage event (shown at right)
- Frictional event or simply *unwanted noise*



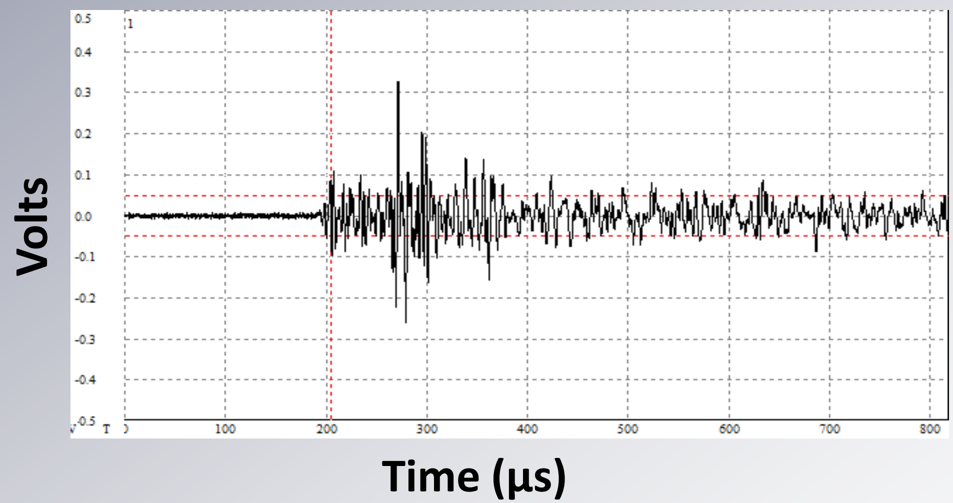


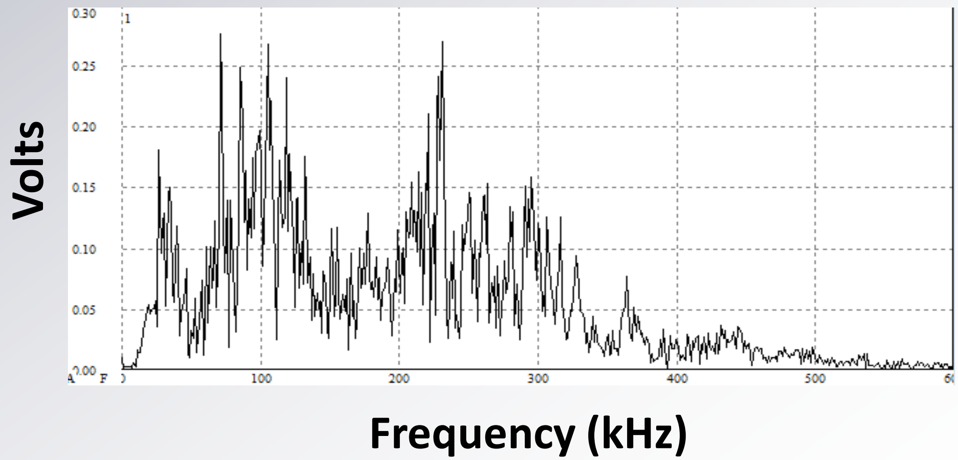
Noise A



Matrix Crack Waveform

- Shape and spectrum is different from fiber event seen in previous slide.





Noise must be identified and eliminated or conclusions may be wrong

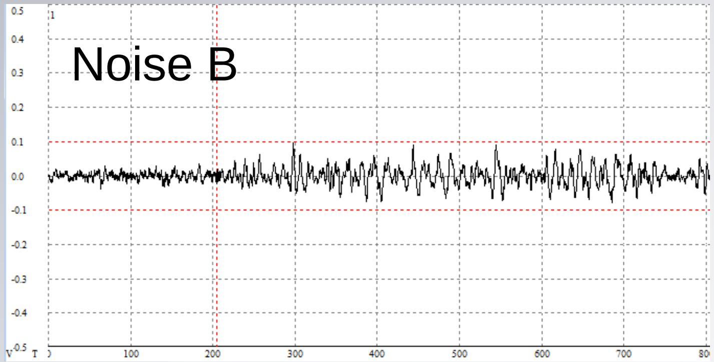
- BUT - noise comes

in many forms, in narrow,

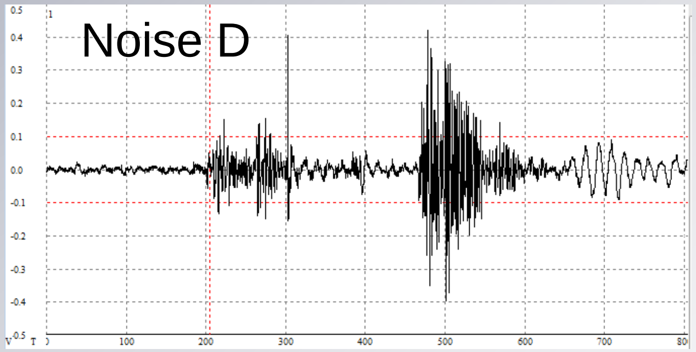
medium, and wide bandwidths. Boeing

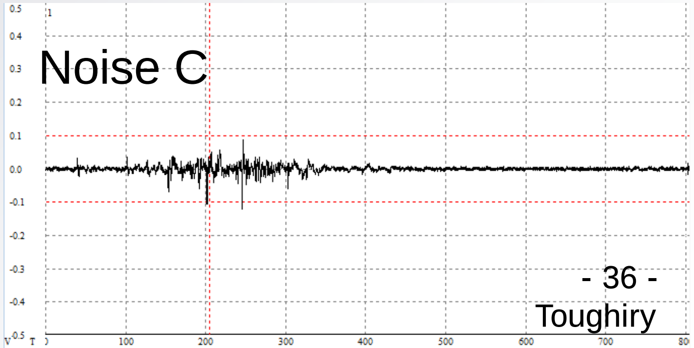
researchers concluded that MAE parameters

can be the same for different waves.



Distinguishing signals and noise is a critical function of Modal AE.



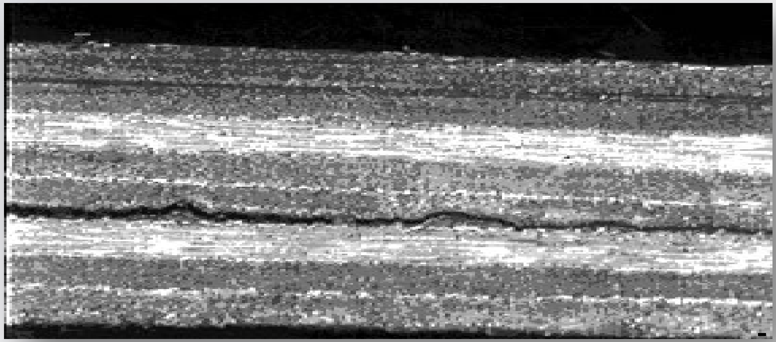


MAE System Set-Up

- MAE system set-up measures both pressure and structure-generated stress waves in real-time. The signals are detected by a series of externally attached sensors. A dedicated data acquisition unit resolves, displays and logs the resultant data for subsequent analysis.

MAE System Features and Capabilities

- Detect delamination;
- Detect fiber breakage;
- Detect stress corrosion through resin coating;
- Locate growing defects in liner
- Detection of failure onset in fatigue or on pressure holds
- Detect, locate and size leaks
- Locate fatigue cracks



Steps To Understanding

- Theory is critical for source identification
  - Elastodynamic calculations can predict waveforms for various sources that model the experimental waveforms fairly well.
- Understanding the nature of composite materials under stress and strain is also critical.
- When the above are put together in a good scientific study of particular structure such as COPV, then valid accept/reject criteria can be developed.

COPV Performance and Accept/Reject Criteria

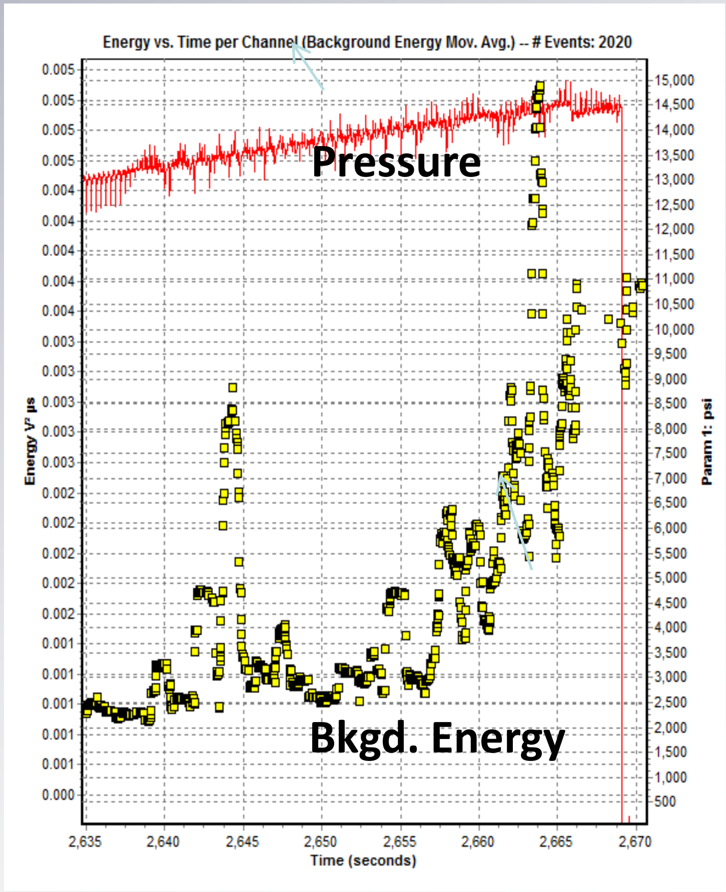
- Since sources in composites can be readily identified, the question is what do they mean to COPV performance?
- Composites are very strong and resilient, so, how does a COPV rupture?
  - Failure is progressive fiber breakage in a region
- Do all fiber breaks matter?
  - The answer is no. Composites fiber overwrapped work by transferring load to unbroken portions of the same and neighboring fibers
- How can we tell which fiber events matter?

Critical Failure Criteria

- When they are very close to one another and the background energy rises and begins to oscillate
- The AE wave energies are large, meaning multiple tow failure energy levels. (Value computed for particular fiber material.)
- Partial fiber bundle failure occurs at operating pressure (No fiber breakage is expected since each COPV was autofrettaged or proof pressure tested during manufacturing)
- The stability curve is not satisfied.

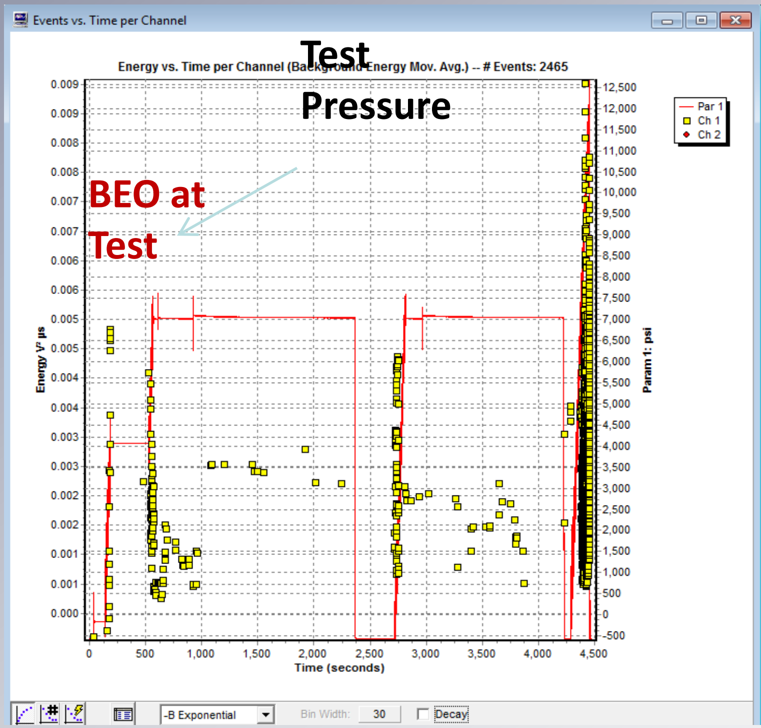
Background Energy Oscillation Effect

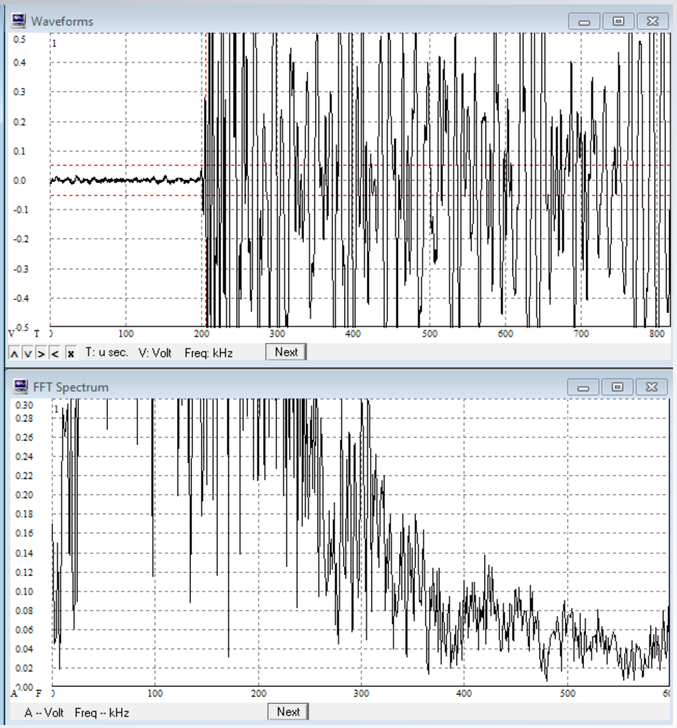
- Fiber breaks concentrate in a region
- Stress increases on neighboring fibers
- Additional fibers break
- Composite stabilizes
- Fewer ruptures occur
- Instability occurs
- Composite exhibits background-Energy oscillation (BEO) effect.



DOT FRP-1 COPV – Failed Below Min Burst

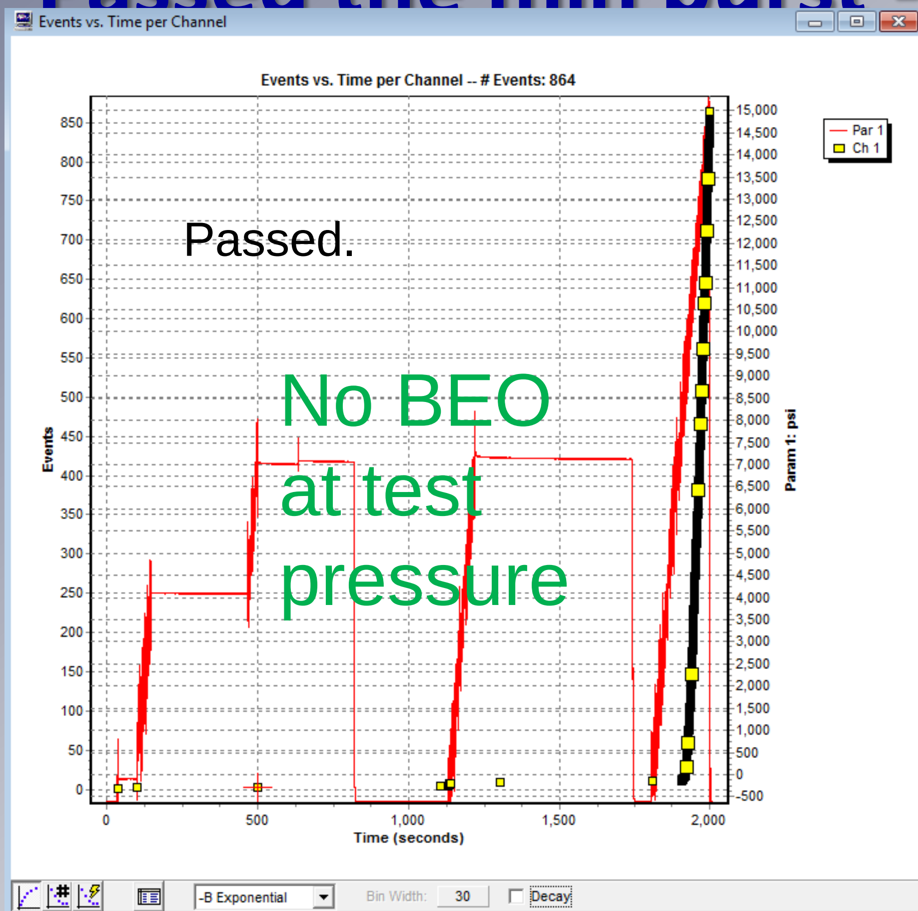
- Notched PV/Cycled 10 K then Burst @12,558 psi
- Failed on energy data that included BEO

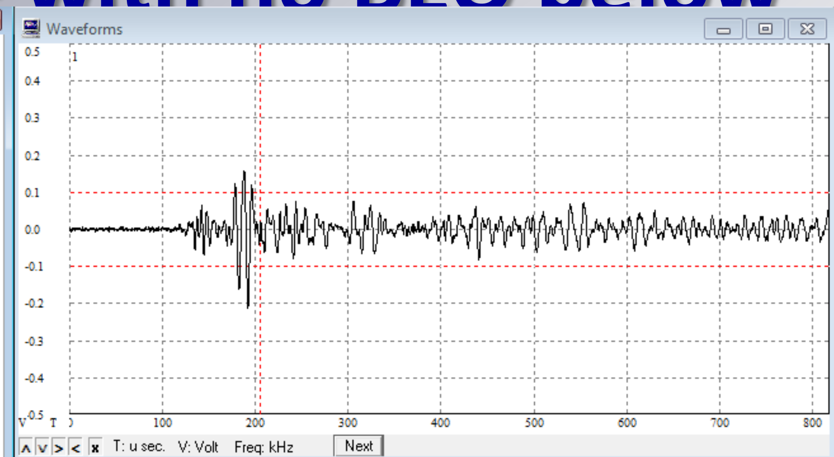


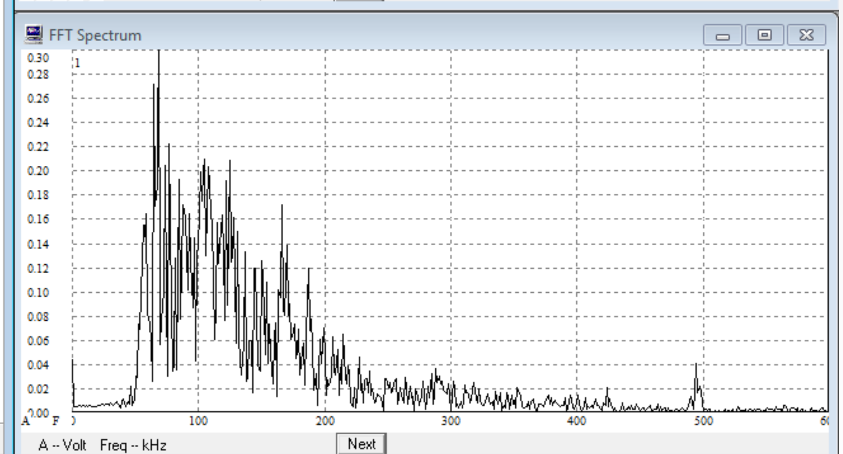


DOT FRP-1 COPV

Passed the min burst - with no BEO below







Application of MOE on a DOT CFFC COPV After the 15' Drop

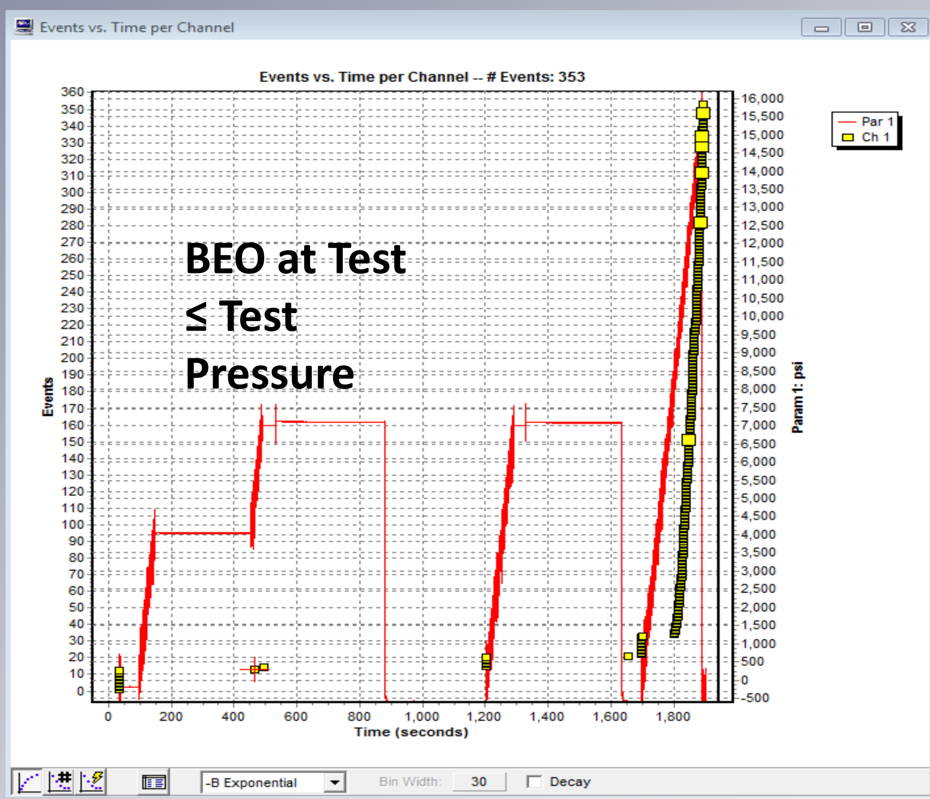
- Service Pressure = 4,500 PSI
- Test Pressure = 7, 500 PSI
- Lot Average Burst Pressure = 20,156 psi.

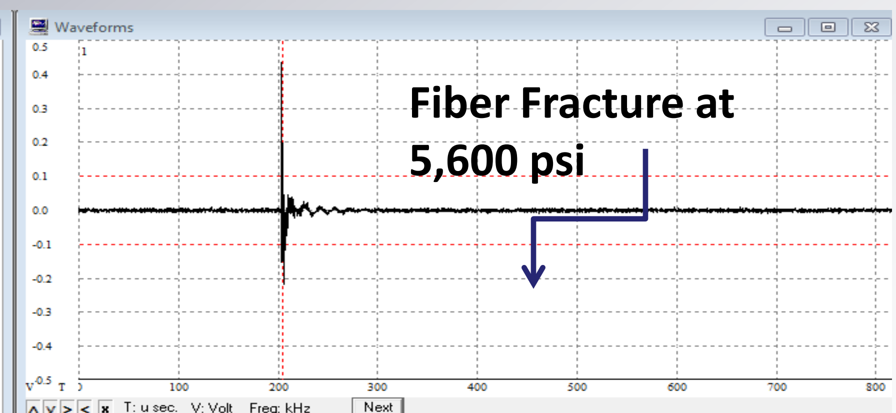
Barely Visible Damage on DOT CFFC After 15’ Drop

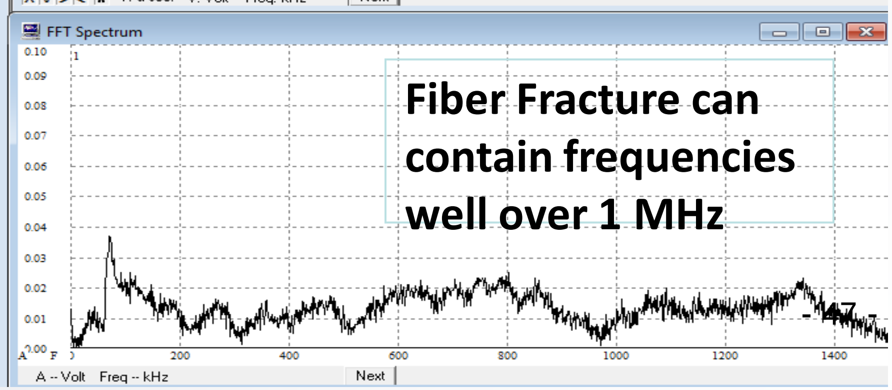
DOT CFFC COPV

AE Measurements During Pressurization

- AE Indication started at 800 PSI well bellow test pressure of 6,750
- Cylinder Busted at 16, 561 PSI ≤82% of Actual Average Burst pressure
- AE accept/reject. criteria. IL 433880 CFRP 16,561 psi burst.

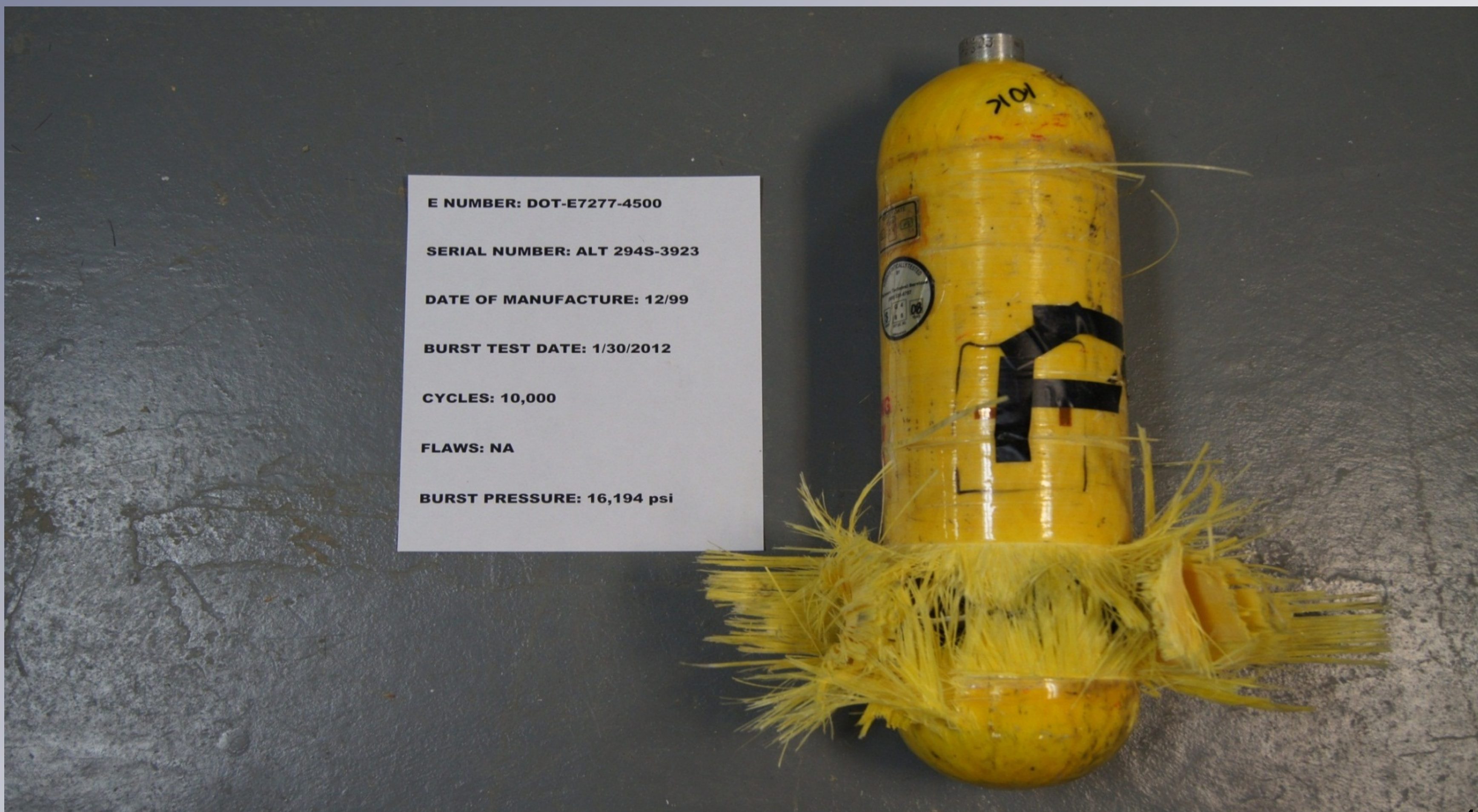






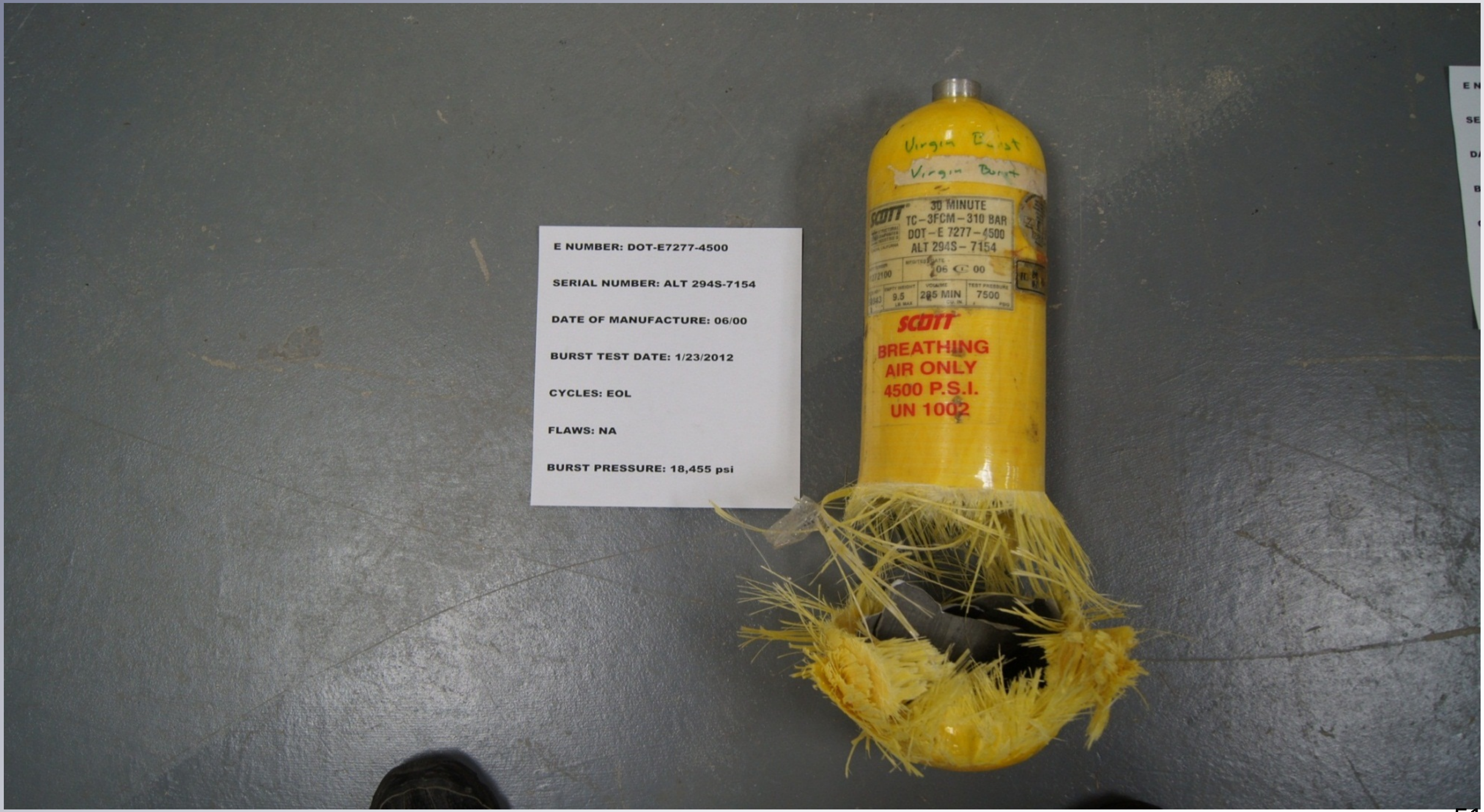
Visual Indication of DOT CFFC After 15' Drop

DOT SCBA Cylinder Burst Mode



DOT SCBA Cylinder Burst Mode

DOT SCBA Cylinder Burst Mode



Conclusion

- Most SCBA (DOT FRP-1 & CFFC) Cylinders for this project met Design Qualification Testing (Performance);
- MAE Predicted FRP-1 Cylinder with Critical Fibers Breakage (Notched)
- MAE Predicted CFFC Cylinder Impact Damaged (Lower Burst Pressure)

Composite Conference 2012

Elements of Visual Inspection

NASA/WSTF

15-Aug-12

Basic Elements

- Background/Requirements
- Damage Control Planning
- Mapping Convention
- Visual Inspection
- Documentation

Background

- NASA/United States Air Force (USAF) Program
  - Low-velocity impact damage flight-qualified composite overwrapped pressure vessels (COPVs)
  - Assess qualitative vs. quantitative capability
- International Space Station (ISS)/Nitrogen Oxygen Recharge System (NORS)
  - Specific specialized training
  - Photographic documentation
- Department of Energy (DOE)/Department of Transportation (DOT)
  - Standardized mapping convention
  - Damage level identification

DRIVEN By: Safety and Mission Assurance

Requirements

- Interim Policy Letter (23-Nov 1993)
- KNPR 8715.3 (latest Rev)
- AFSPCMAN 91-710: Vol 3&6 (July)
- ANSI/AIAA S-081 (all Revs)
- Local/Shop Requirements
  - WJI-LFACMGMT-0076.C
  - Damage Control Plan

Damage Control Planning

- Required Damage Control Plan shall be created
  - Credible threat assessment
  - Damage mitigation plans, procedures, and required visual inspection points
  - Comprehensive operation, handling, and shipping procedures

Damage Control Planning

- Trained COPV inspectors shall be utilized
  - Training
    - On-the-Job Training (OJT)
    - WSTF Damage Detection Course (DDC)
  - Recognized competent authority
- Expertise equivalent to ASNT or NAS 410
  - Qualification and certification
- Shall be specific to the composite/structure to be inspected
- COPV inspection techniques shall be identified in certification records
- Certification, recertification, and instructor shall be subject to approval from customer and/or authority having jurisdiction (AHJ)

Damage Control Planning

- Responsibility of the ***Prime Contractor***
- Must cover all stages of service life
- Ensures confidence that COPV will not fail due to mechanical damage from cradle-to-grave
- Particular attention required for pressurized work around

Damage Control Planning

- Life of component cradle-to-grave
- Identify inspection points and techniques
- Accept/reject standards shall be established for each point and technique

NOTE: Problematic for composites

Damage Control Visual Inspections

- Performed at steps critical in processing
  - Pre- and post-fabrication
  - Pre- and post-transportation
  - Prior to instrumentation application
  - Prior to integration
  - Before and after any pressure test
  - After operations involving heavy lift or tools
  - Before closeout for launch
  - Prior to any reuse

Mapping Convention

- Reference point must be identified and documented on inspection report
  - All measurements are taken from the documented common reference point
  - Must be clearly stated on inspection form
  - Boss is the typical latitudinal reference
  - Label can indicate circumferential reference
  - May be scribed on boss
  - Review existing inspection reports

Mapping Convention

- Location of indications must be tied to a datum
  - Circumferentially designated in degrees (0 to 360°)
  - Clockwise vs. counterclockwise and orientation
  - All sites are measured down from the base of an identified boss
    - Differentiate between dual-ported COPVs

Visual Inspection

- Must be tied to damage control plan
- Monitors for potential damage
- Performed from fabrication through launch and reuse (cradle-to-grave)

Visual Inspection Ensures

- Test article integrity (known stress state)
- Conformity to specification for pressure rating, materials, component size & shape
- Model and serial number verification
- Verification of pressure connection
- Verification of mounting structures

NOTE: 100% visual inspection (VI) of COPV exterior and interior surfaces (if possible)

Visual Inspection Elements

- Training
  - DDC, OJT, AHJ-accepted
- Written Procedures
  - Impact Control Plan (ICP), Work Authorizing Document (WAD), Standard, other
- Appropriate Lighting
  - 50 candle-watt (Minimum)
- Reporting Mechanism
  - Material Review Board (MRB), inspection sheet, etc.
- Field Equipment
  - Magnification, mirrors, lights, coin

Types of Composite Damage

- Scratch/Cut/Abrasion
  – Matrix and/or fiber level
- Impact/Mechanical Damage
  – Dents, broken fibers, associated delamination
- Discoloration
  – Thermal, chemical, and/or ultraviolet
- Manufacturing
  – Ply disorientations and/or matrix indications

Scratch/Cut/Abrasion

Impact/Mechanical

Discoloration

Manufacturing

Visual Inspection Reporting

- Date
- COPV description
- VI observations
- Key observations
- Sketch
- Digital photo(s)
- Signature/stamp

Visual Inspection Findings

- Report on VI form
- Initiate discrepancy record or nonconformance
- MRB
- Dispose/approve hardware

Documentation

- Map damage for future inspections
- Discuss findings without COPV present
- Clear records preclude confusion
  - Large components
  - Multiple damage sites
- Quick identification of damage for MRB
- Pictures and sketches are invaluable

Documentation

- Record/retain data for the life of the COPV
- Review periodically and assess to evaluate associated trends/anomalies
- Results should be basis of corrective action

Damage Detection Course Contacts

Contractor

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Composites 2012
Las Cruces, New Mexico

Quantitative Shearography NDT of COPV and CPV

Presented By

John W. Newman

Laser Technology Inc.

What is Shearography NDT?

- **Vibration resistant imaging laser interferometer**
- **Measures changes of test part surface to 1 nm.**
- **Images material defects when combined with an engineered stress.**
- **Portable and large production systems available.**

Features:

- **Non-Contact, Real Time NDT**
- **Electronic Images in JPEG, TIF or PMF format**
- **Detects and measures:**

- Disbonds	**- Core damage**	**- Porosity**
- Delaminations	**- Impact Damage**	**- Wrinkled Fibers**

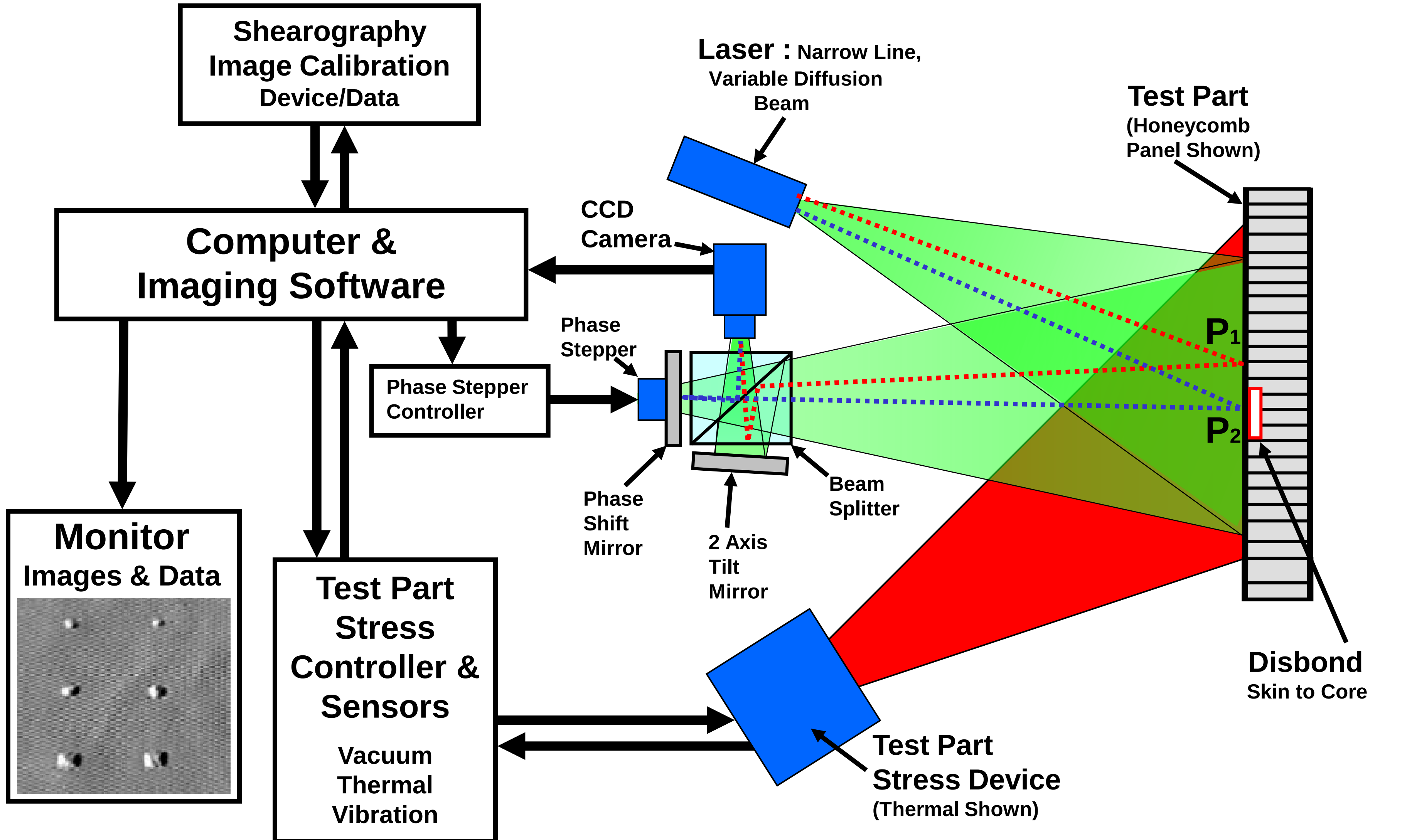
Why is Shearography NDT Important?

- **Shearography NDT delivers large increase in aerospace composite manufacturing productivity at a reduced cost.**
- **Tests parts 3-150 times faster than UT C-Scan.**
- **Non-Contact, Non-Contaminating part inspection for porosity, disbonds, delamination, core damage, impact**
- **Test parts during build up- allowing repair or scrapping part at lowest possible cost.**
- **Offers unique engineering solutions for advanced materials and structures.**

Shearography NDT Theory

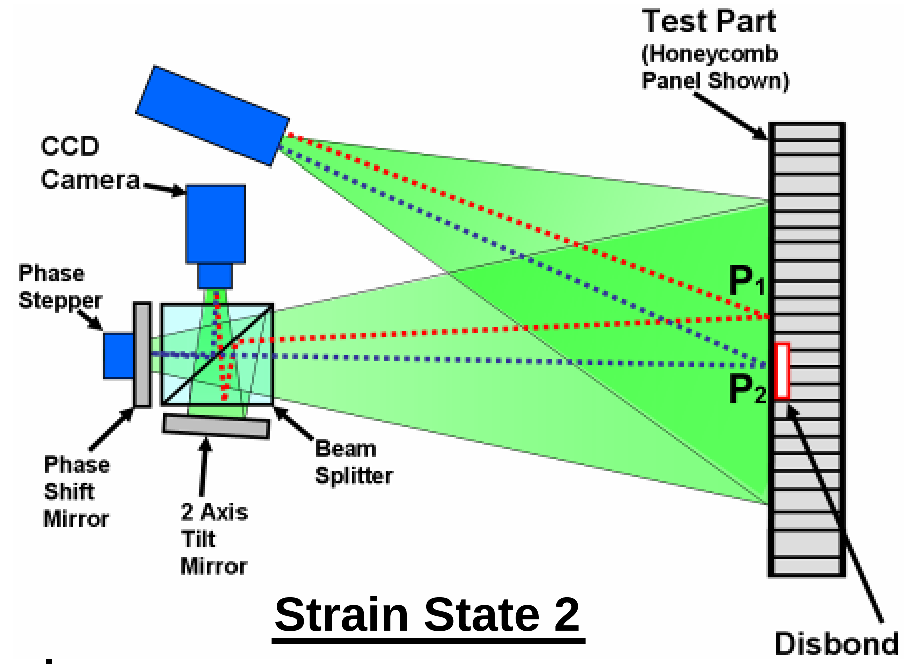
How it works…

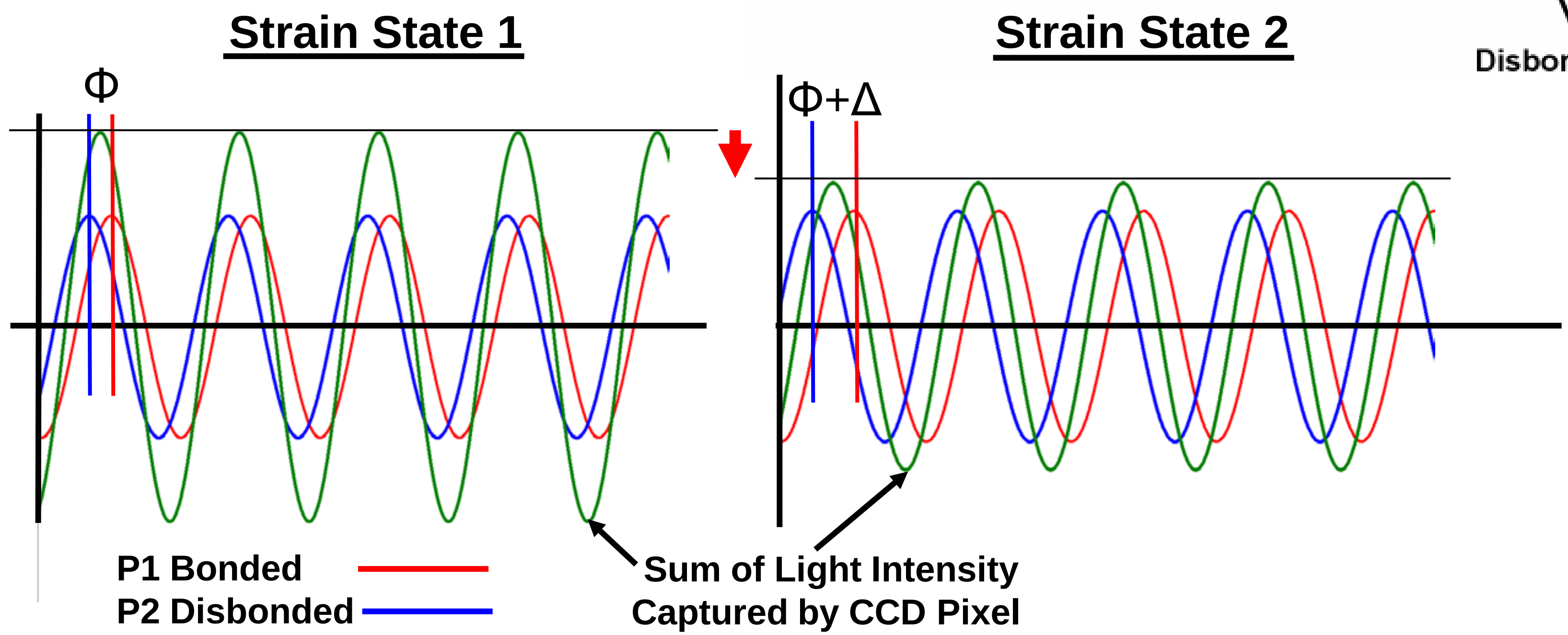
Shearography NDT System Schematic Diagram



CCD Pixel voltage output changes between two strain states caused by a phase shift Δ due to the presence of an disbond or other anomaly.

Phase Difference Strain State 1 = Φ
Phase Difference Strain State 2 = Φ+Δ





Phase Stepping Shearography Imaging

We can directly solve for the deformation (Δ) between states 1 and 2

Object Strain State 1

- $I_1(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y)]$
- $I_2(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y) + \pi/2]$
- $I_3(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y) + \pi]$
- $I_4(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y) + 3\pi/2]$

Object Strain State 2

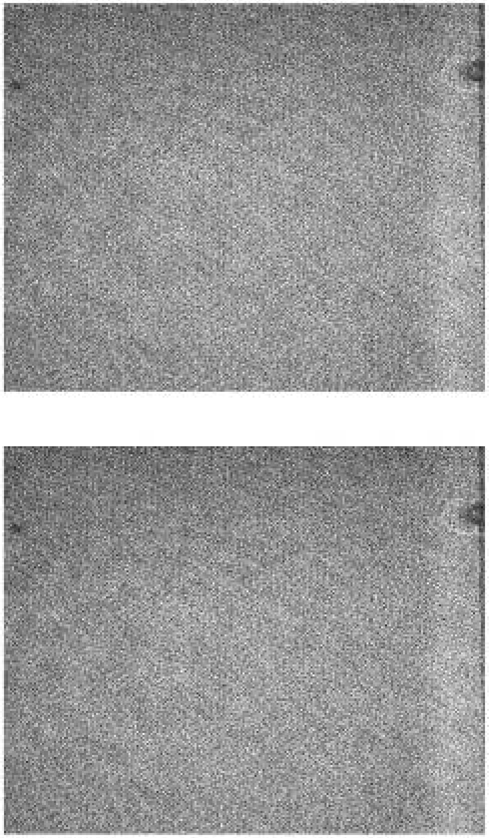
- $I_5(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y) + \Delta(x,y)]$
- $I_6(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y) + \Delta(x,y) + \pi/2]$ $I_7(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y) + \Delta(x,y) + \pi]$
- $I_8(x,y) = I'(x,y) + I''(x,y) \cos[\phi(x,y) + \Delta(x,y) + 3\pi/2]$

- $$\Delta(x,y) = \tan^{-1}\left[\frac{I_8(x,y) - I_6(x,y)}{I_5(x,y) - I_7(x,y)}\right] - \tan^{-1}\left[\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right]$$

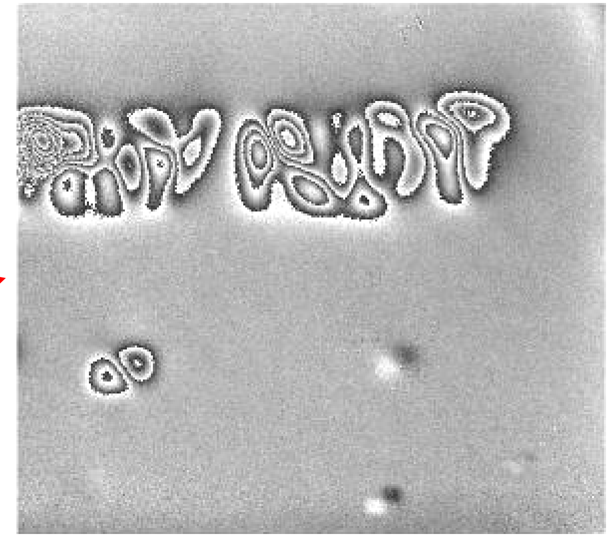
and where,
I' = the bias intensity
I" = the modulation intensity
Φ = the random phase variable due to reflection of the laser light from test object
Δ = a quantity directly proportional to the differential displacement due to the test part deformation from the applied load change

Images of the Part with Changing Strain State are combined to produce a Wrapped & Unwrapped Phase Map

Images at Strain States 1 & 2



Final Shearography Wrapped Image

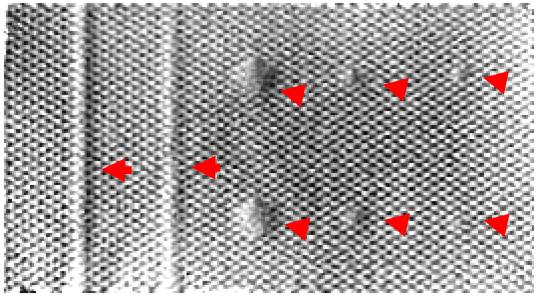


Final Shearography Unwrapped Image

Shearography Test Results By Stress Method

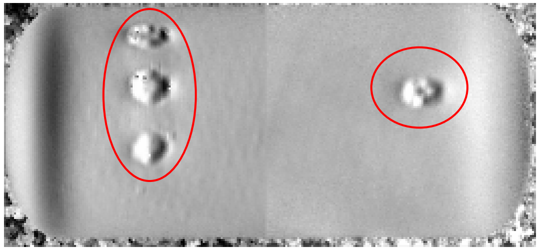
Thermal Shearography

Aluminum Honeycomb Panel



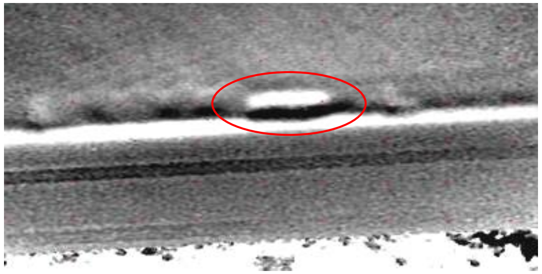
Pressure Shearography

COPV



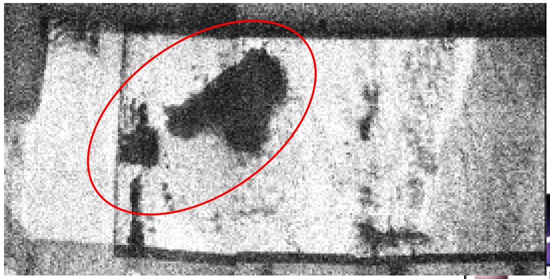
Vacuum Shearography

Composite/Nomex Honeycomb



Acoustic Shearography

Foam Cryogenic Fuel Tank TPS



LTI-5100 All Mode, Digital Shearography System

Designed for the Ultimate in Shearography NDT Imaging Quality, Throughput and Image Analysis

Features

1. Built in single frequency Laser:
   150, 300 or 500 mw
2. Full motion remote control:
   Camera pan, tilt
3. Full laser remote control:
   X,Y pan variable zoom diffuser
4. Full Camera remote control:
   Focus, Iris, Zoom
5. Full Shearogram Calibration:
   Laser spot projection with
   manual/automatic image calibration
6. High Def. 12 bit CCD @ 30 fr./sec
7. Real Time Hi Def Phase Maps
9. Integrated NDT Functions
10. Advanced shearography
    image analysis tools

LTI Shearography NDE Systems

Helicopter Blade Inspection

Boeing Delta IV Foam TPS NDT

Boat Composites Inspection

Composite Aircraft Fuselage NDT

NASA Space Shuttle ET Foam NDT

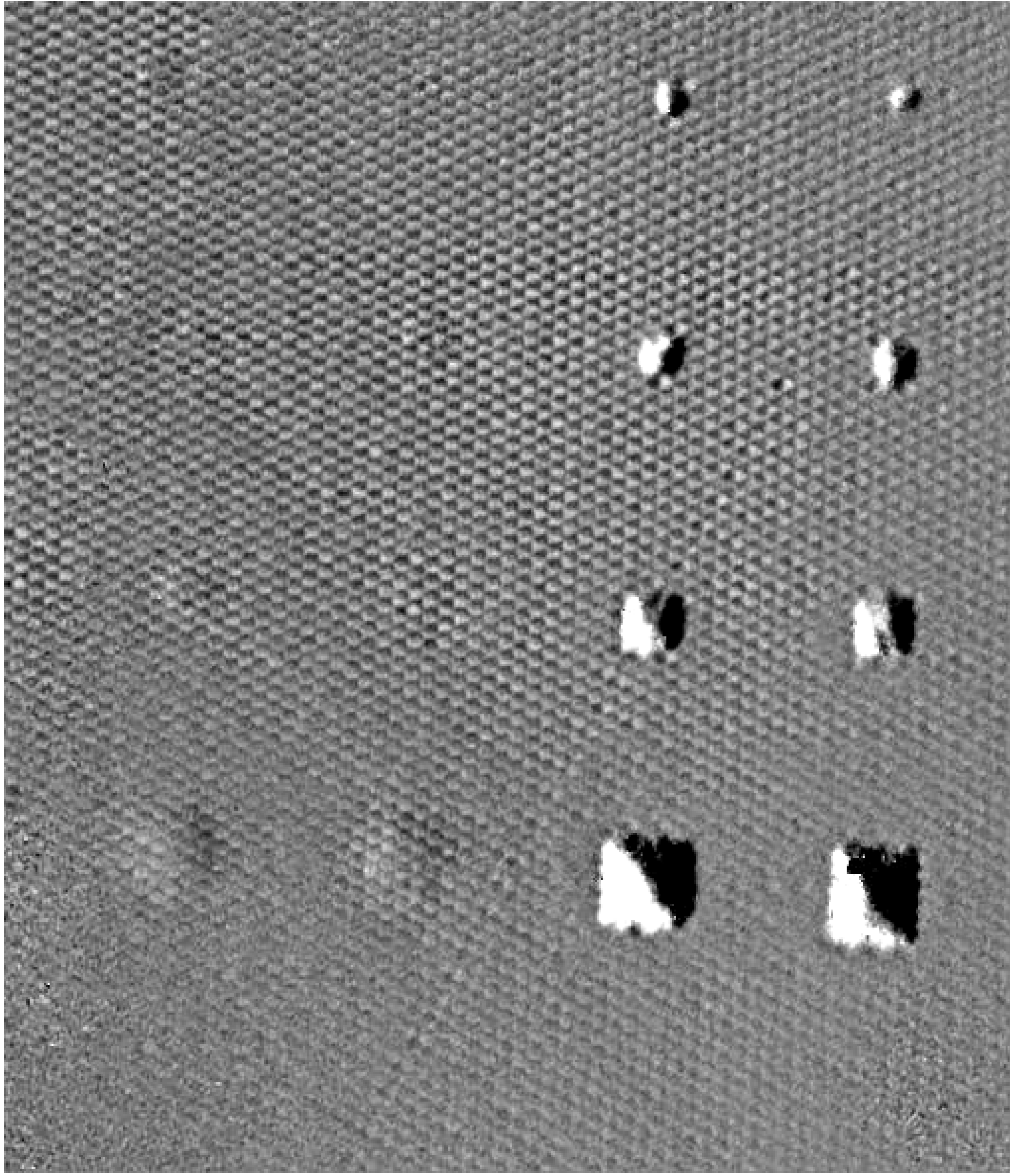
Shearography NDT Results on Aerospace Materials and Structures

Honeycomb Panel
Carbon Fiber Face Sheet With Aluminum Core

- All near side face sheet to core disbonds detected with thermal shearography.
- Two side inspection recommended.

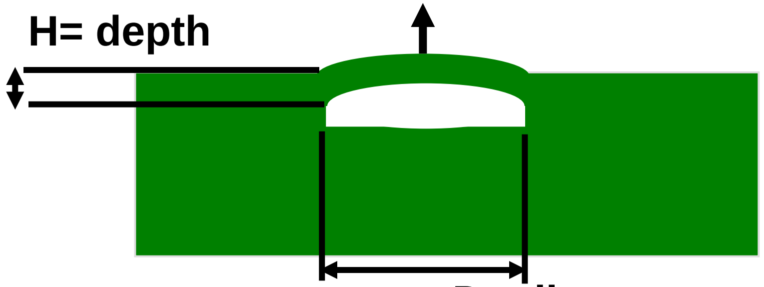
Inspection Time/Side = ***<u>5 seconds</u>***

Panel Dim. Shown = 16 x 16 inches



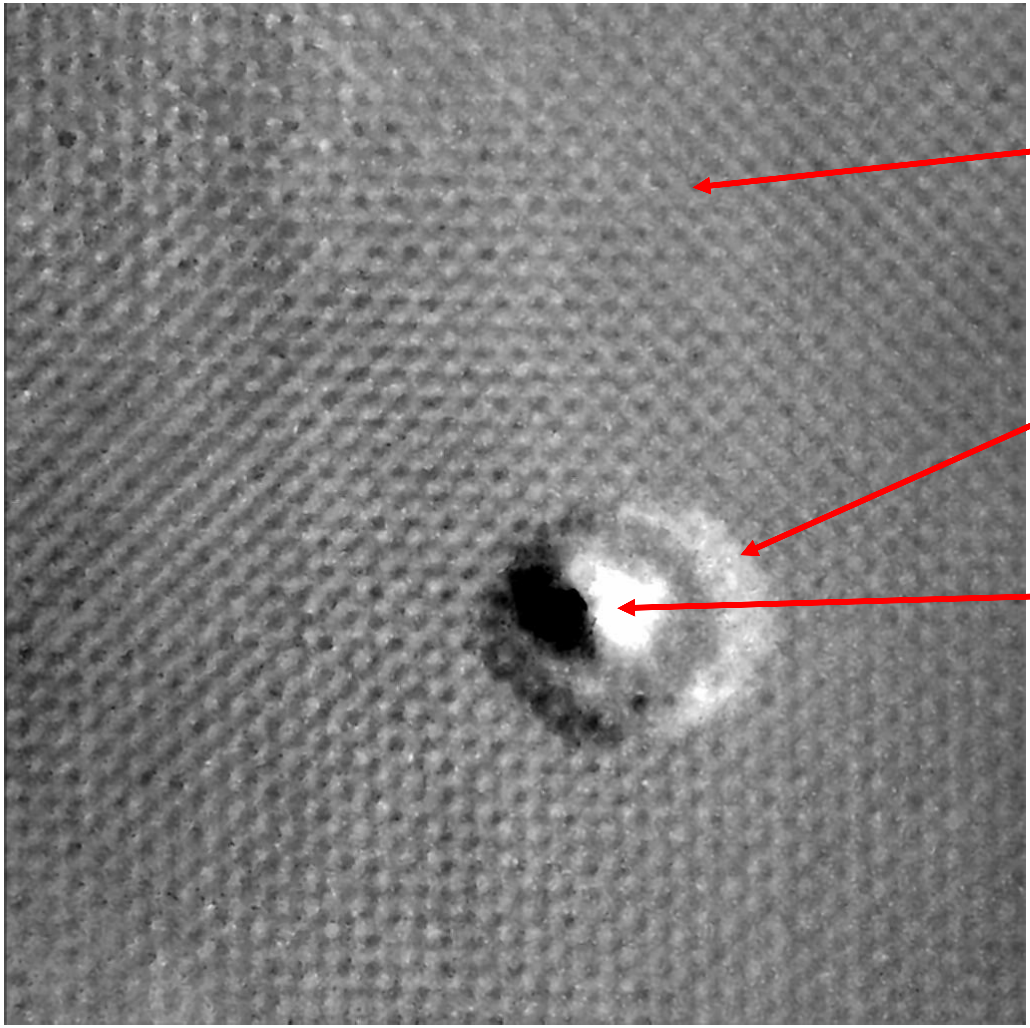
The Z-axis displacement W for the partial vacuum stressed disbond in an isotropic material may be calculated

$$W = k\left(\frac{PD^4}{EH^3}\right)$$



- The Z-axis displacement increases with the 4th power of the disbond diameter D.
- The displacement also decreases with the 3rd power of the depth H.
- For a defect with the same diameter at twice the depth, the displacement is eight times smaller.
- Small changes in the defect diameter can have a large affect on the resulting displacement. To double the displacement for give size disbond a defect would have to be only 18.9% larger.

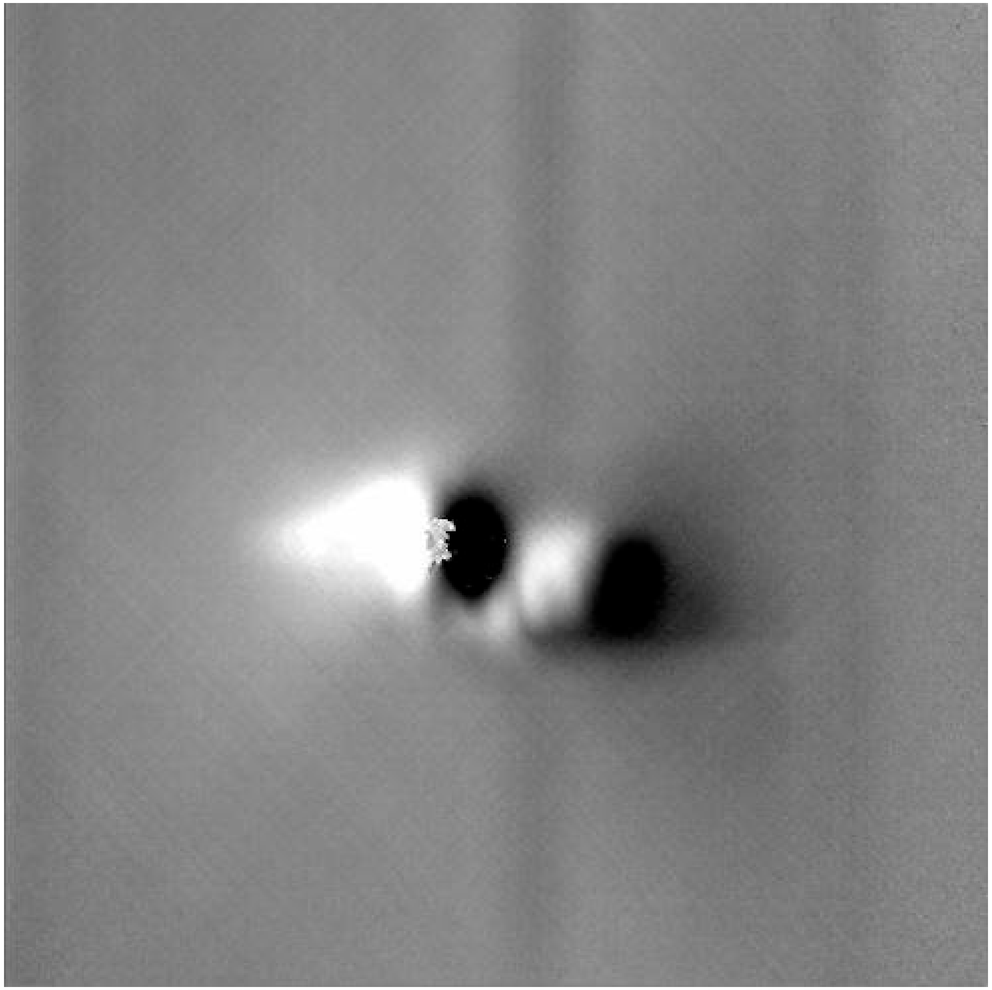
25 Ply Carbon Fiber Laminate Panel With Teflon Insert



- Well consolidated Carbon fiber laminate
- Round Teflon Insert is seen with Thermal shearography.
- Smaller disbond seen on top of insert.

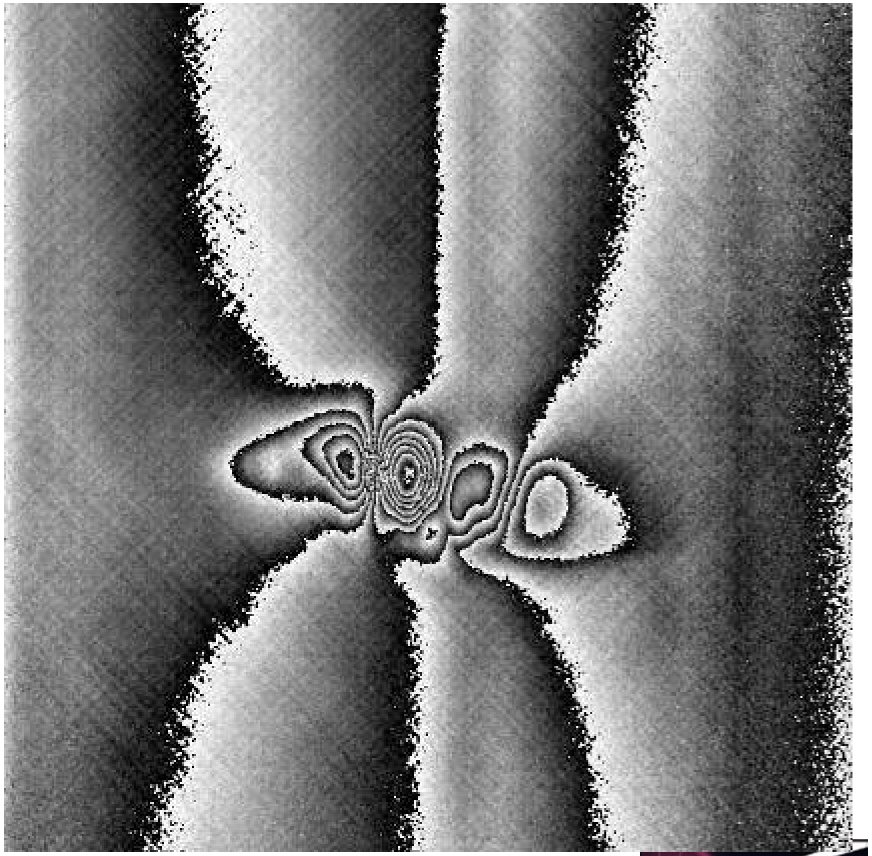
Impact Damage to Solid Laminate Panel

8x8 inches



Unwrapped Phase Map

- Non-Visible Damage easily detected.
- Broken fibers
- Delamination
- Cracking matrix
- Results Correlate with UT C-Scan



Wrapped Phase Map

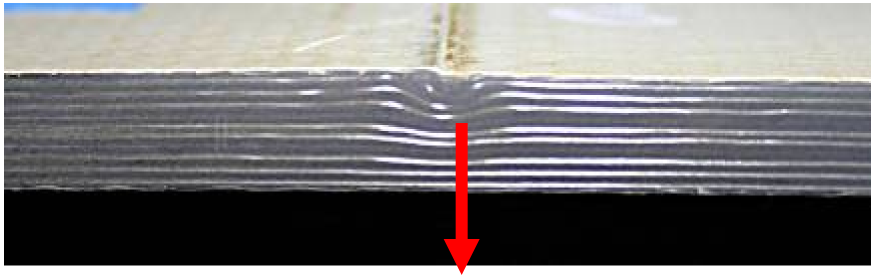
Non-Visible Impact Damage Detection and Measurement

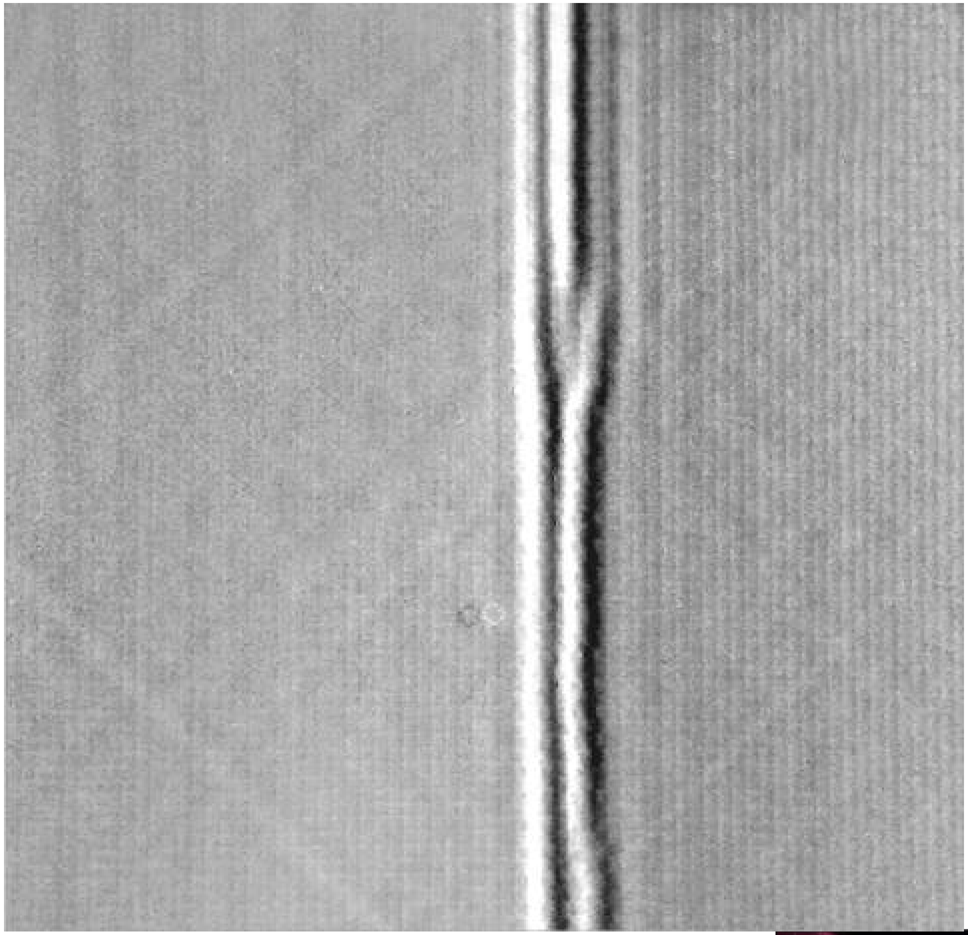
LTI-6200 Image of a Tool Drop Impact Damage To AV-8B Harrier Wing Skin Made With Carbon Fiber Laminate

Shearography Imaging of Wrinkled Fibers

- Fiber wrinkles substantially reduce panel stiffness and in-plane tensile strength.

- Shearography can detect fiber wrinkles from a single side allowing inspection of foam cored wind turbine blade skins.

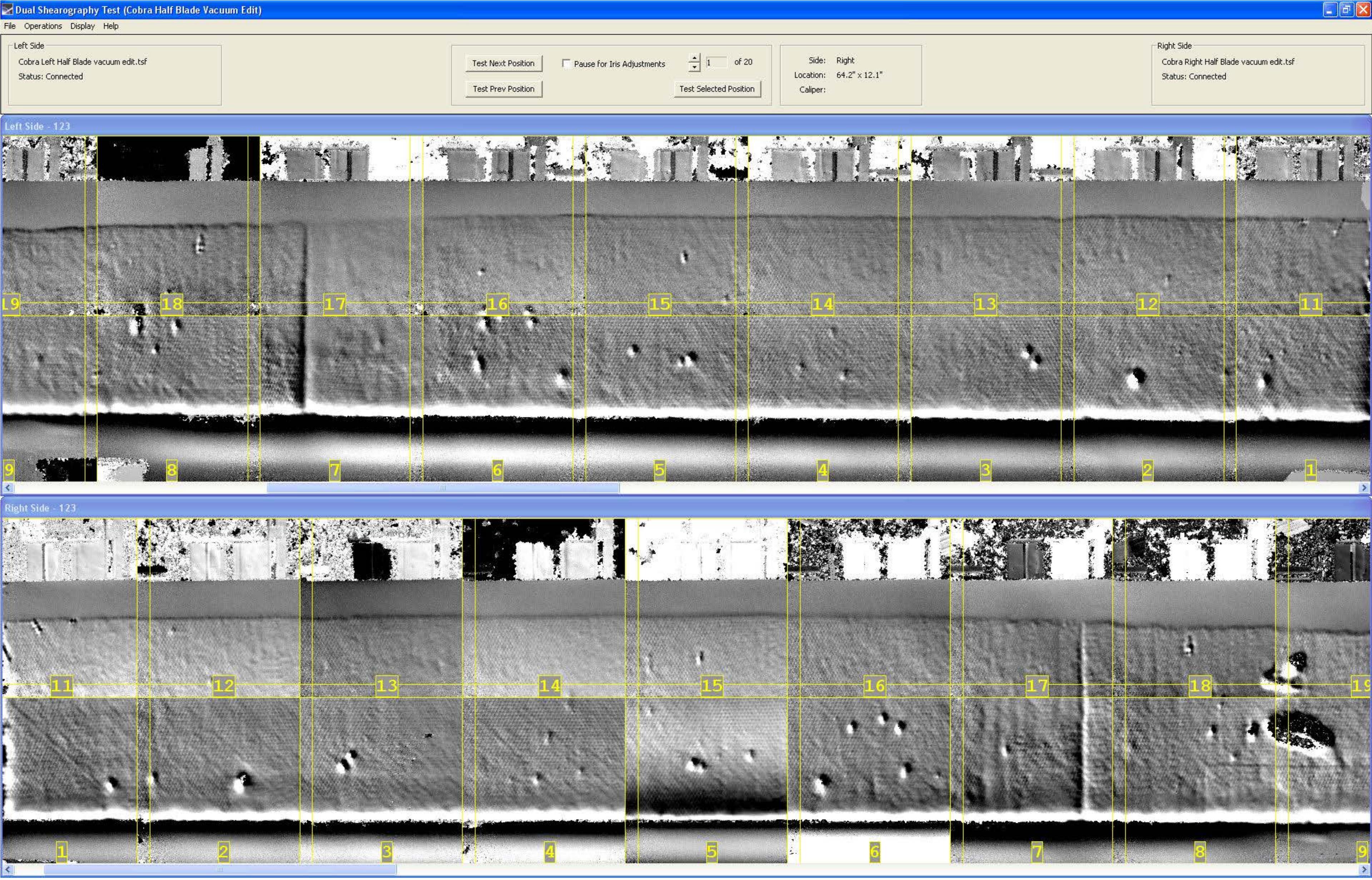




Above: Cross section of carbon fiber laminate panel with fiber wrinkles

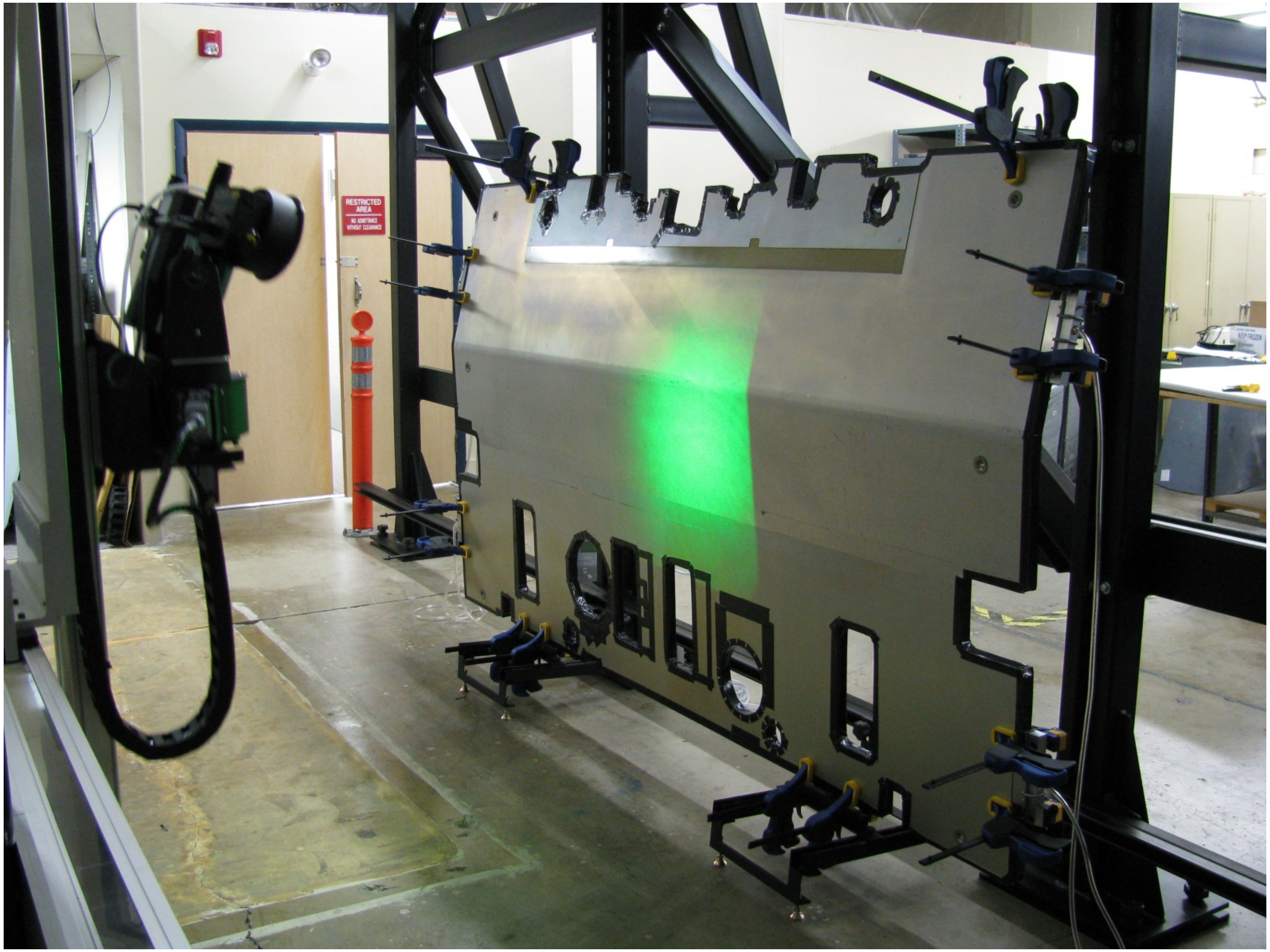
Below: Shearography image of the panel face.

The LTI-7290 Production Shearography Helicopter Blade Inspection System Manufactured For: Bell Helicopter Textron, Hurst, Texas

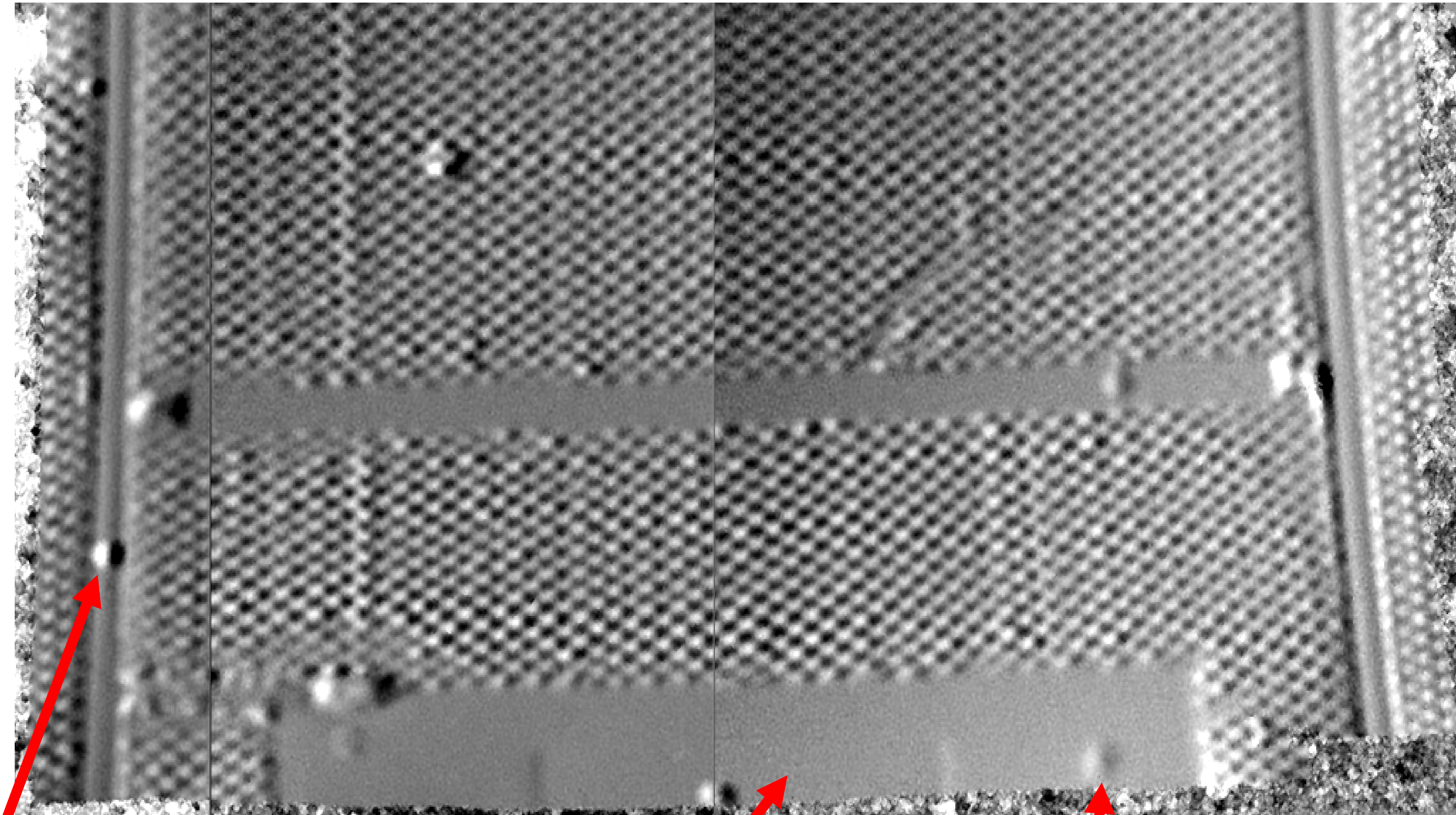


6 Meter Blade with Nomex core tested both sides in 7 minutes

Spacecraft Honeycomb Panel



Section of Spacecraft Radiator Panel 30 x 22 inches
2 shearograms, 20 seconds

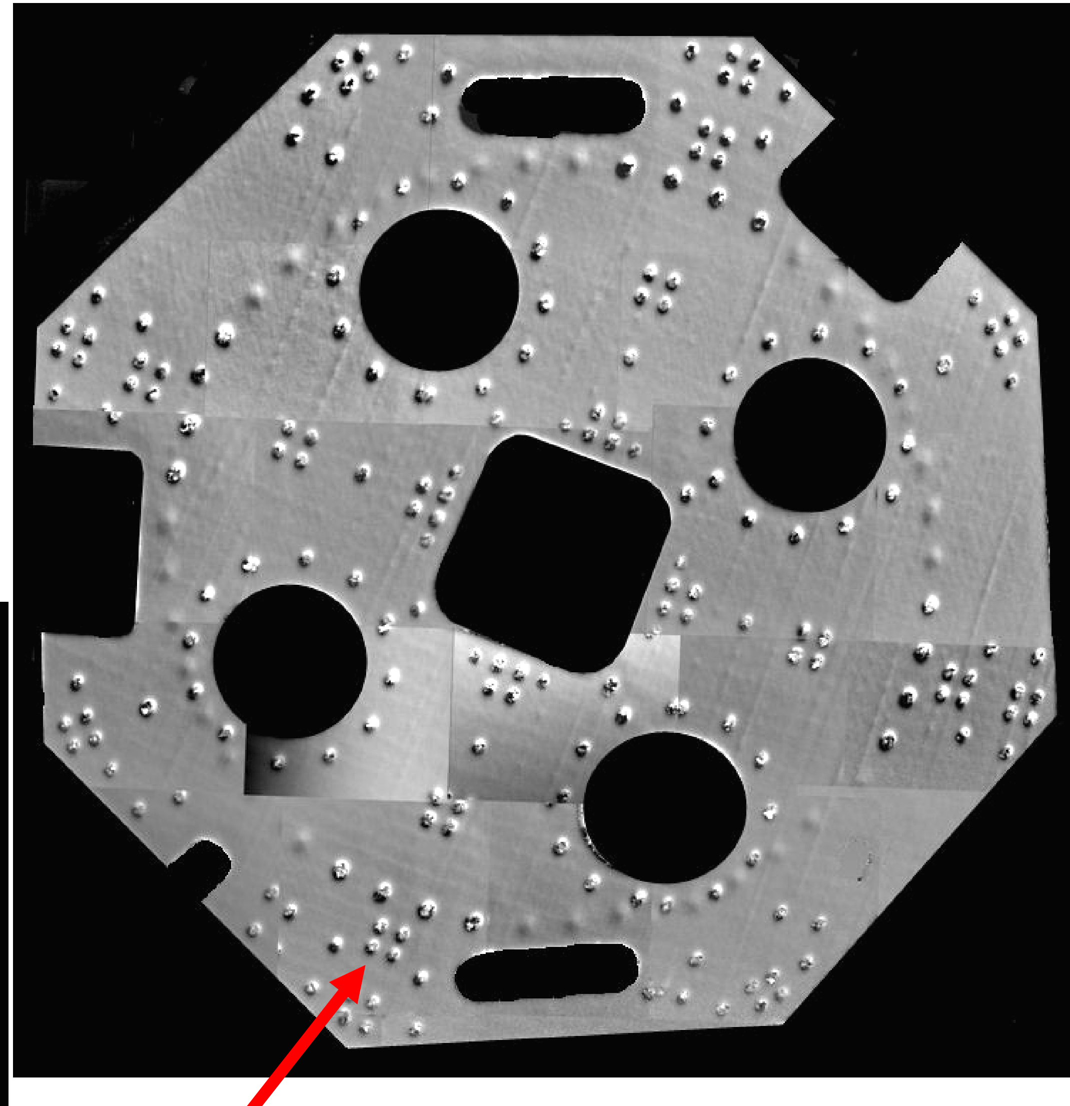


Disbond over Ammonia Coolant Tube

Metal Block Insert

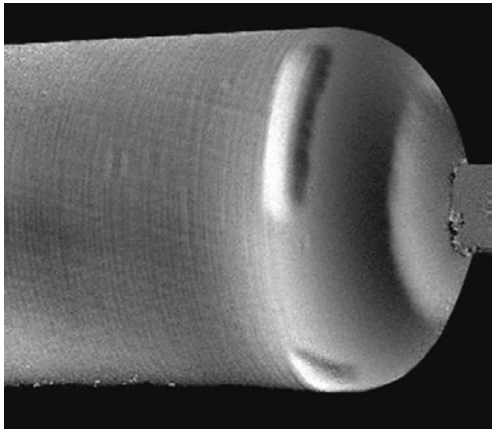
Disbonds under Doubler

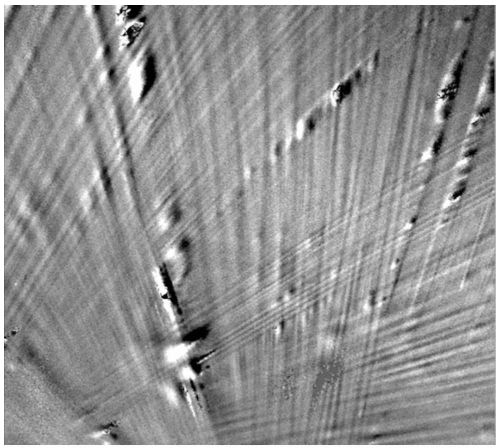
Thermal Shearography NDT of a 6.5 ft. diameter composite honeycomb panel for NASA Lunar Atmosphere & Dust Environment Explorer (LADEE) orbiting spacecraft

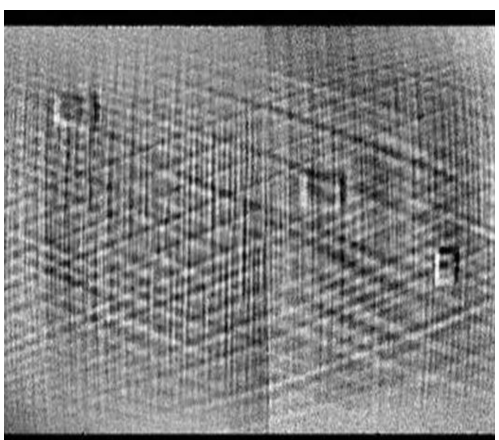


Potted fasteners – No defect Indications

Shearography Inspection of Falcon 9 Merlin Engines





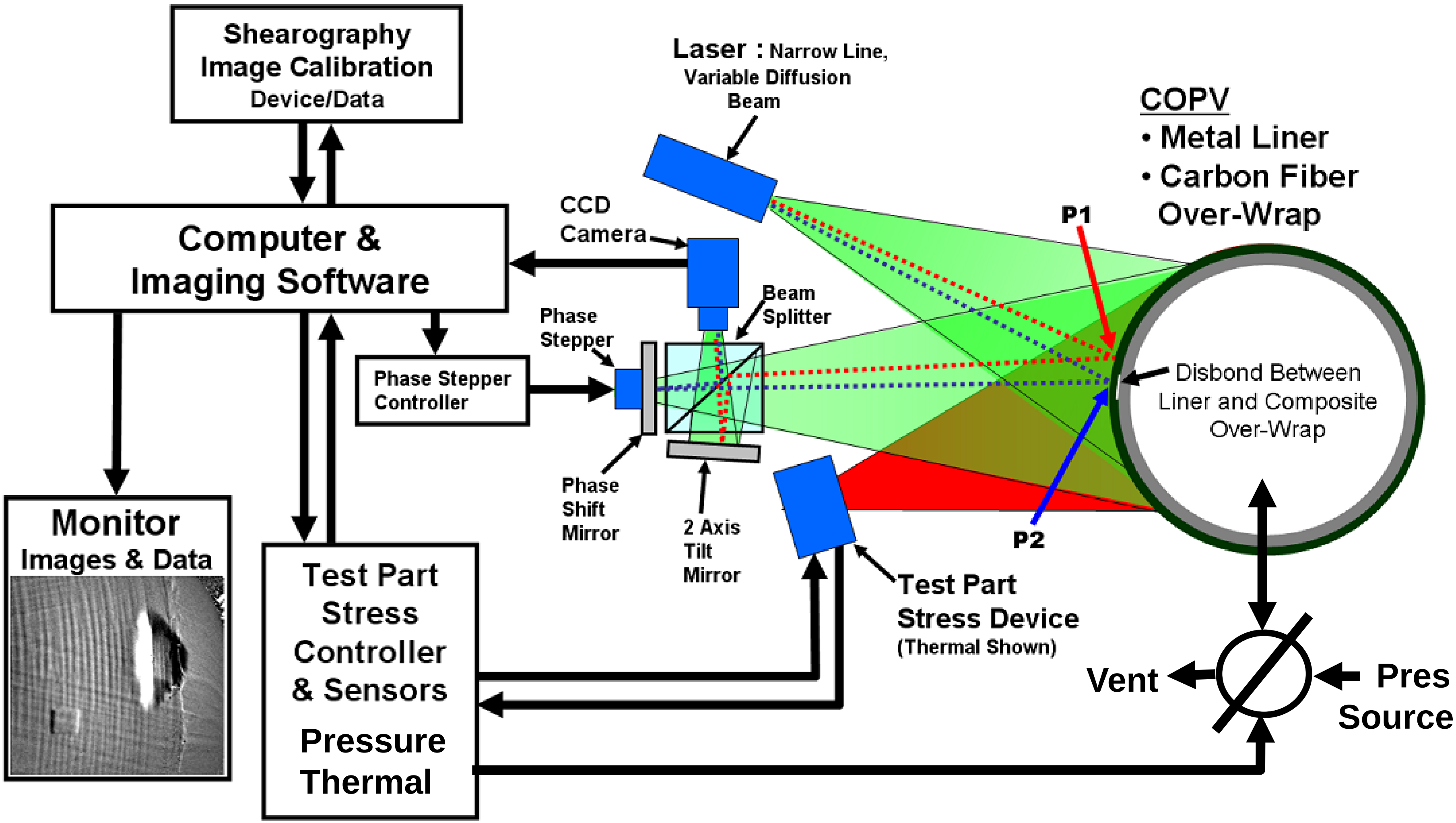


COPV/CPV Inspection

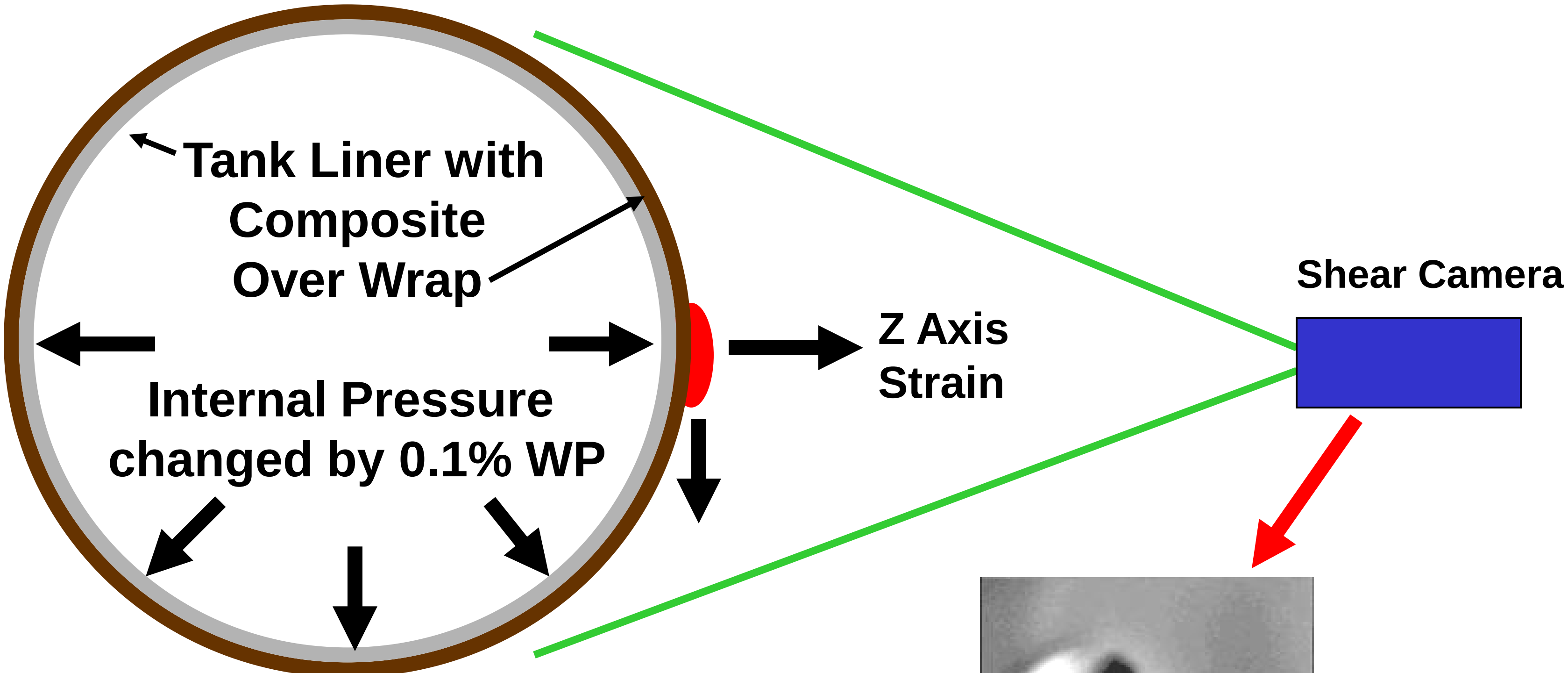
<u>Latent Defects Including:</u>

- **Fiber Bridging**
- **Porosity**
- **Liner to Composite Disbonds**
- **Boss fitting disbonds**
- **Cracks**
- **Broken Fibers**
- **Impact/Handling Damage**

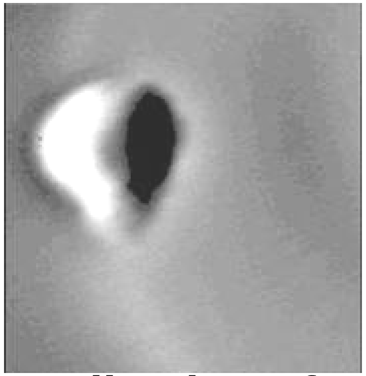
Shearography Schematic Diagram for COPV



Technical Approach: Shearography Detection of Strain Concentrations Due to Damage



- Increased pressure increases hoop and longitudinal strain.
- Z axis component of strain concentrations are detected by the shearography camera.
- As pressure increases, strain rates at damage sites are greater than good areas.

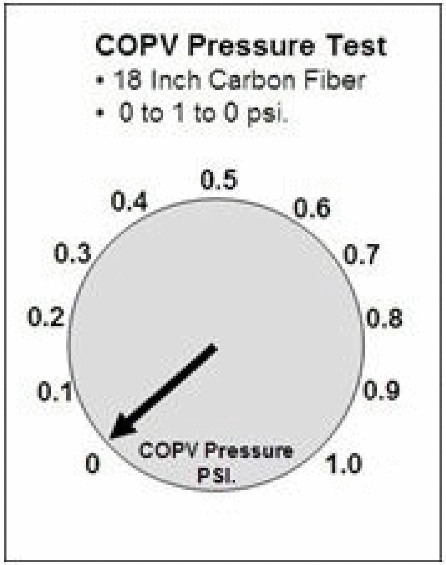


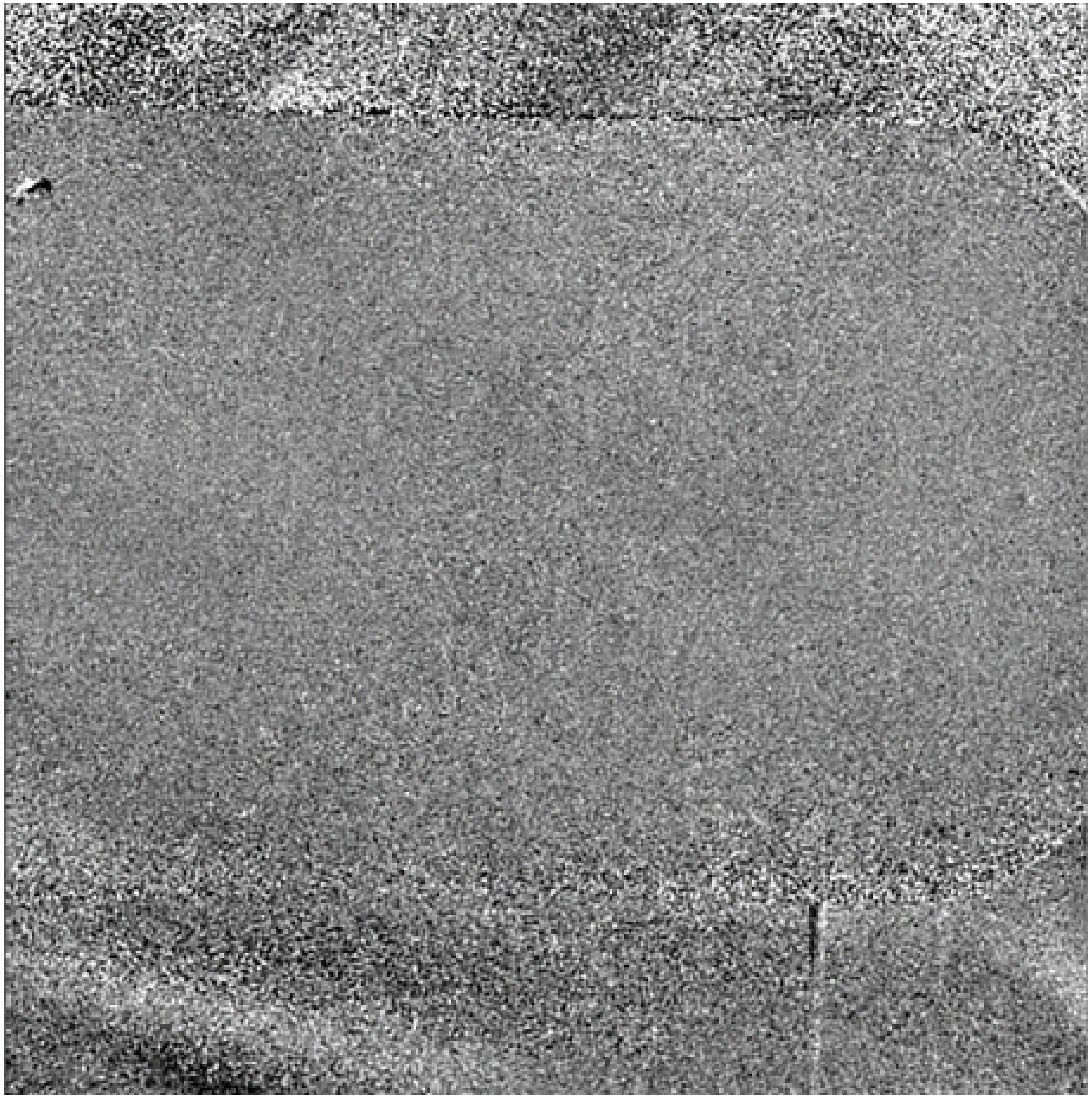
Indication of Impact Damage

6 x 18 Inch Carbon Fiber COPV

18 Inch COPV Shearography
Impact Damage Test

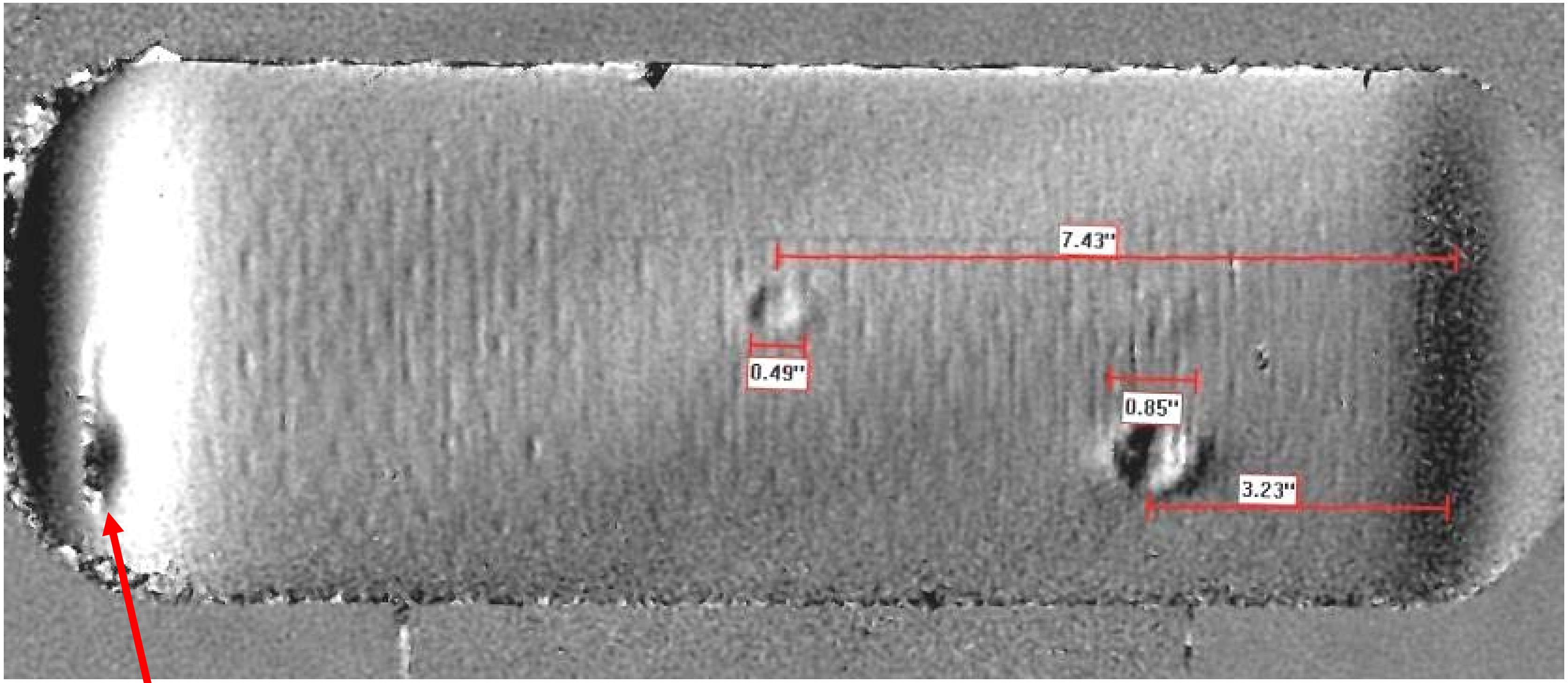
Pressure



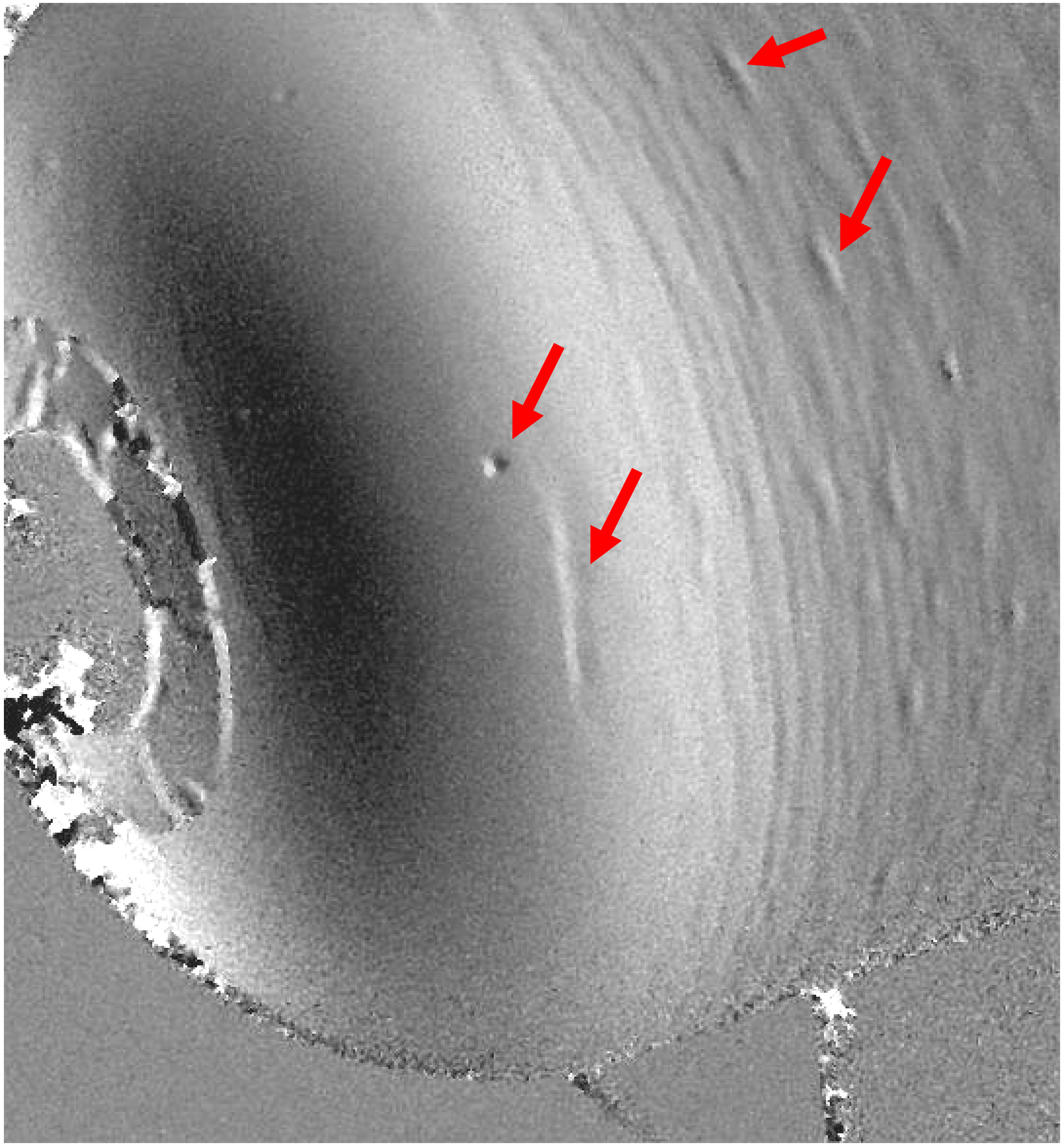


6 x 18 Inch Carbon Fiber COPV

Measurement of several damage indications.

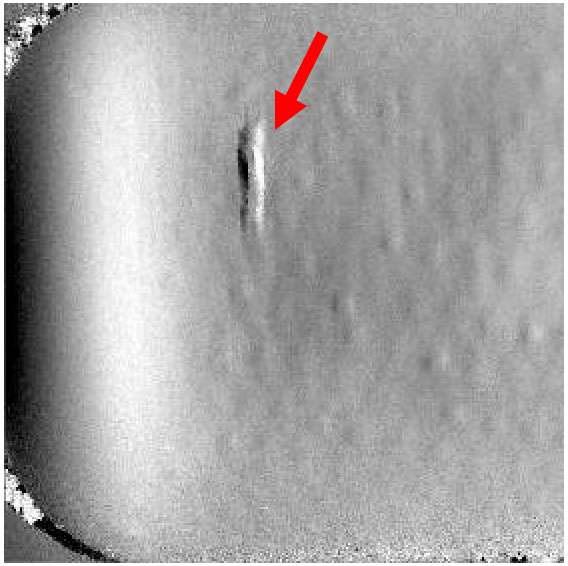


Crack

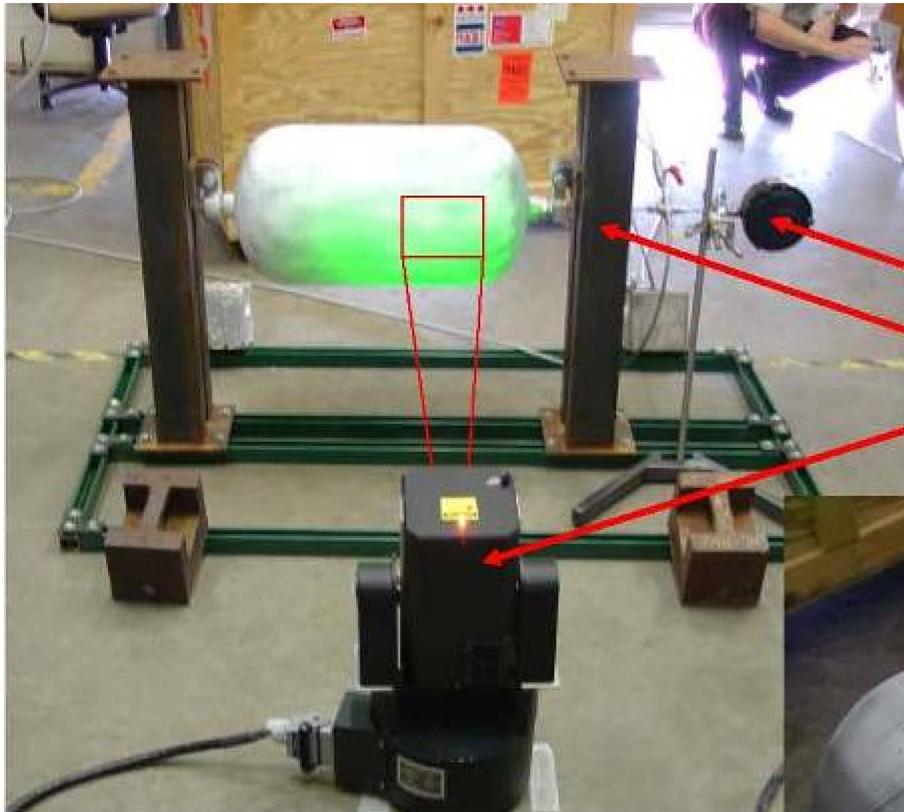


6 x 18 Inch Carbon Fiber COPV

- Small indications of cracks and impact (white/black indication) and small areas of strain reduction due to fiber wrap pattern (black/ white) on barrel section of COPV.



Shearography Test Set Up



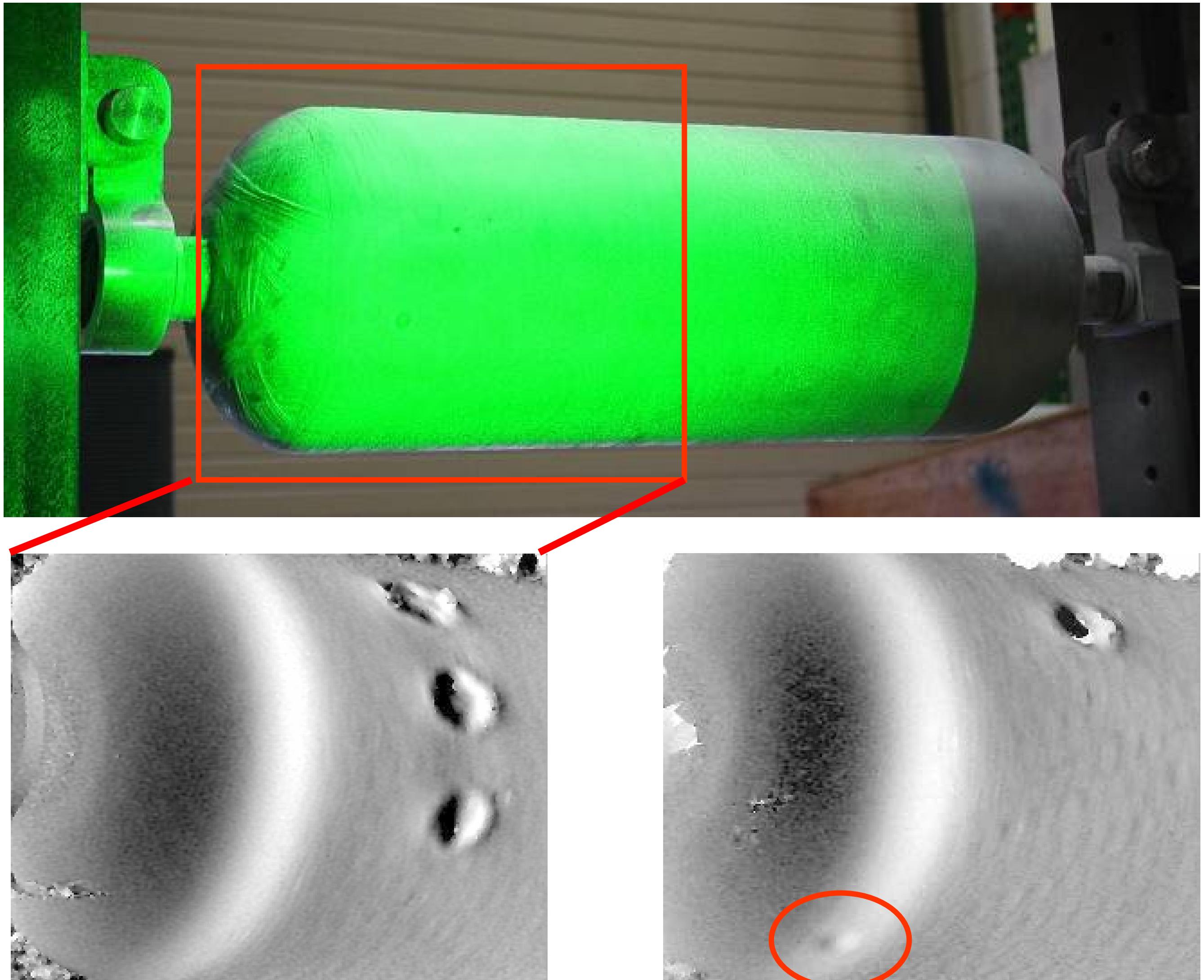
Shearography Test Set-Up for 13 x 25 Inch Graphite COPV

Pressure Gage

Support Frame

LTI-5100 Shearography Camera

6 x 22 Inch Graphite COPV Shearography Inspected with 10 psid. Crater like indications are impact induced damage and delamination to the composite.

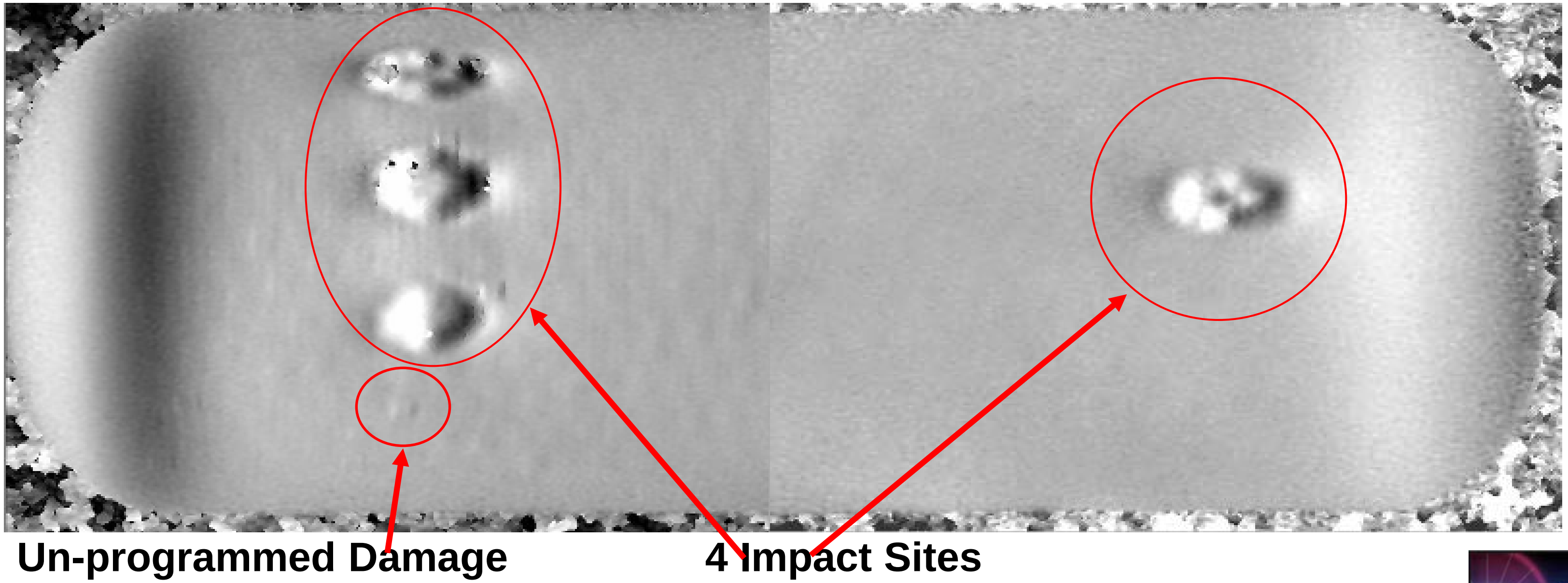


Centered At 30

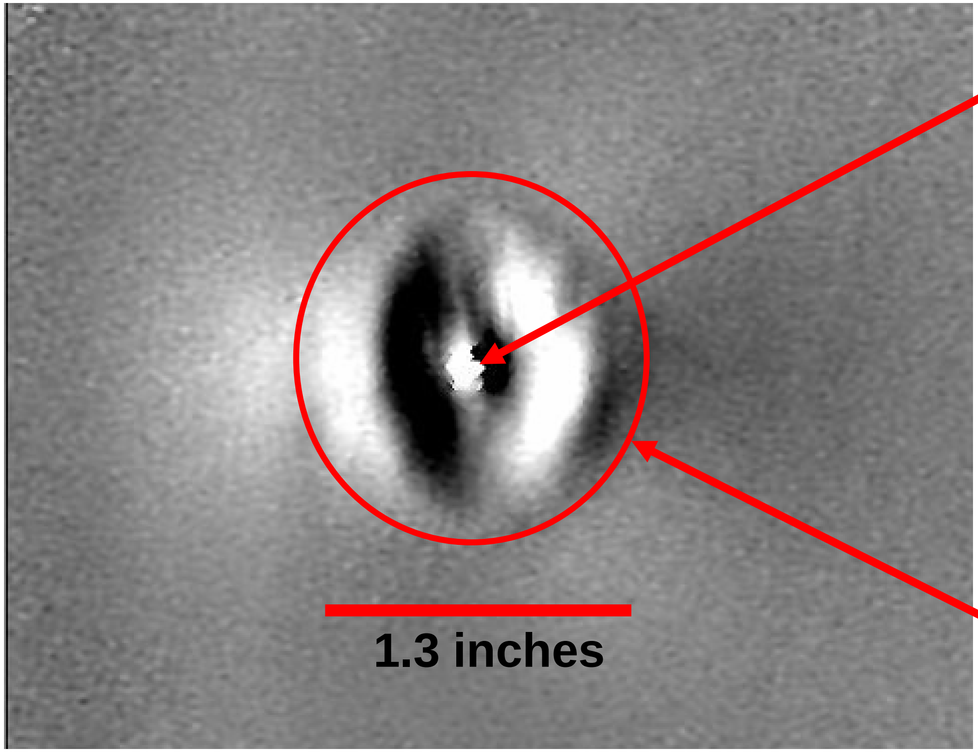
Centered At 60

Un-programmed Damage

6 x 22 Inch Graphite COPV Shearography Inspected with 10 psid. Three impact areas are seen and one small un-programmed defect.



Shearography and Visual Indications of COPV Impact Damage



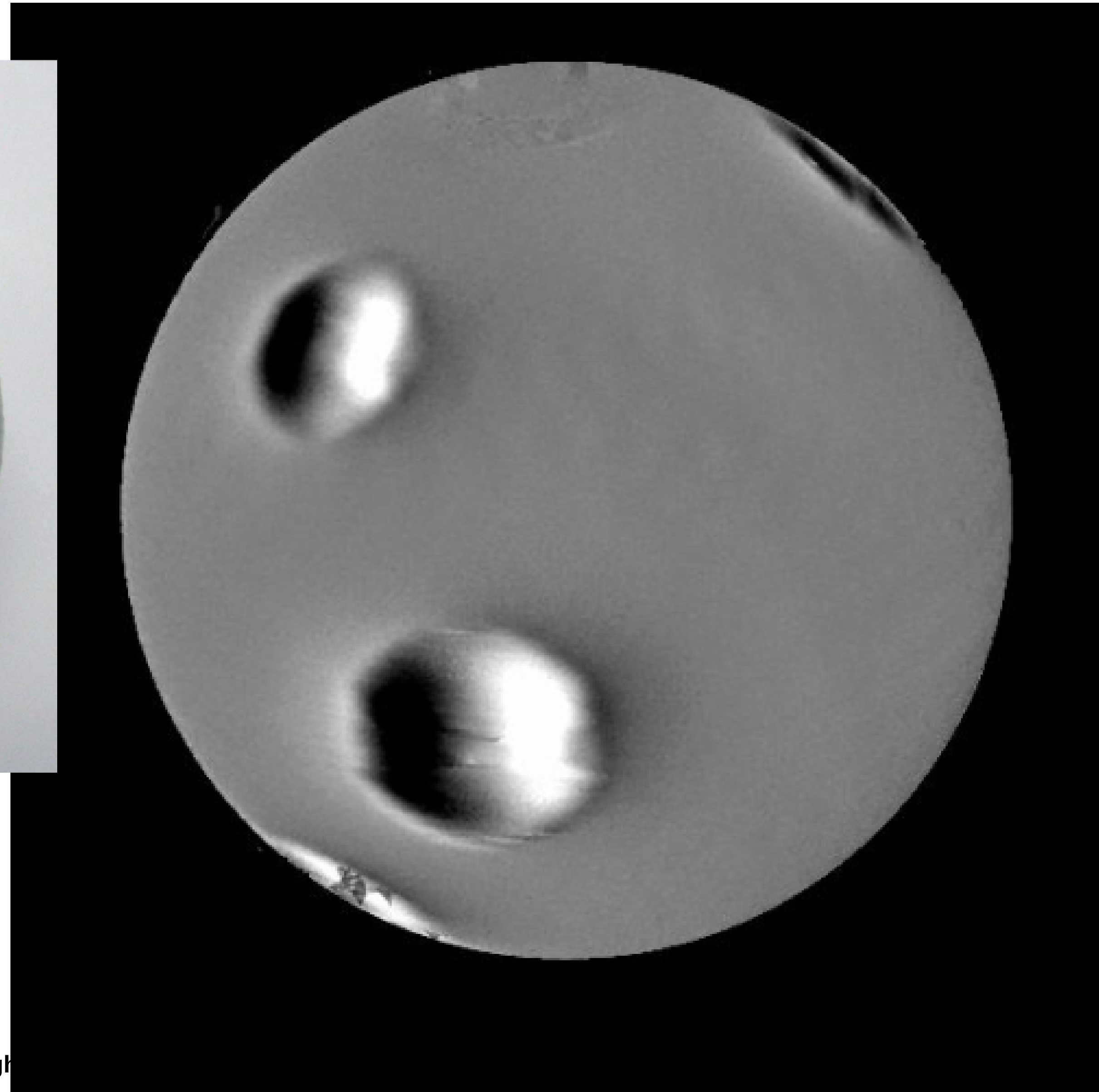
Impact Site for intentional Defects are seen visually as dimple, fiber breakage and/or color change.

Visual indication of composite damage ranged from severe fracturing at area around impact site to a small crack or dimple, to no visual indication.

Shearography indications seen in graphite COPV ranged from 0.2 to 4 inches in diameter.

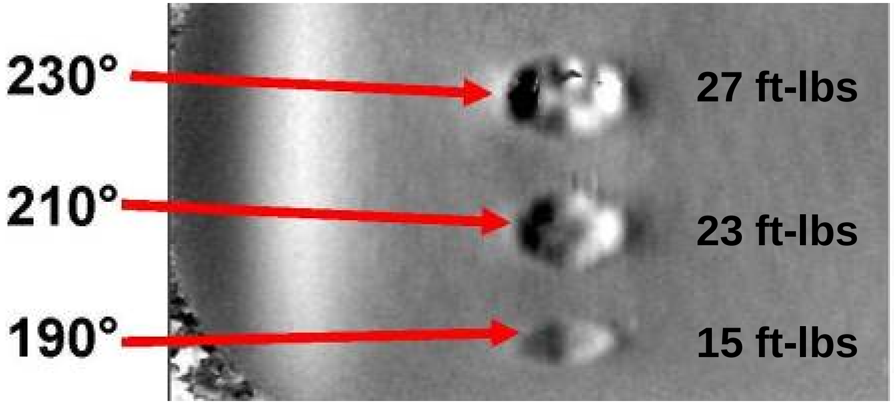
Damage Visualization 10.25-in Flight Weight Spheres

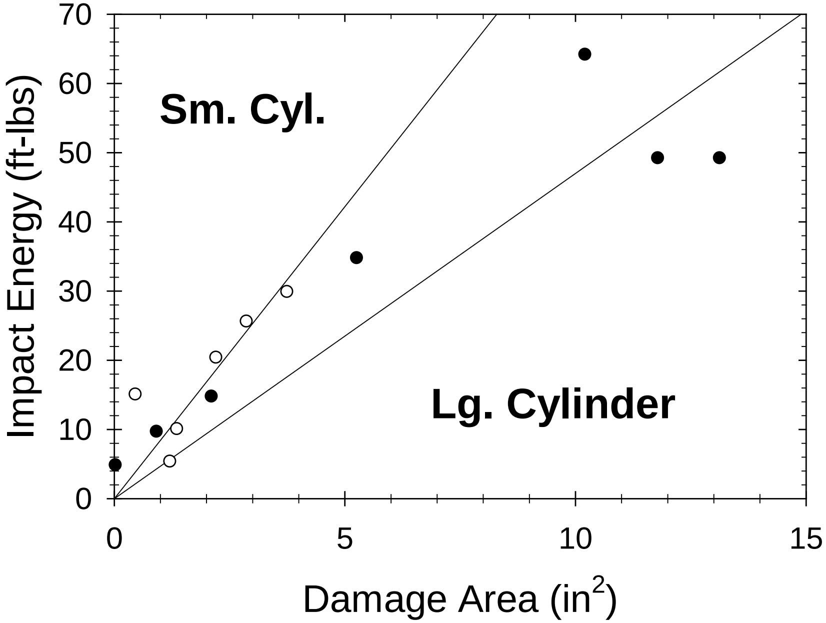
10 Inch Dia. Carbon Fiber COPV **Shearography Test with 1.2 psid**



Area of Impact Indication vs Impact Energy

1. Shearography detected small damage sites below the visual detection threshold
2. Shearography Indicated damage is much more extensive than is visually evident
3. Damage area increases with impact energy for all COPVs



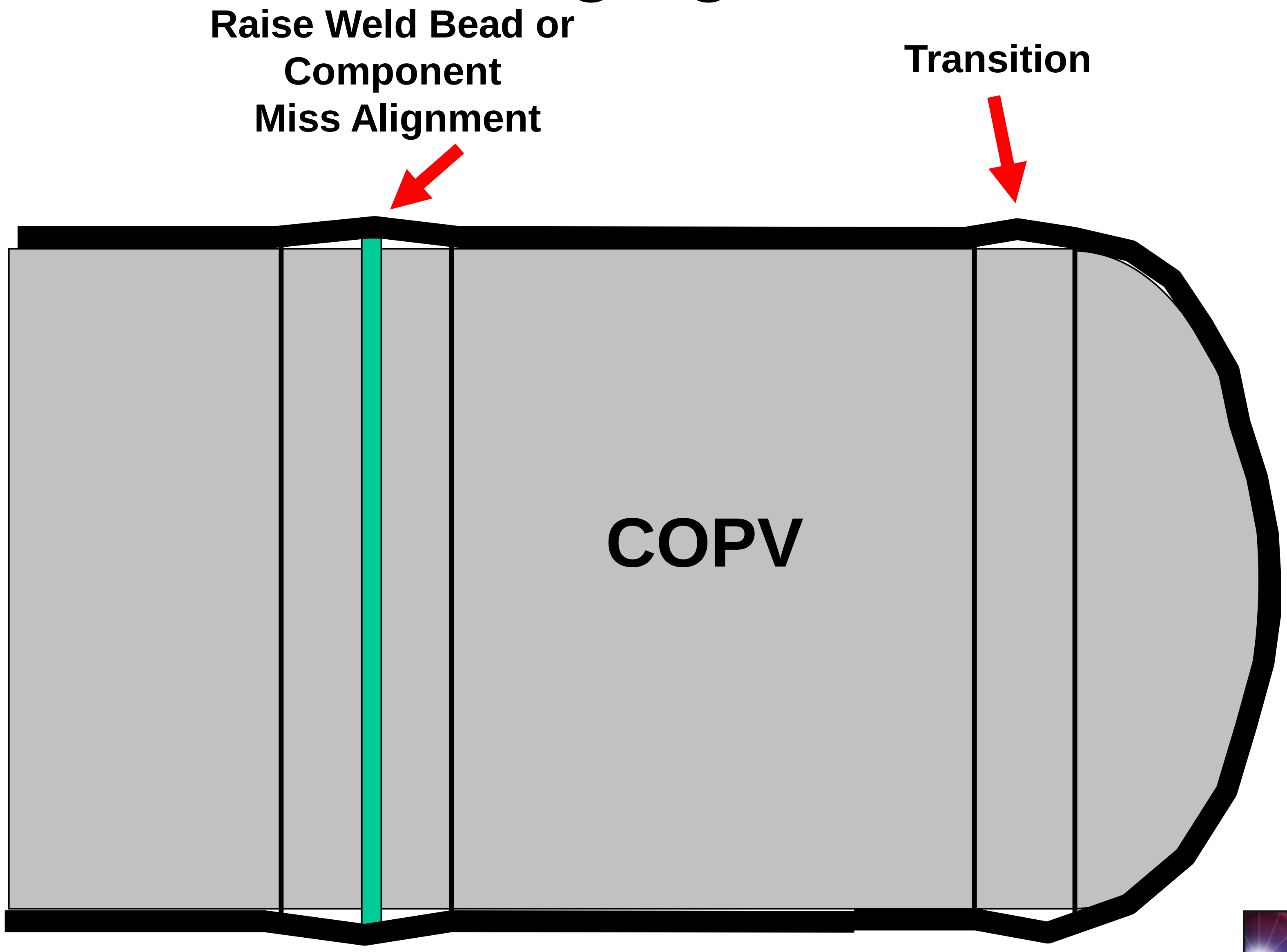


Courtesy NASA WSTF

<u>COPV Latent Defects</u>

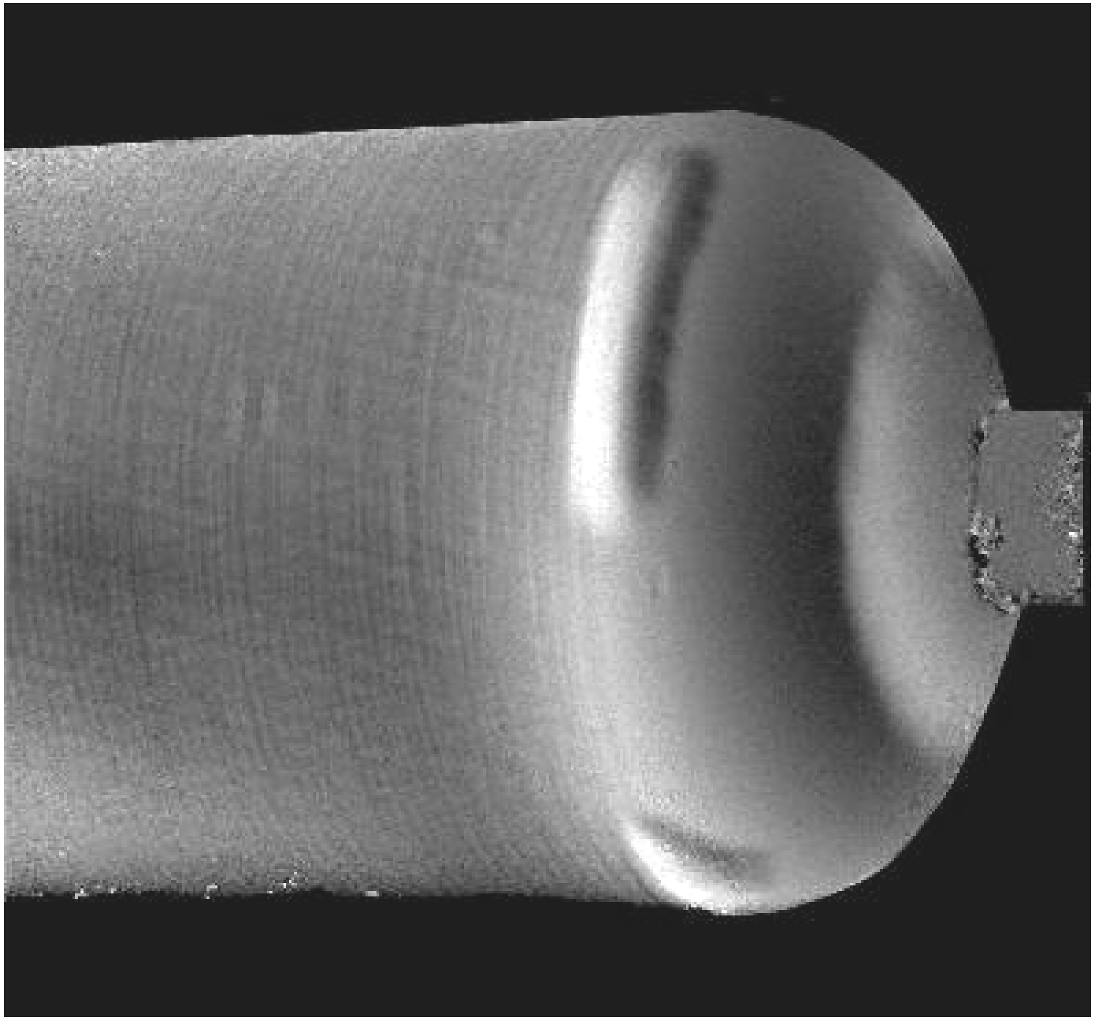
Fiber Bridging, Porosity, Liner-to-Composite Disbonds & Broken Fibers

Fiber Bridging Latent Defect



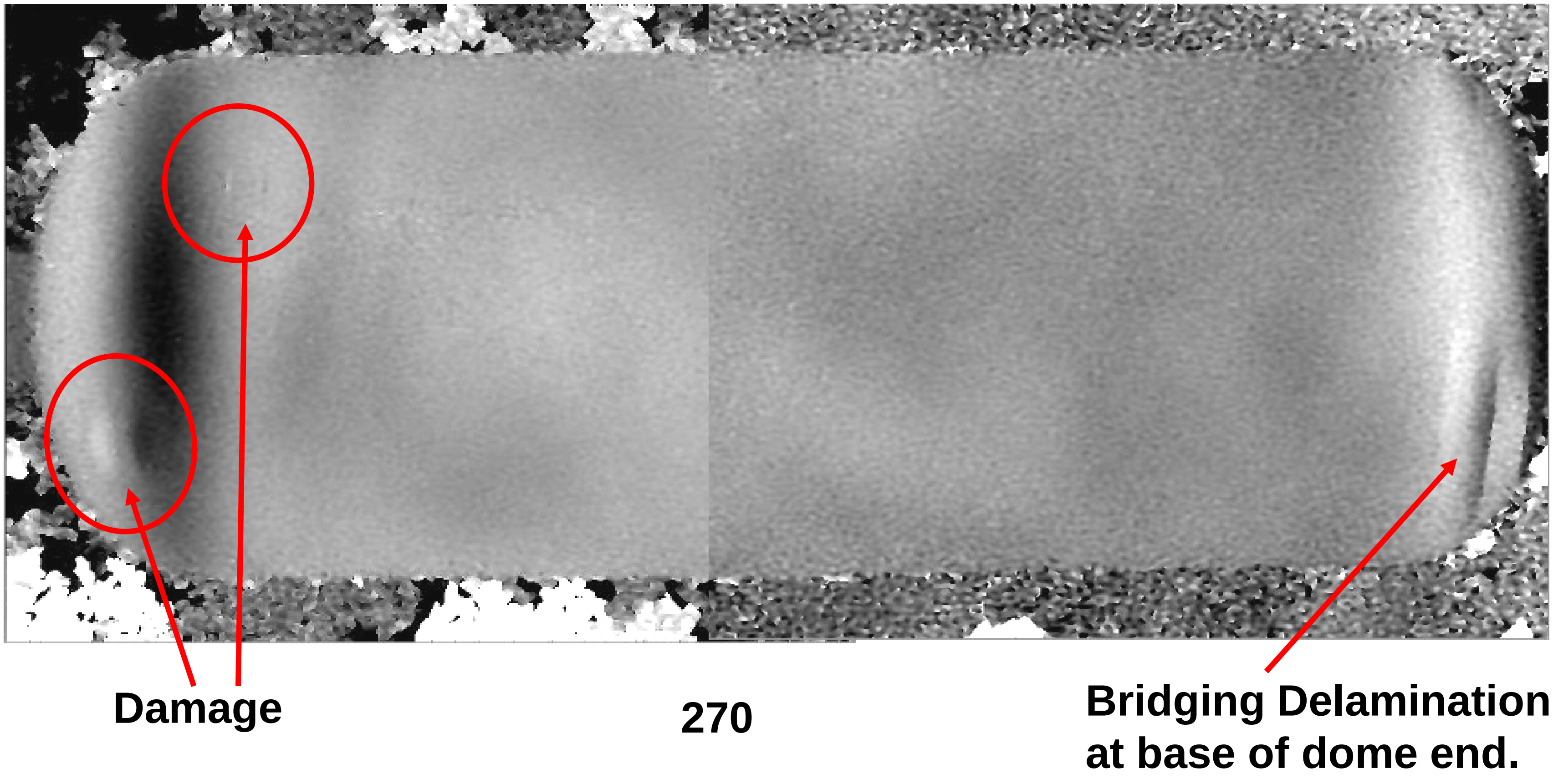
Composite Over-wrapped Pressure Vessels (COPV)

Indications of Fiber Bridging Voids



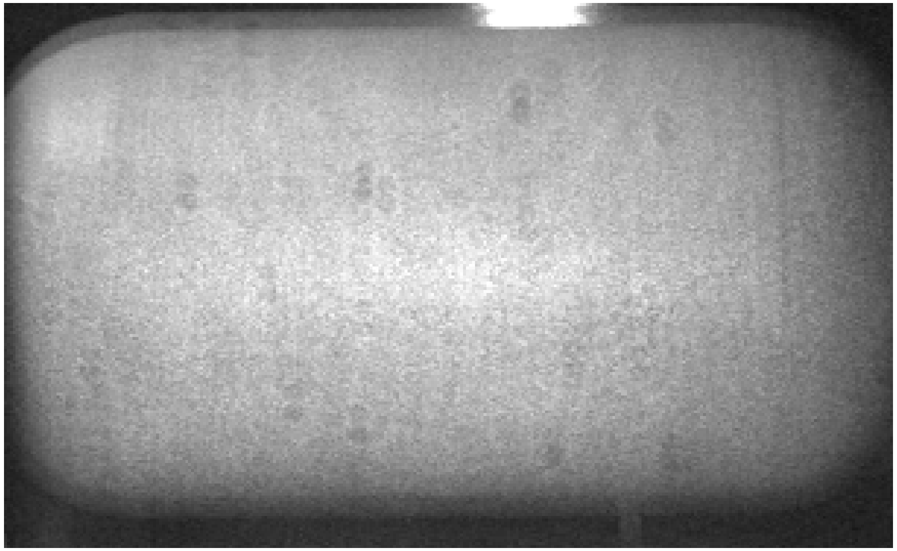
Shearography COPV Test Data

6 x 22 Inch Graphite Cylinder <u>s/n 139</u>

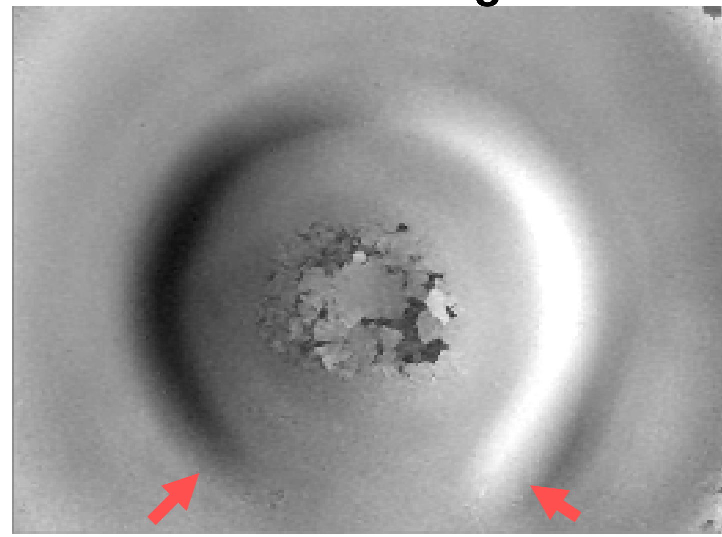


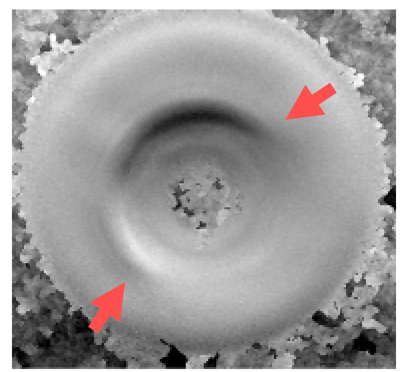
Launch Vehicle Helium COPV: Liner Disbond And Fiber Bridging

COPV Tank as seen live thru shear cam

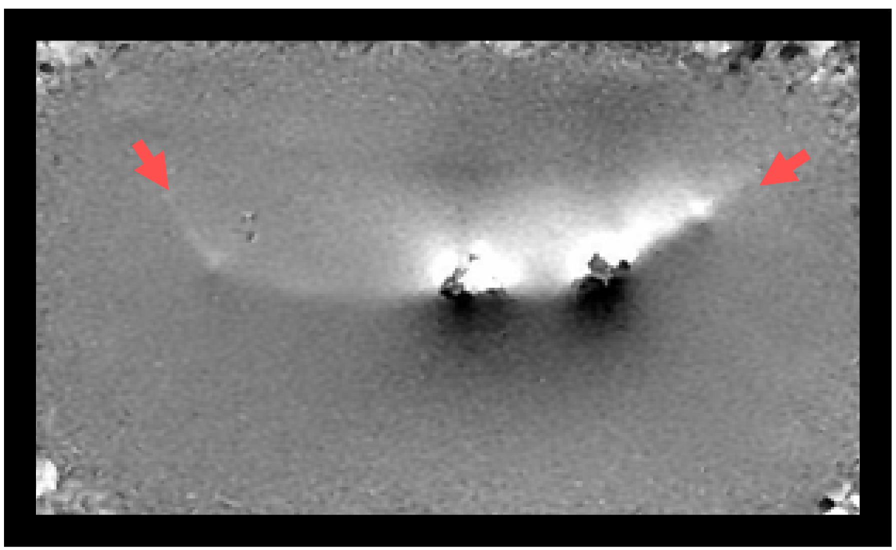


Fiber Bridging 280 around tank end fitting.





Fiber Bridging 180 around tank end fitting.



Shearography image showing debonding of metal liner from composite over wrap.

COPV as received at LTI. White circles are areas where fluid emerged during hydrostatic pressure testing. COPV failed to reach proof load.

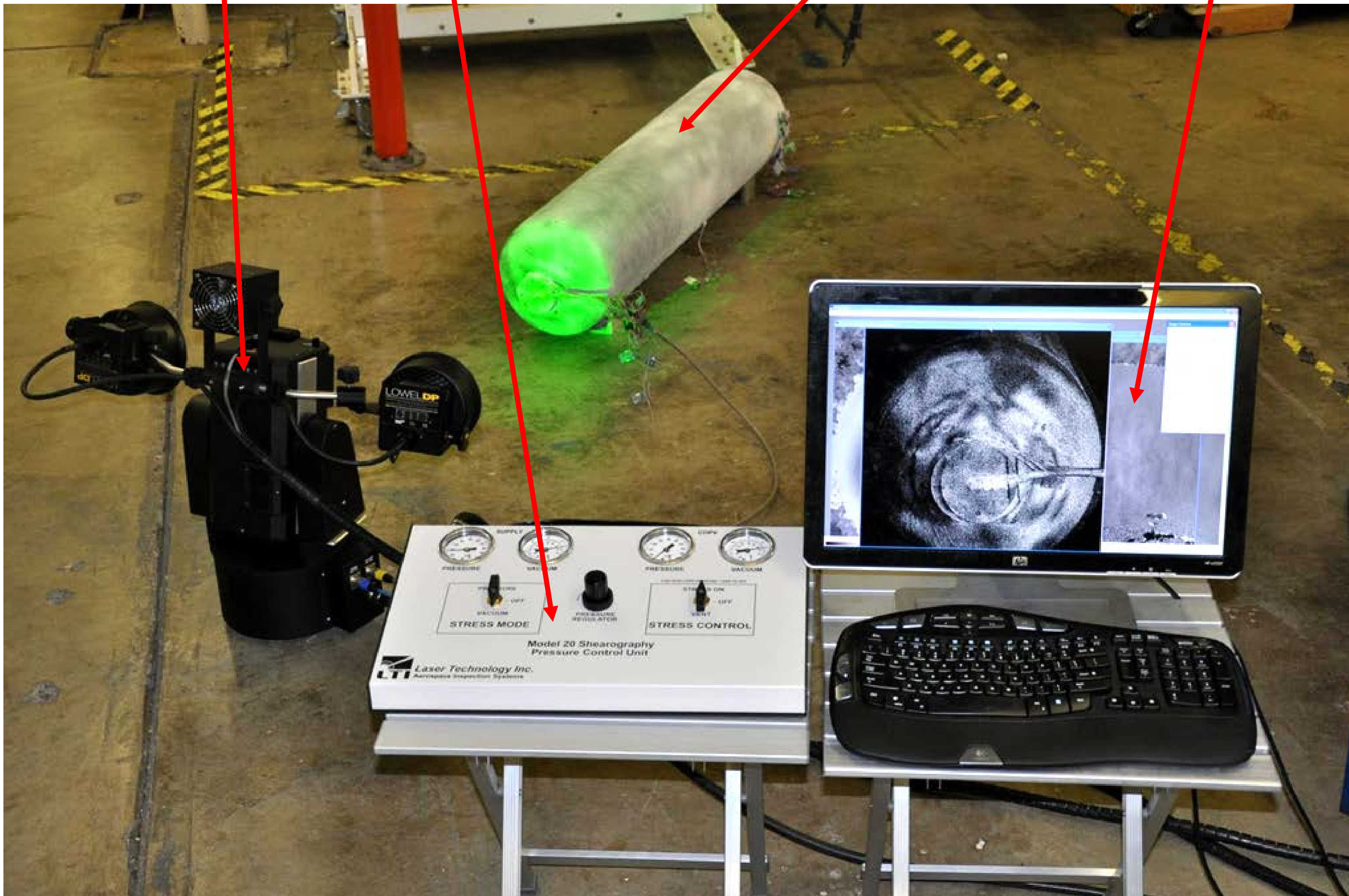
50 Inch COPV Shearography Test Set Up

LTI-5100HD Shear Camera

Model 20 COPV Test Unit

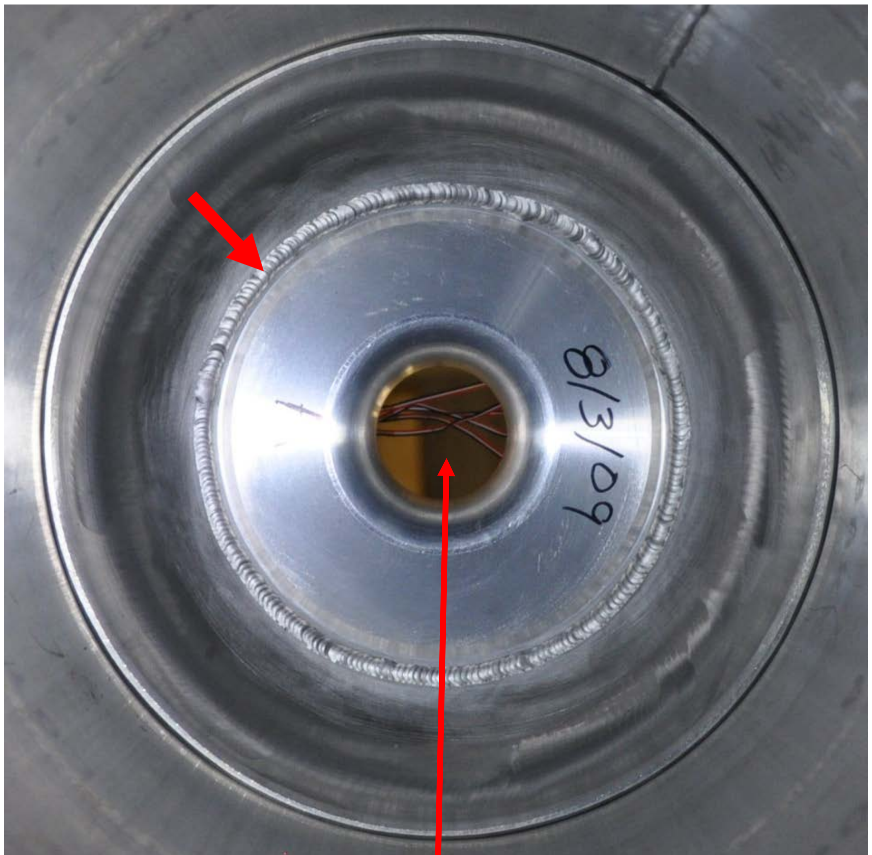
Test COPV

Monitor



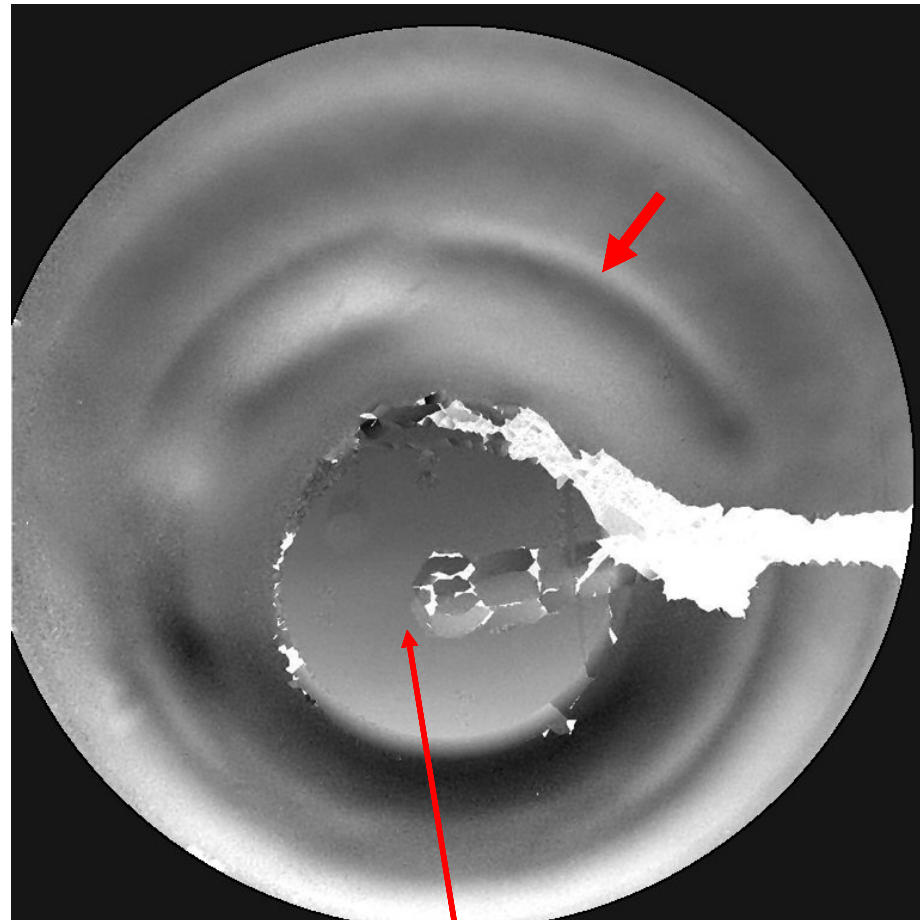
Bridging defects and voids appear at the location of the boss-liner weld (red arrows).

Photo of left end dome from inside tank.



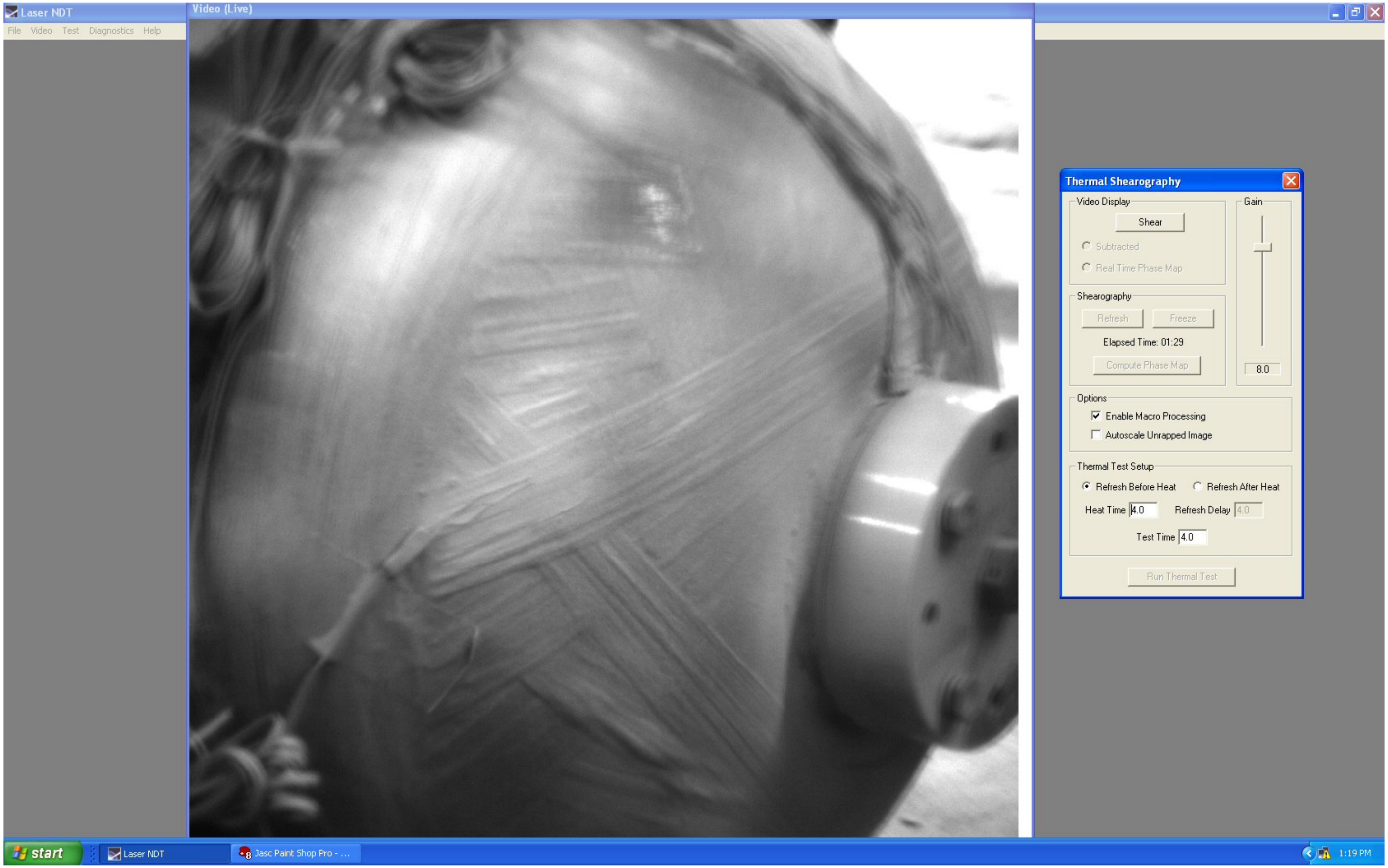
Boss Opening

Shearogram from outside

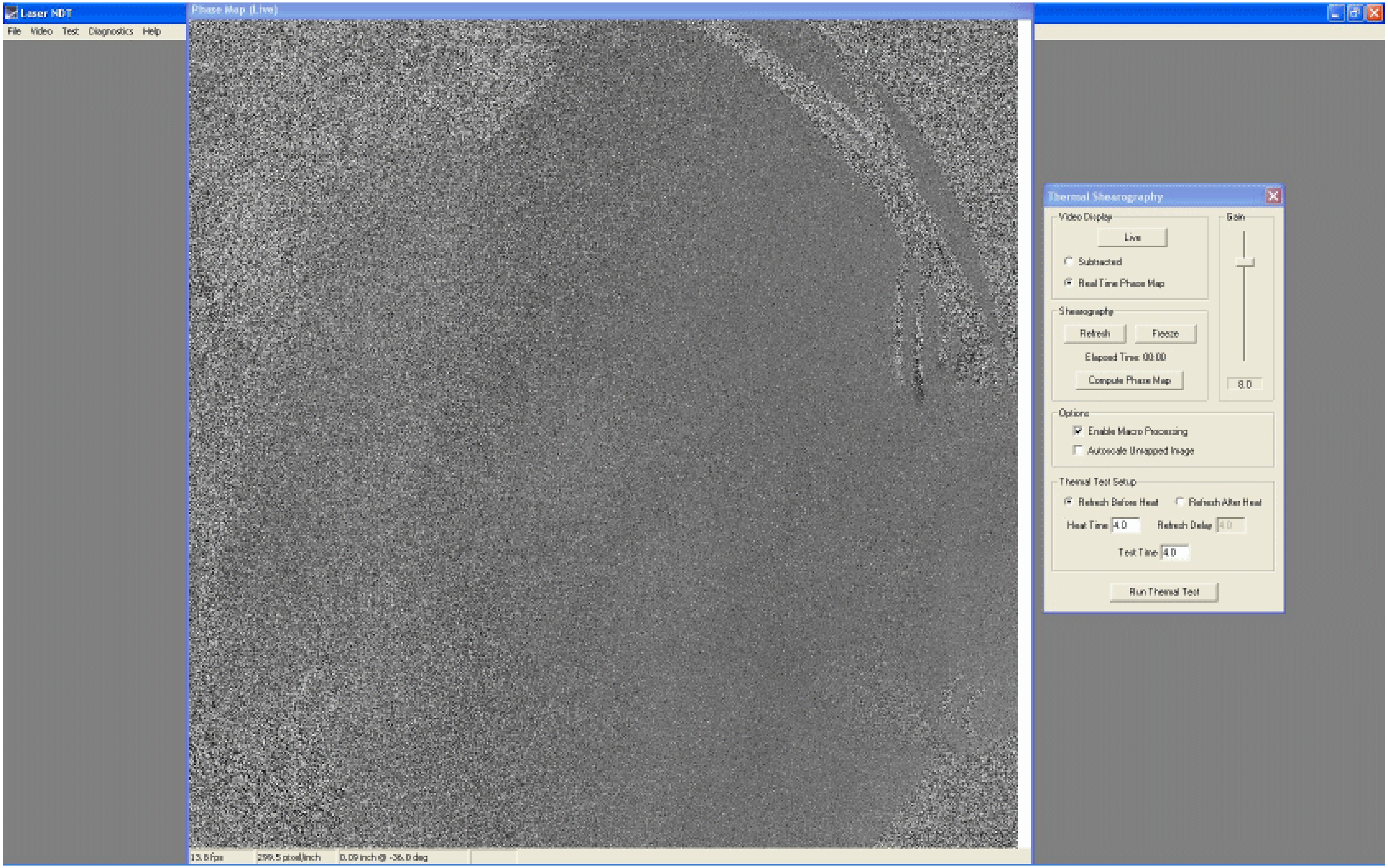


Bolted Aluminum Flange

8 x 50 Inch COPV End Dome Damage



8 x 50 Inch COPV End Dome Damage

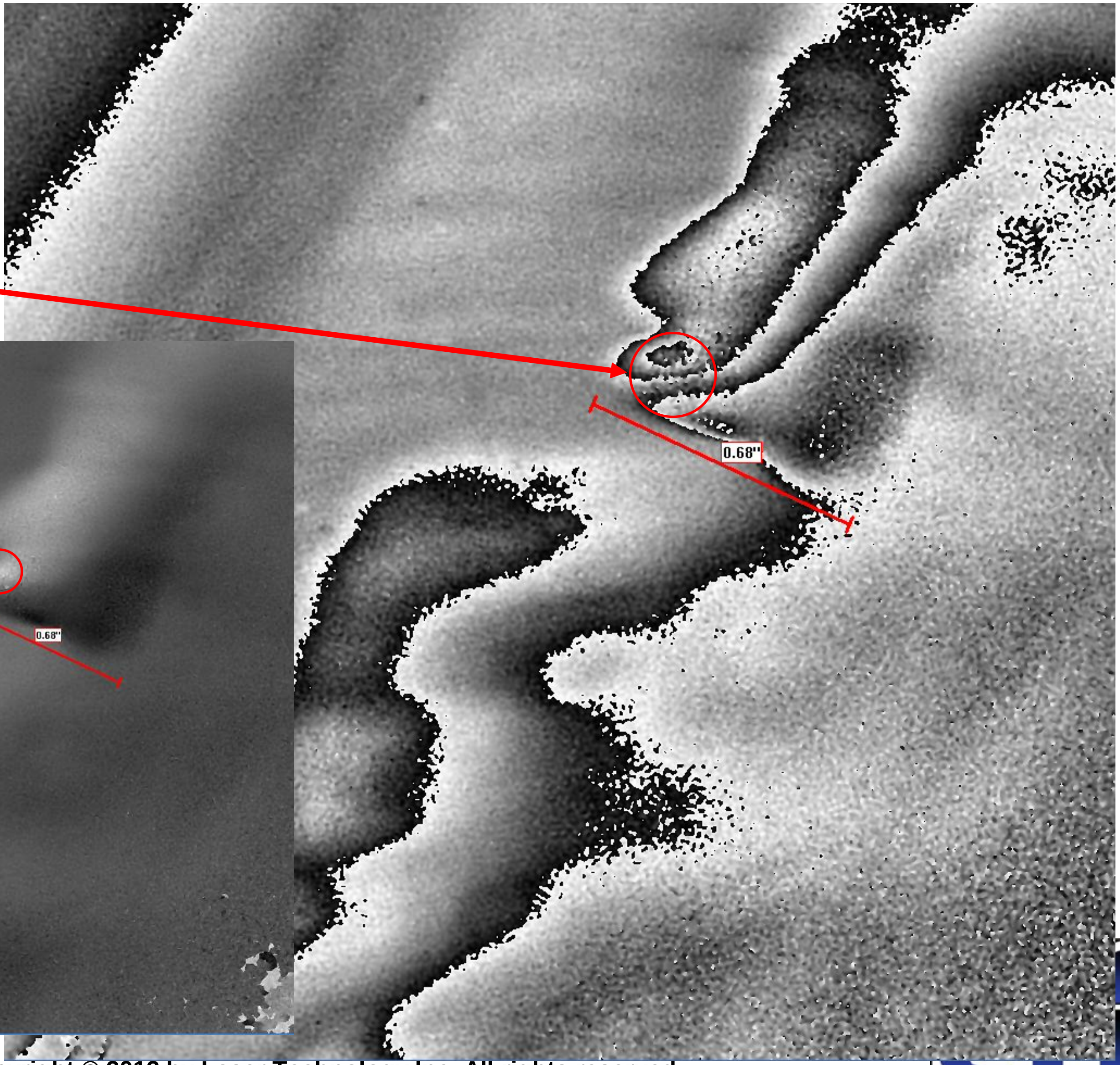


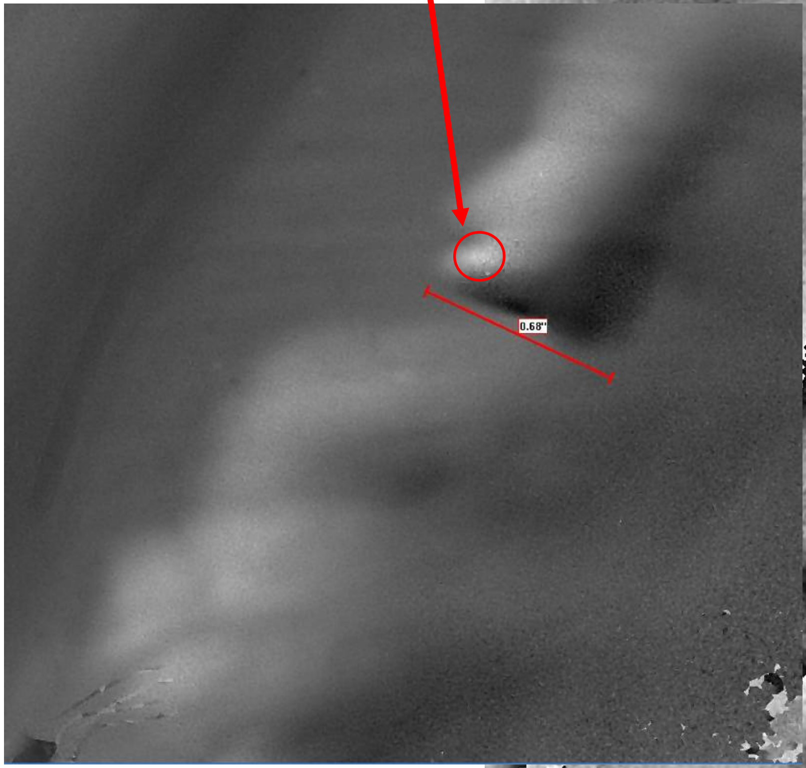
Defect Dimension Measurement Tool

Impact Damage Induced Delamination

Width= 0.68 inches to 1.4 inches

Impact Site



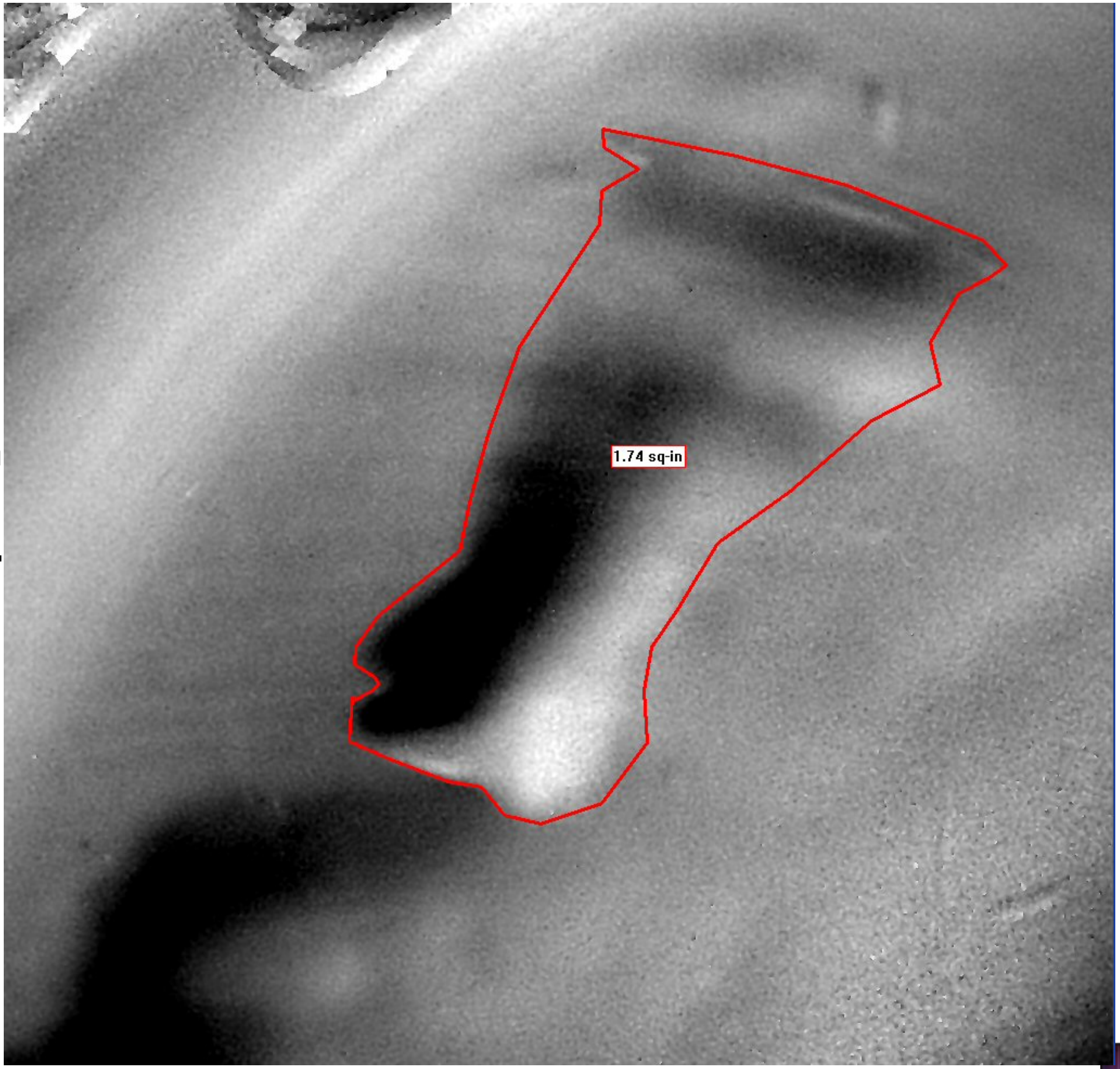


Unwrapped phase Map Image

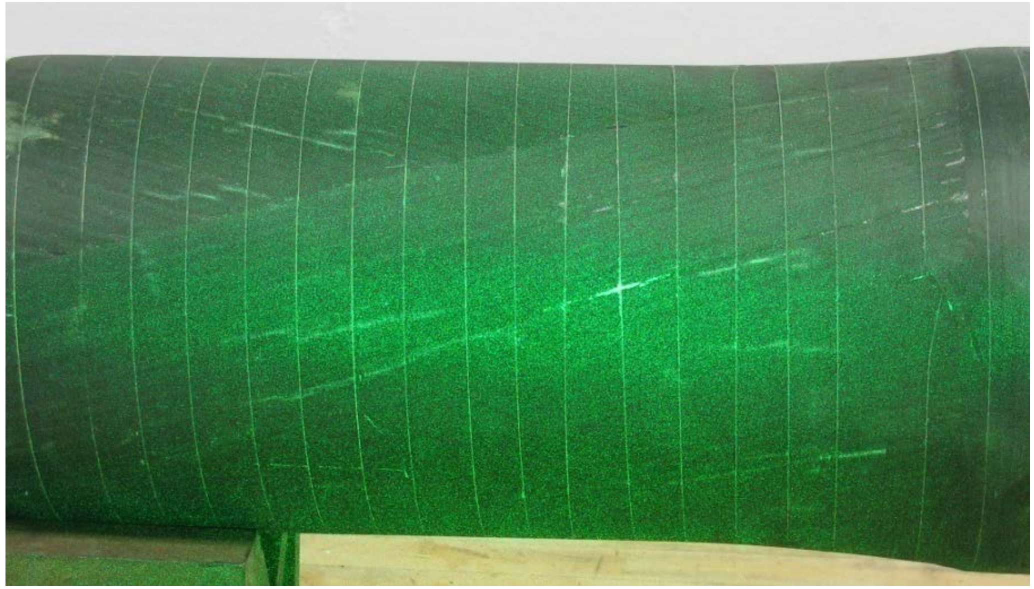
Defect Area Measurement Tool

Impact Damage
Induced Delamination

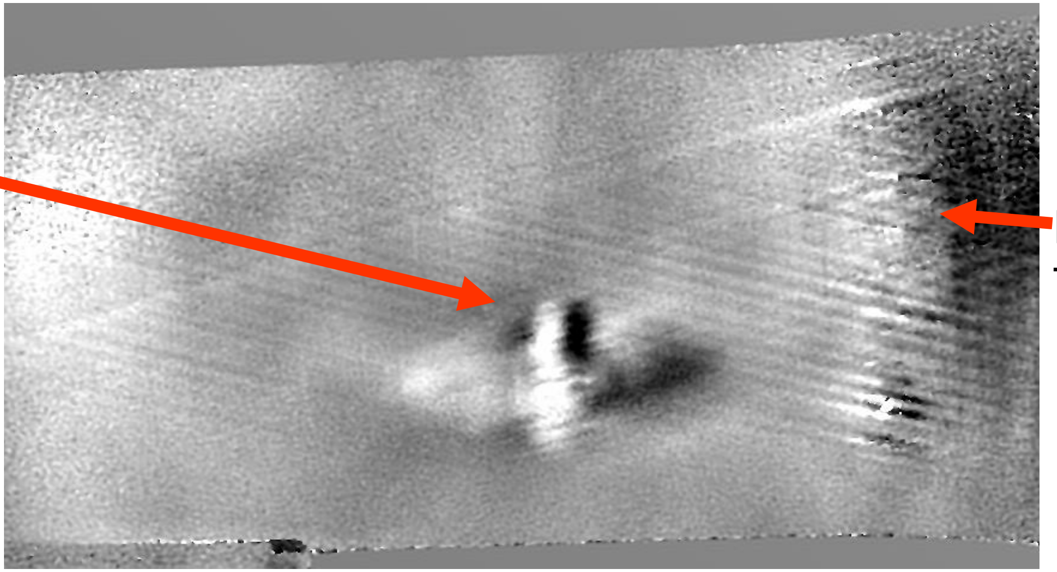
Area of Part of Delam.
1.74 sq. in.



CPV with Non-Visible Impact Damage and Porosity At Diameter Transition

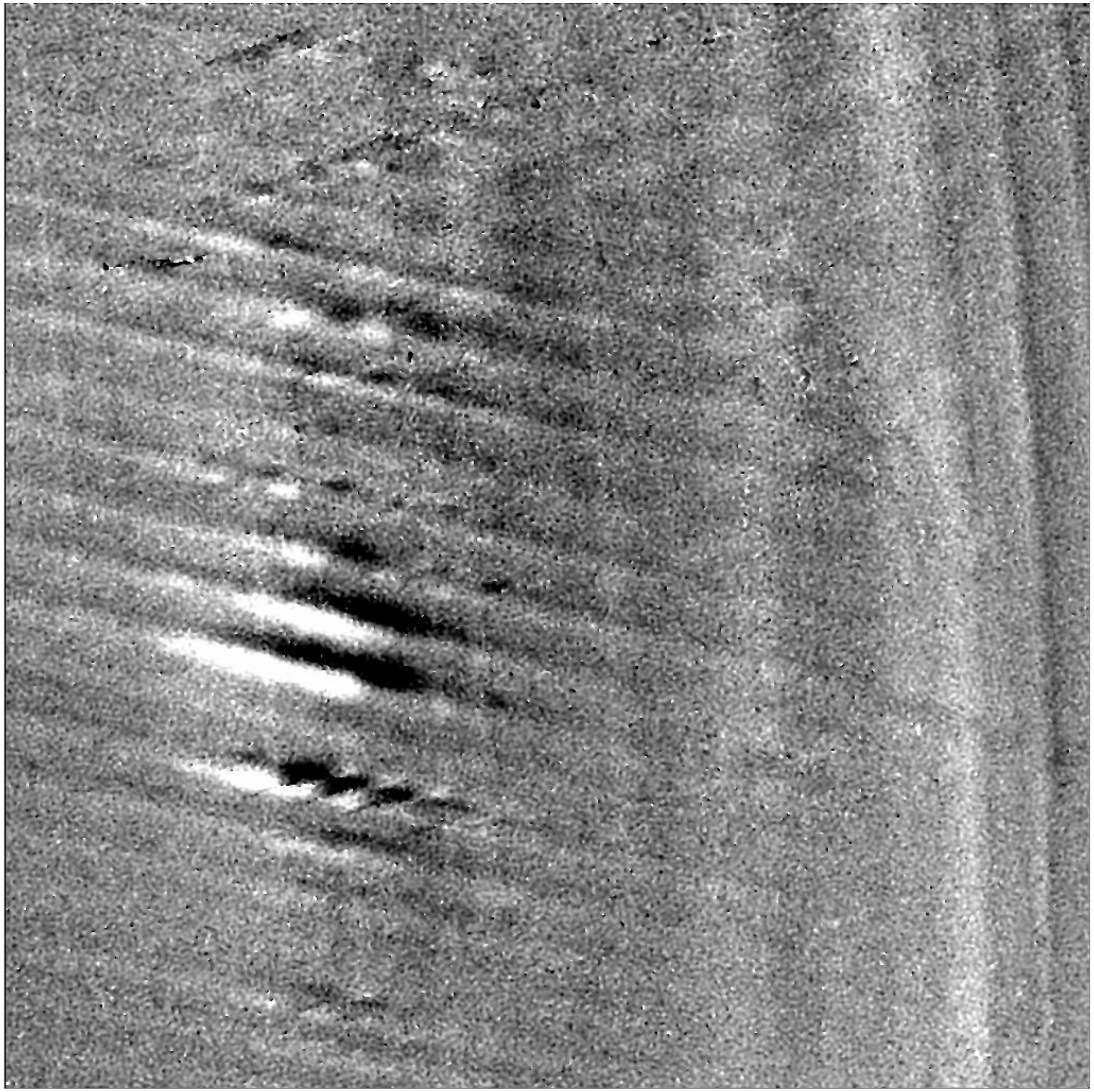


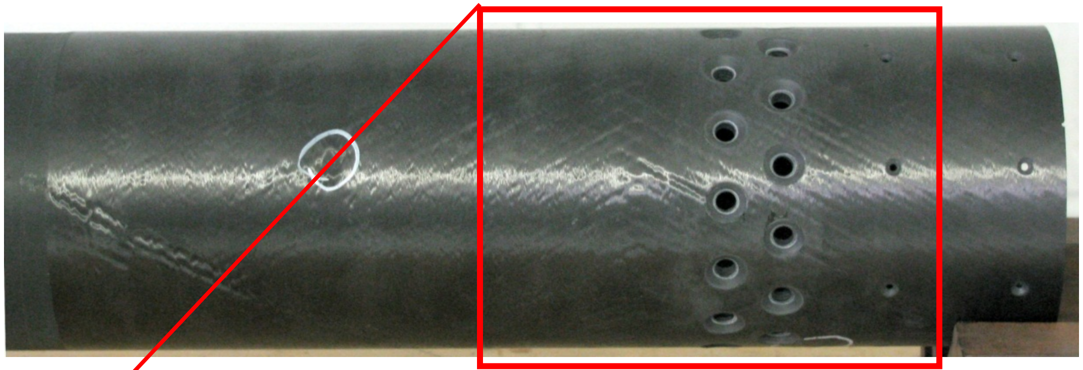
Non-Visible Impact Damage



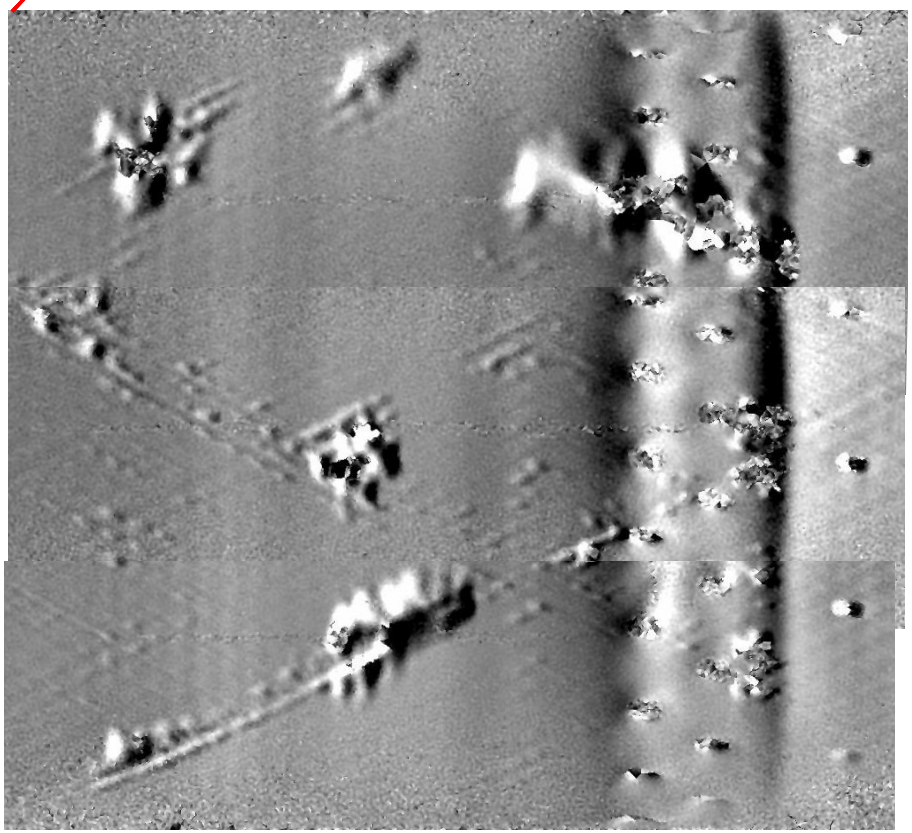
Porosity at Transition

Close-Up Porosity at Transition





Internal Thermal Stress Load for Rocket Motor Casing

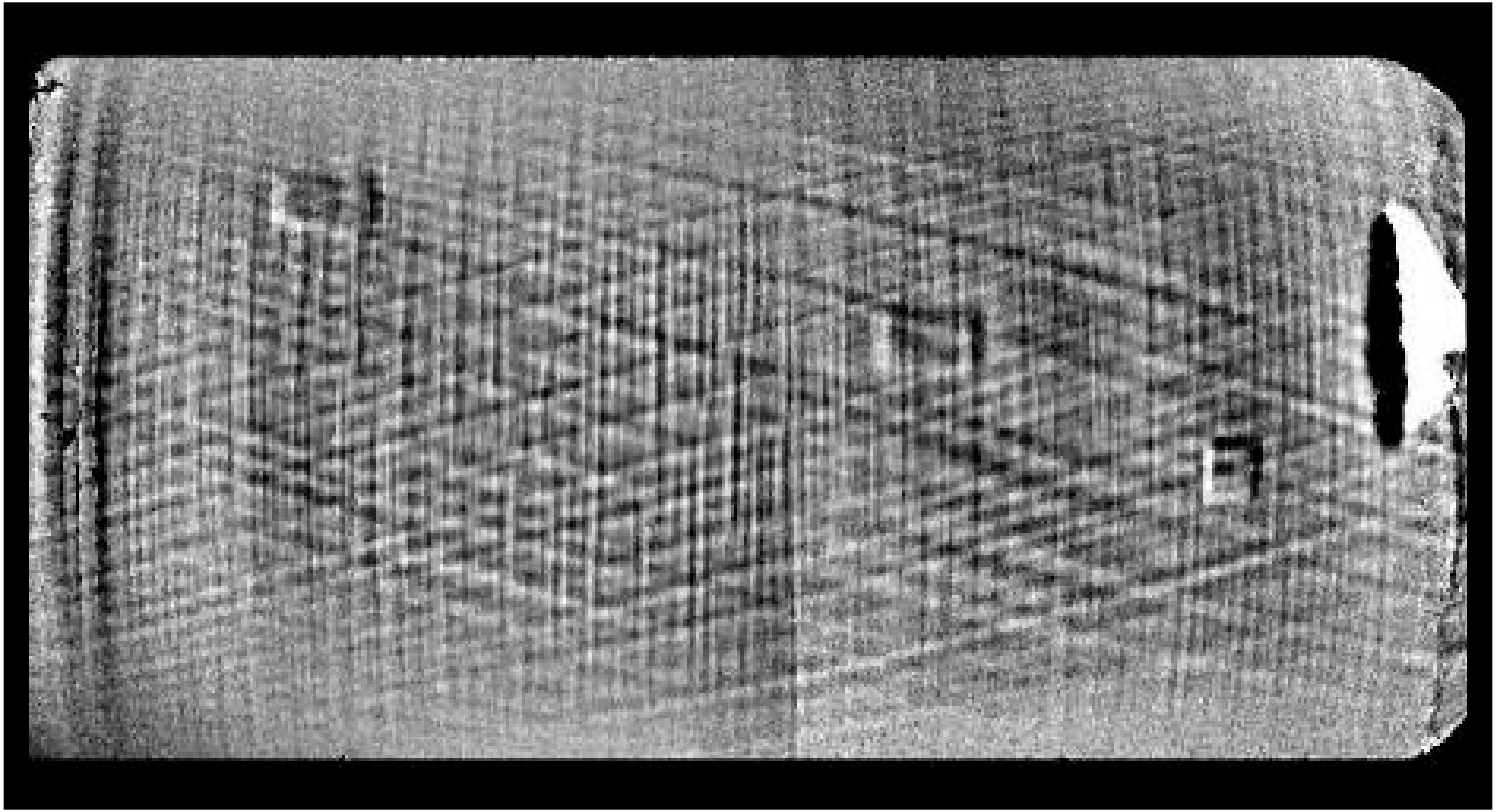


- Porosity
- Delamination
- Poor Compaction

Thermal Shearography: Composite to Liner Disbonds

-Teflon inserts at liner

- Fiber Bridging at Transition



Broken Fiber Detection- Carbon Fiber COPV

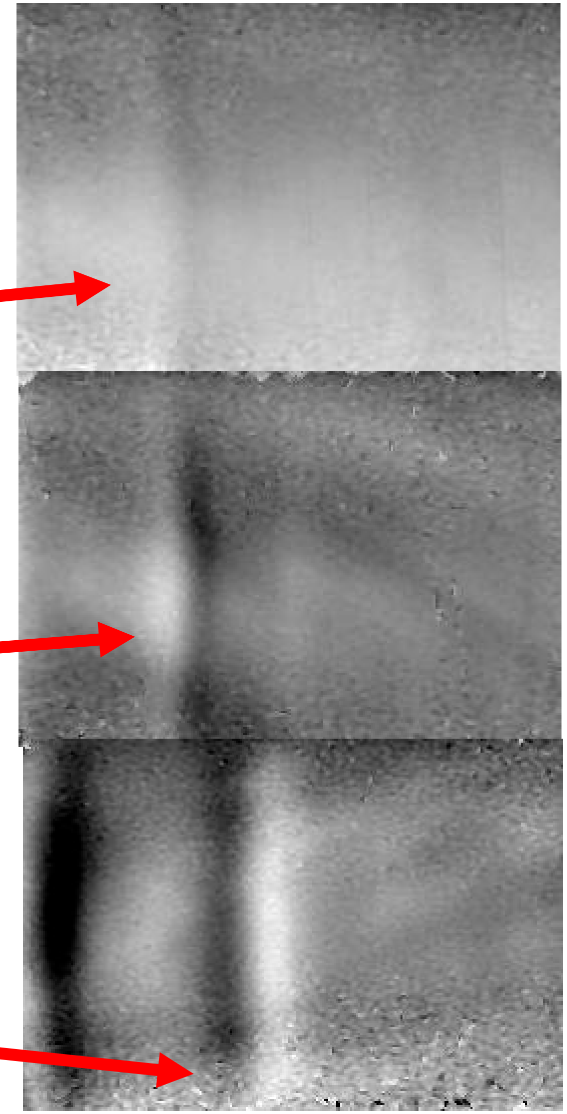
3 COPV with various width fiber cuts
- **Shear data taken between 25-45 psid.**
- **Shear Vector 0.12 in. @ 0**

Carbon Fiber Test COPV and LTI-5100 Shearography Camera.

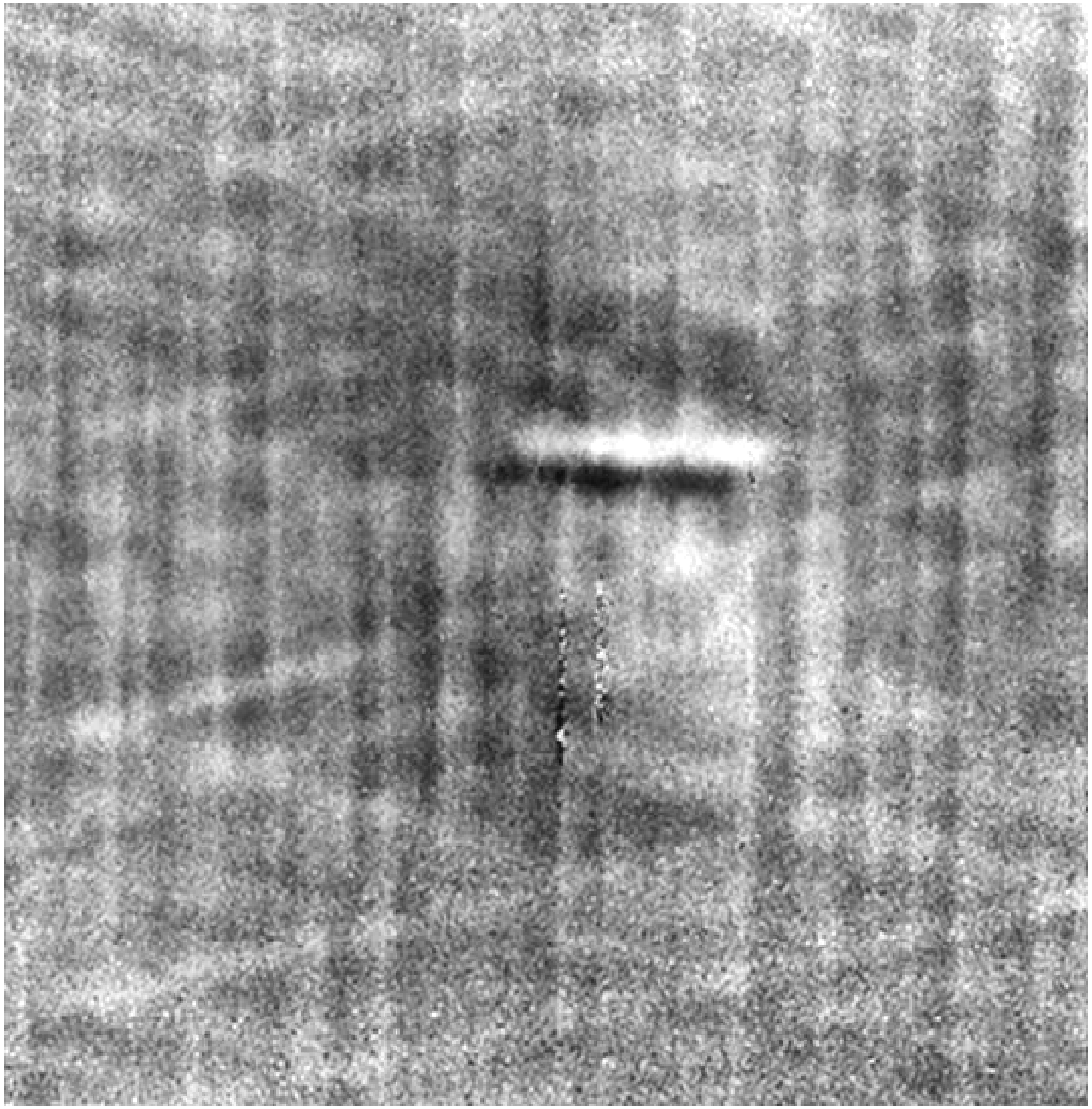
Cut Fibers 0.050 in. wide

0.100 in. wide

0.150 in. wide

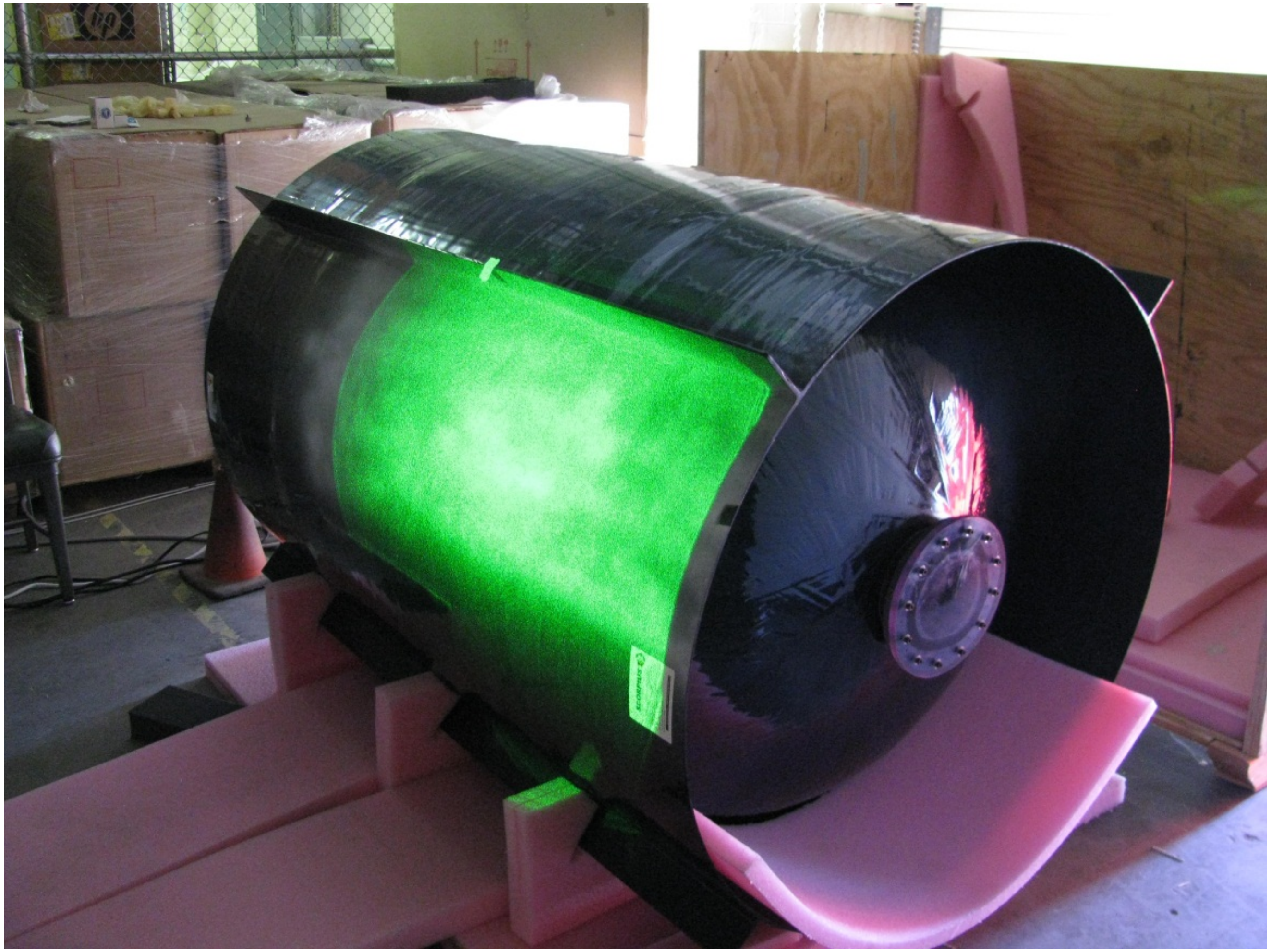


Cut Fiber: 18 Inch Carbon Fiber COPV



CPV Test at WSTF

CPV Manufactured by: Scorpius Space Launch Company
Unibody All-Composite Pressure Vessel



Data presented with permission of Microcosm, Inc. & NASA WSTF

Shearography Test Set-Up for Scorpius Sapphire CPV Inspection

CPV Pressure Gage   CPV   Thermal Lamps (1kW x 2)   LTI-5100HD Shear Camera

Pressure Control Manifold

Data presented with permission of Microcosm, Inc. & NASA WSTF

Shearography Test Set-Up for Scorpius Sapphire CPV Inspection

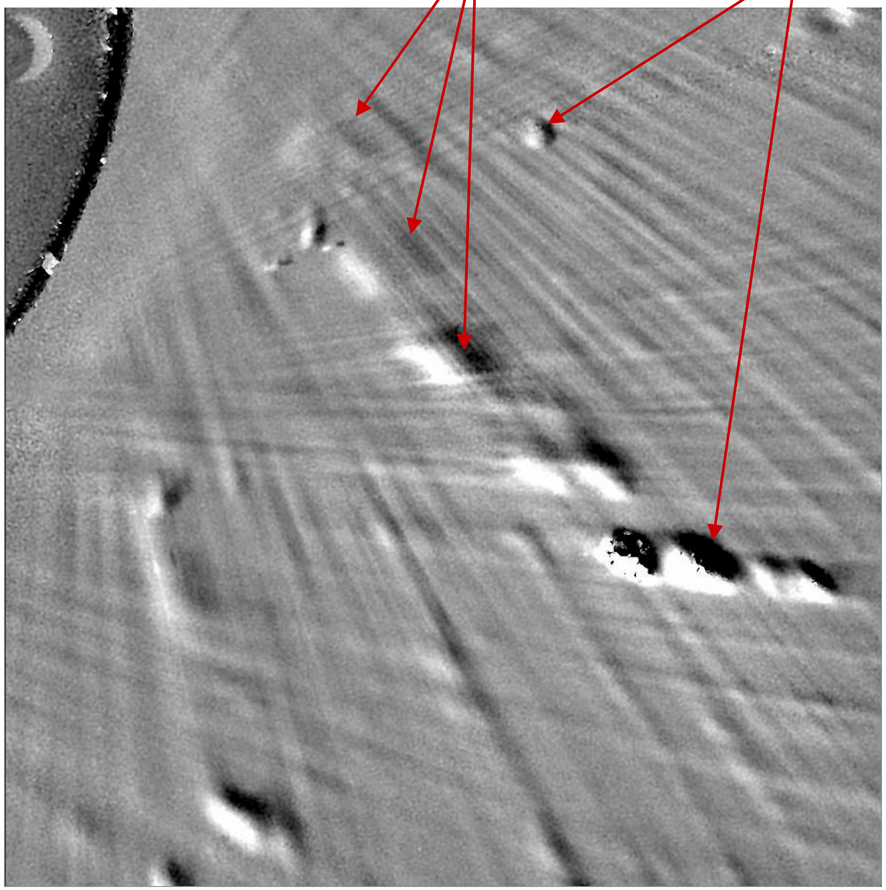
End Dome Inspection

End Dome Inspection – Camera centered over each dome quadrant

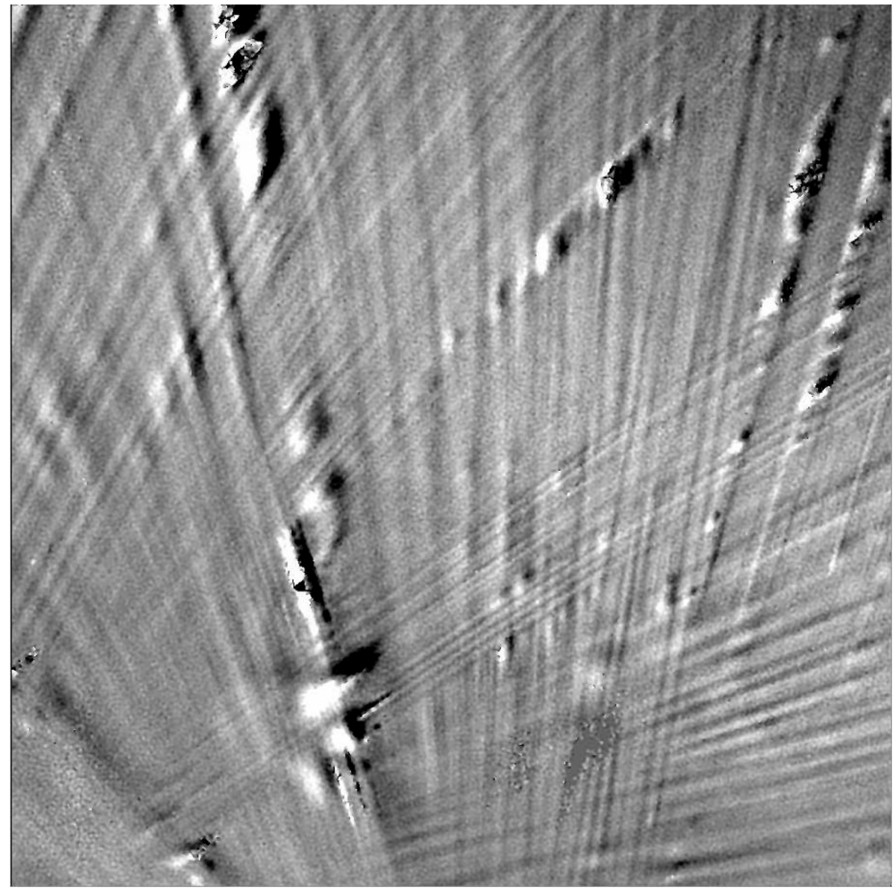
Data presented with permission of Microcosm, Inc. & NASA WSTF

Typical Shearography Indications Detected on Sapphire 77 CPV (Thermal Shearography)

Void Indications: Deeper & Near Surface



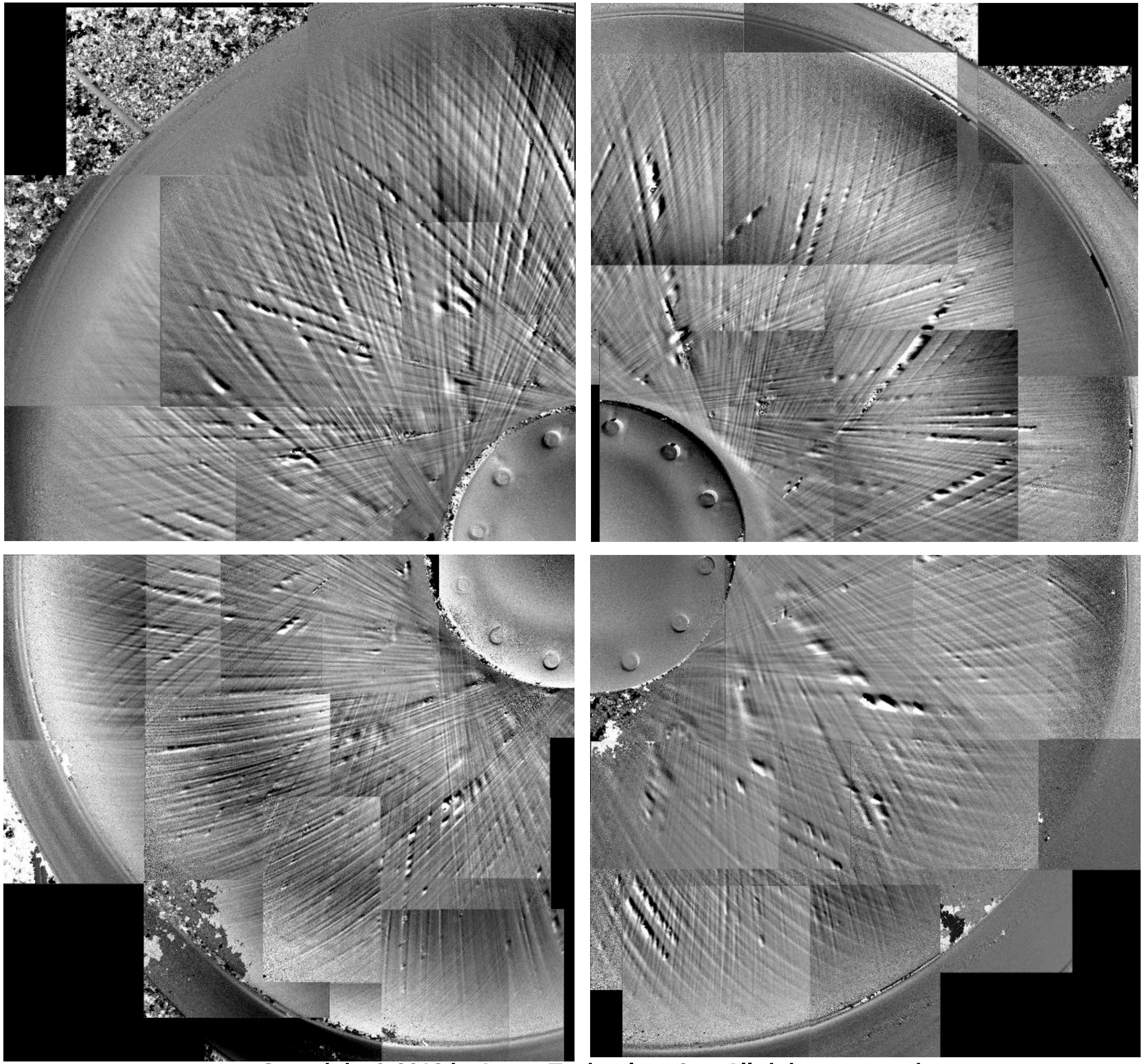
Voids and Porosity Along Fiber Tows



Note: By design, voids detected do not affect CPV performance.

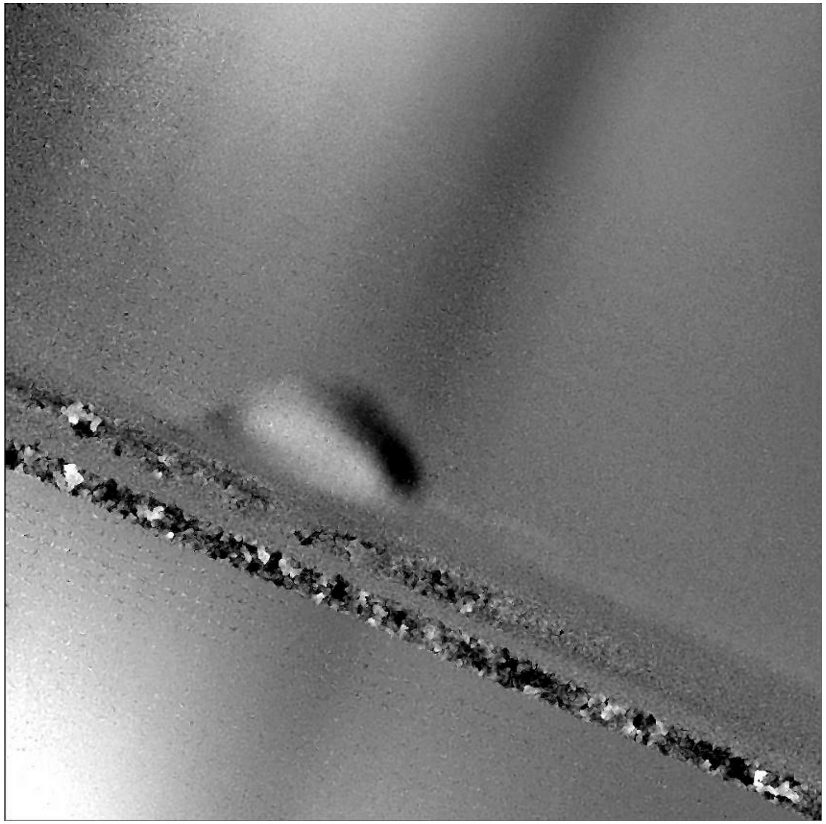
Data presented with permission of Microcosm, Inc. & NASA WSTF

Label End Dome- Thermal Shearography RBH, H=2 sec., Sv= 0.18 inches @ +45

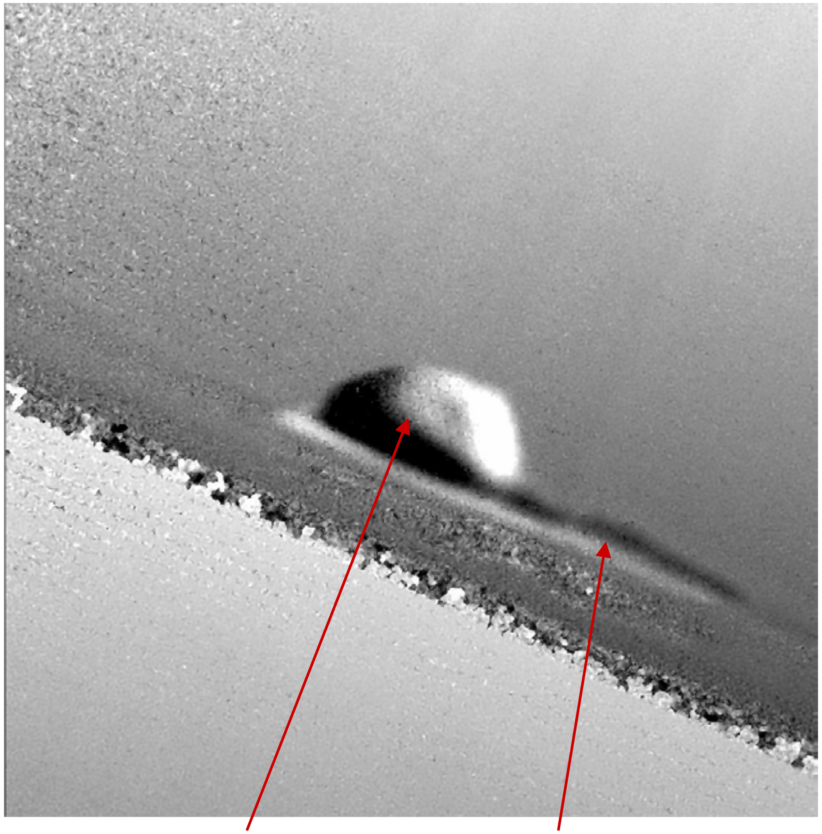


Data presented
With permission
of Microcosm,
Inc. & NASA
WSTF

<u>Pressure Shearography</u> 1psid.
Delamination detected.



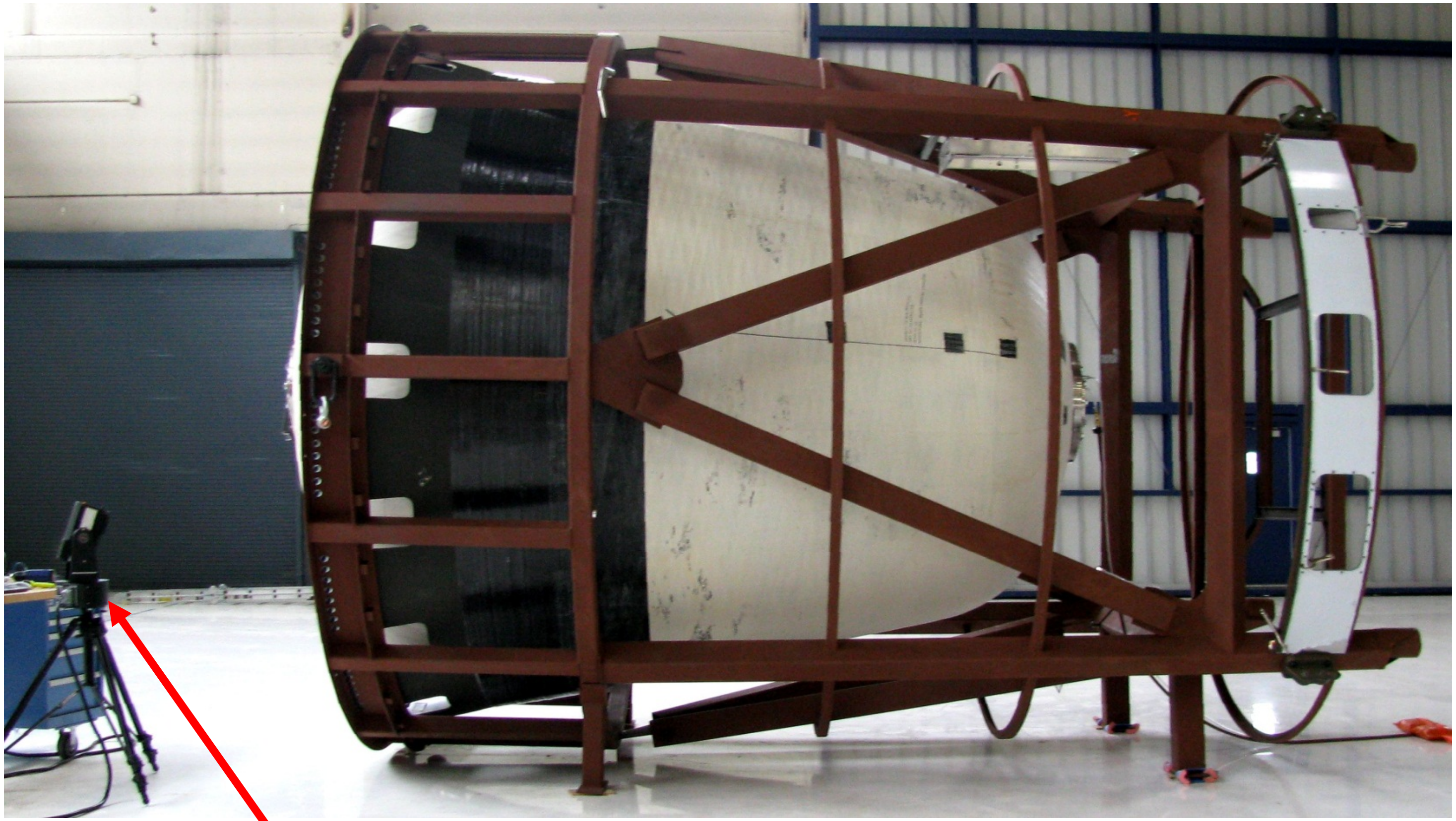
<u>Thermal Shearography</u> showing both delamination and fiber bridging at stringer to barrel section transition. Delamination axial length estimated at 3 inches (image was not calibrated)



Note: By design, fiber bridging at stiffeners joints detected do not affect CPV performance.

Launch Vehicle Propellant COPV

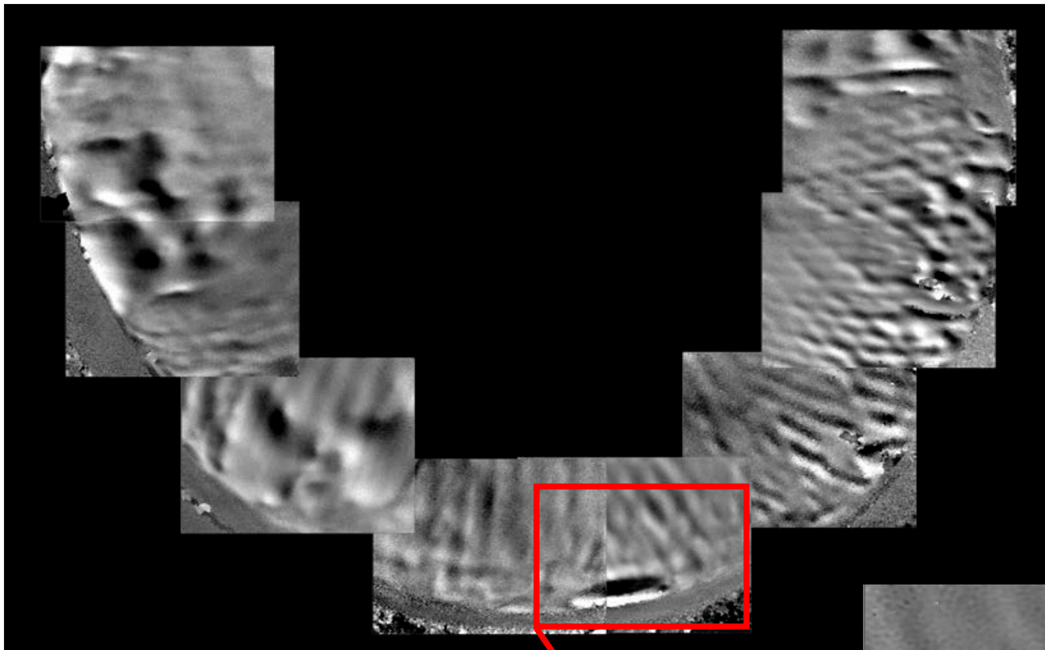
Carbon Fiber 114 x 130 in. COPV for launch vehicle propellant.
Shearography used to evaluate structural integrity of end dome.



Shear Camera

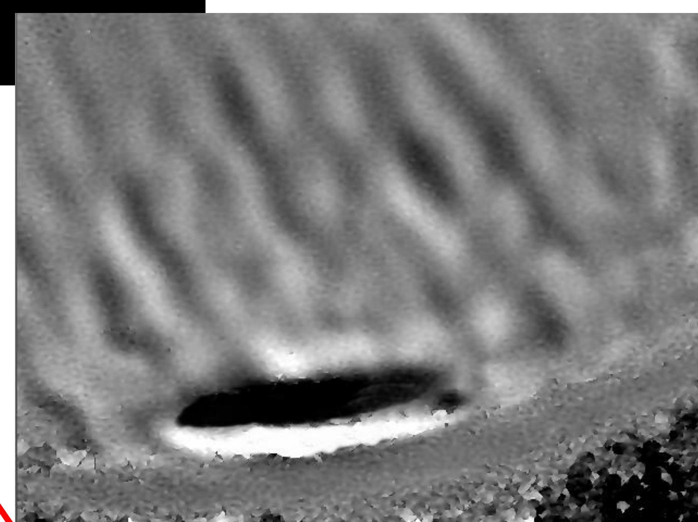
Courtesy Blue Origin

Circumferential Scan 114 x 130 Inch COPV

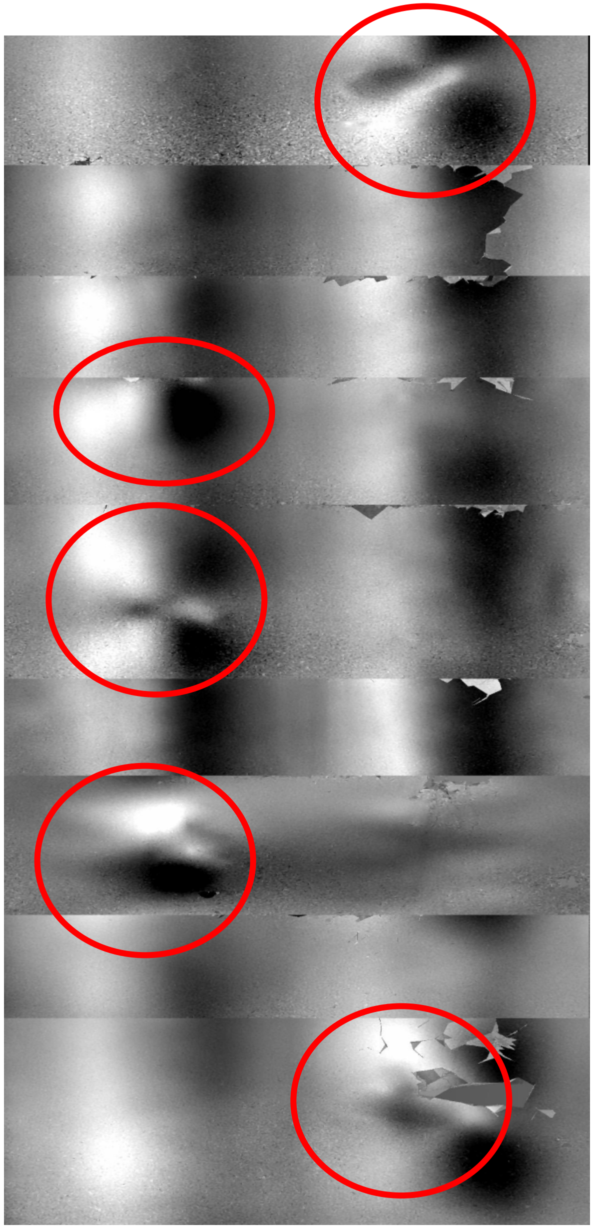


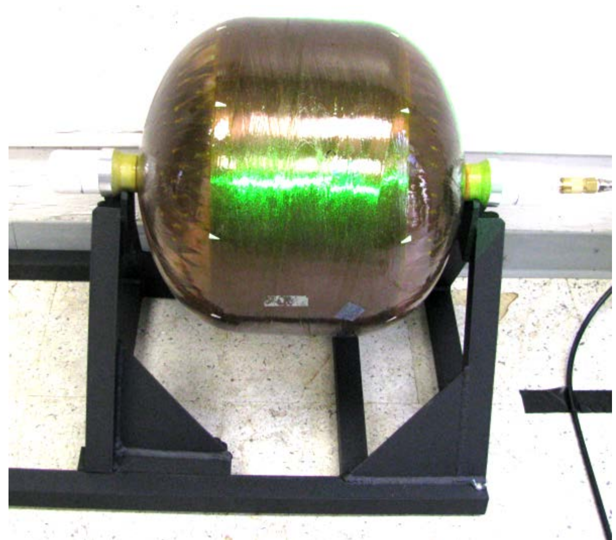
Reject Criteria based on:
- **Area**
- **Z axis deformation/psi**

Rejectable Damage Area
11 x 2 in./60µ/psi



Mars Exploration Rover Cruise COPV Fuel Tank: Liner Wrinkles





Shearography with 1.5 psid.

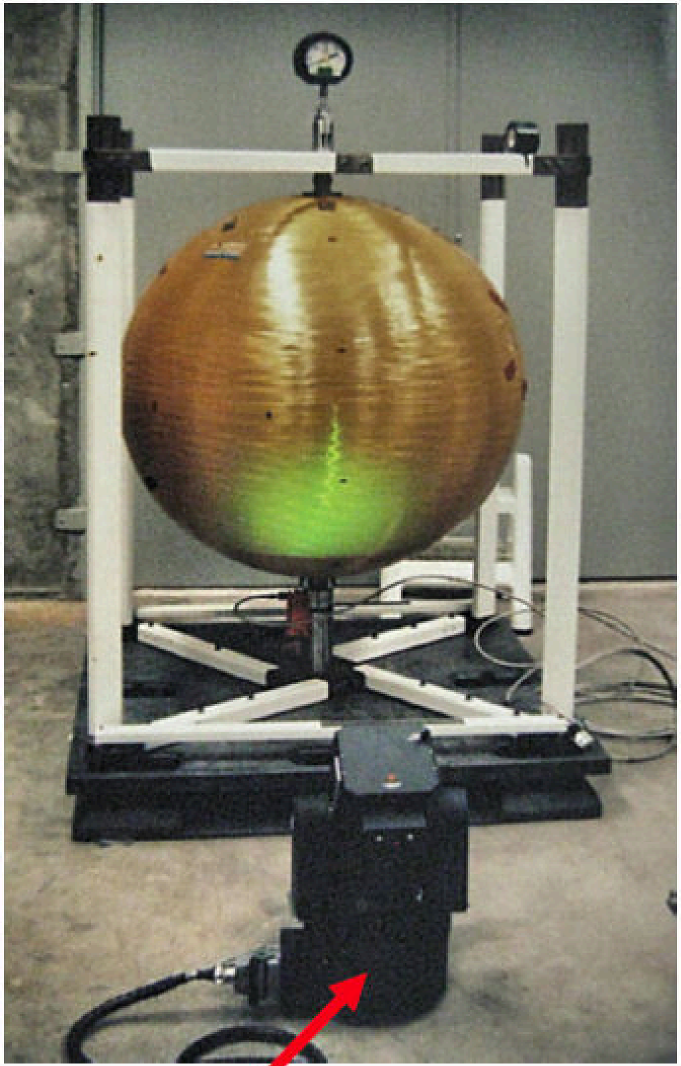
Vector: 0.5inch @ 0

Shearography Detection of COPV Liner Wrinkles

Shearography Set-Up
S/N 7 6/12/08

- LTI-5100HD Shearography Camera
- COPV pressured with GN2

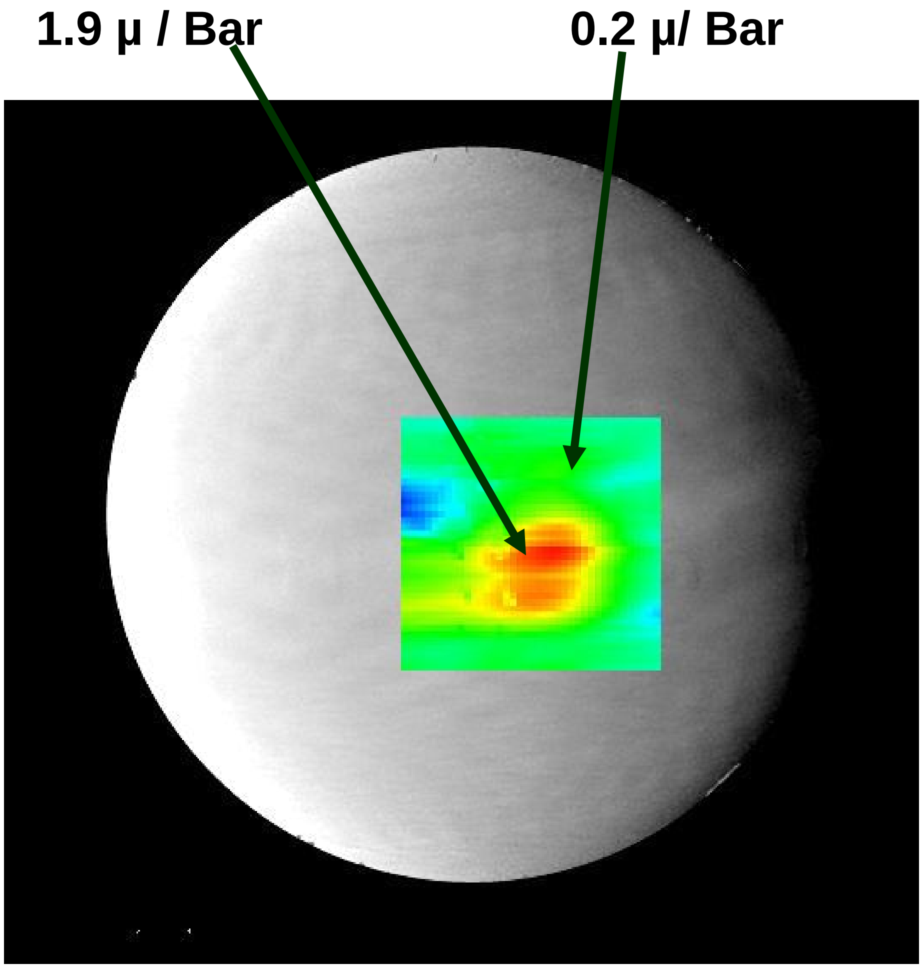
<u>**Test Parameters:**</u>
- COPV Bias pressure 70 psi.
- Test Pressure Differential 10 psi.
- Shear Vector 0.375 in. X, Y
- Field of View 14.25 inches

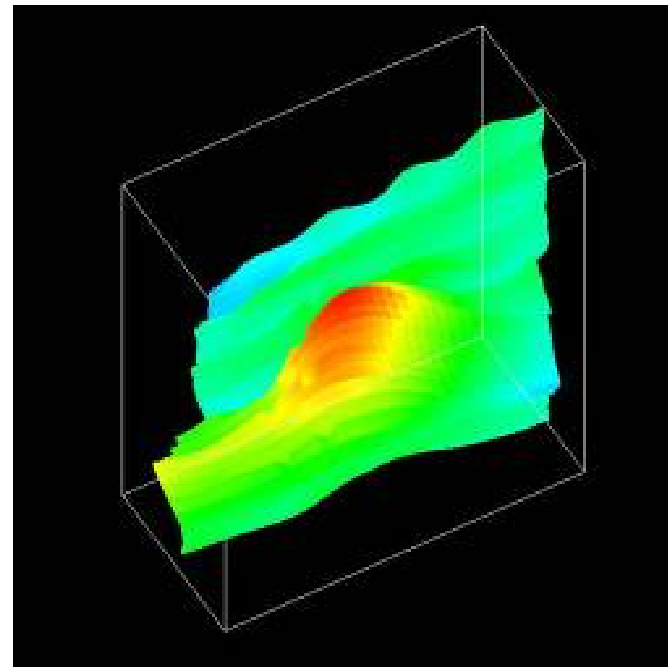


LTI5100 HD on floor for Band 4 Test

Shearography Detection of COPV Liner Wrinkles

Shearography Measurement of Deformation Rates
Liner Wrinkle

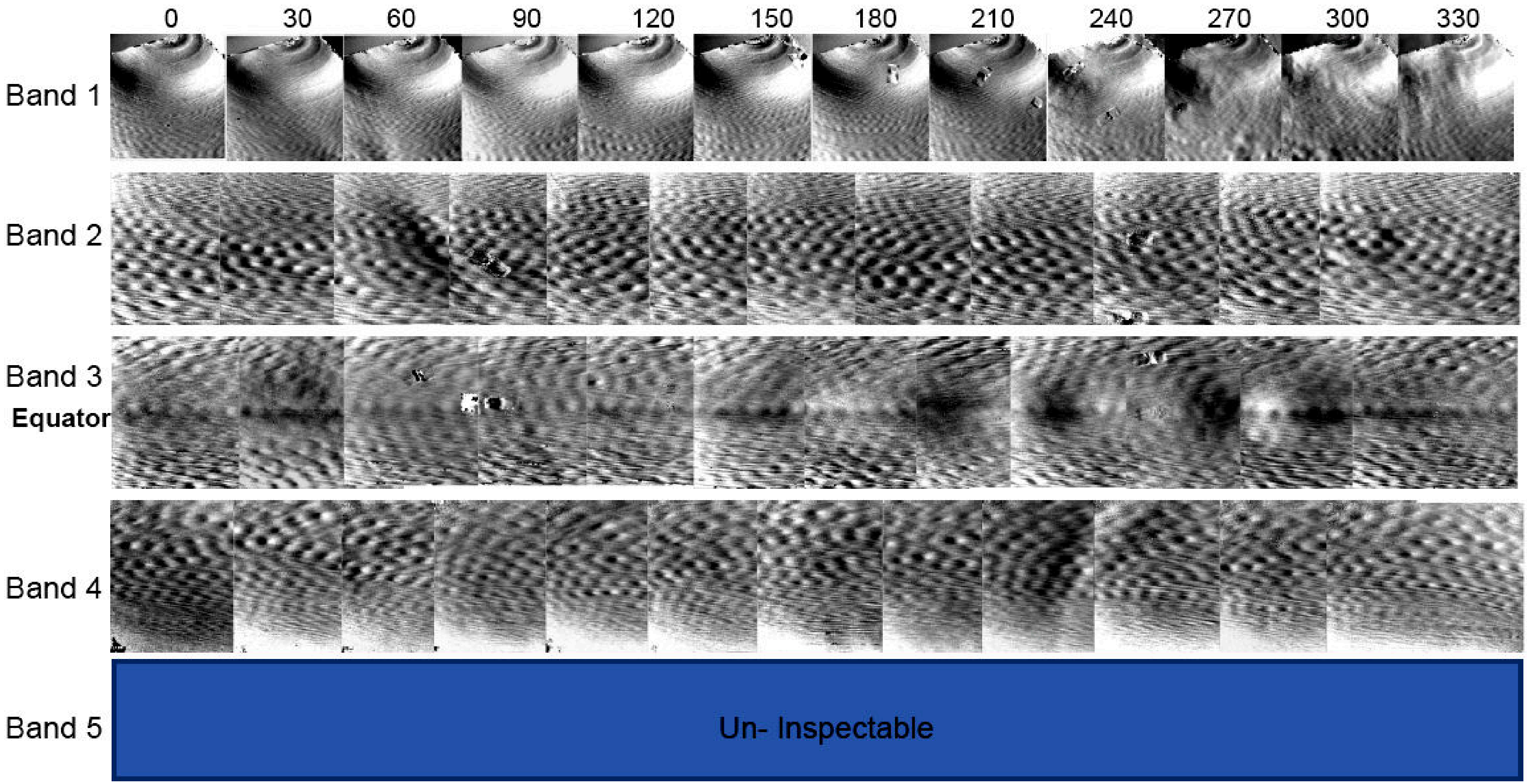




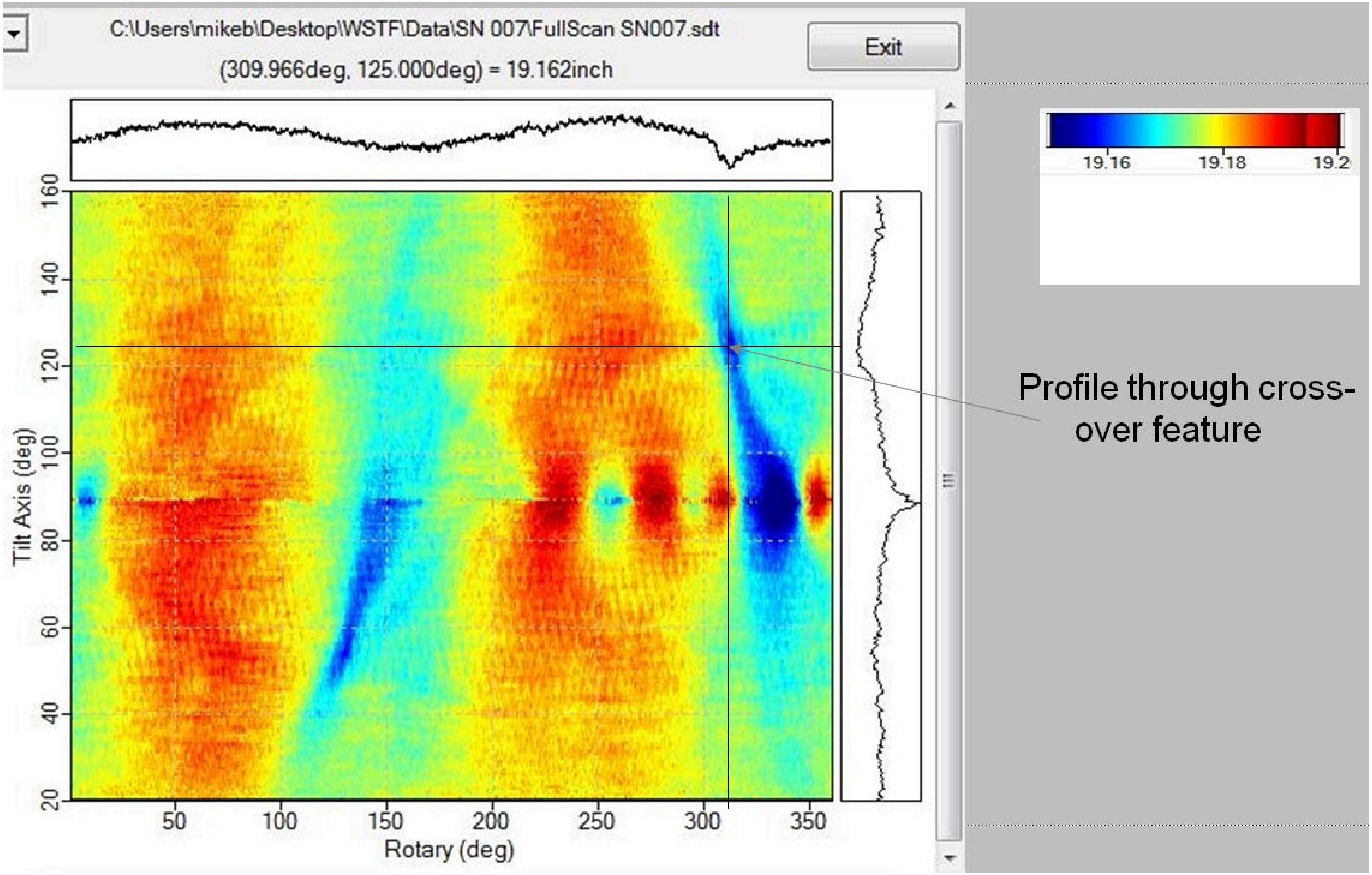
Shearography Detection of COPV Liner Wrinkles

40 Inch Kevlar COPV - X Shear 10 psid.
0-360º

Top of COPV AN-4



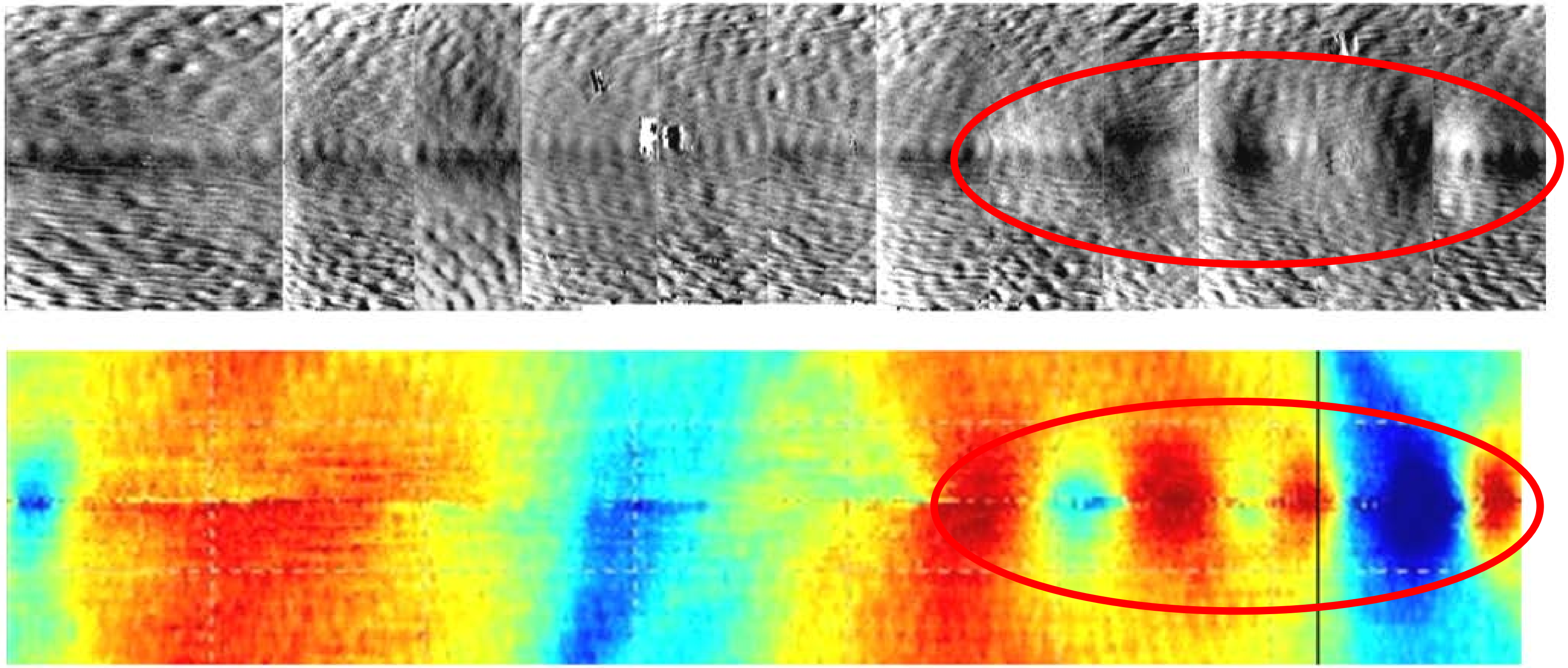
NASA WSTF Profilometer Scan



Courtesy NASA WSTF

Correlation Between Shearography and Internal Laser Profilometry Scan for Liner Wrinkles

40 Inch Kevlar COPV
Correlation between Pressure Shearography (X shear Vector) and Interior Liner Profilometry



Courtesy NASA WSTF

COPV Defect Detection Capability
Pressure Shearography

Defect Type	Recommended Shear Vector	Typical Test Pressure
Impact Damage	0.125 to 0.25 inches @ 0°	Δ10 to 25 psid
Cracks	0.12 inches @ 0°, +45°, -45°	Δ 5 to 15 psid
Broken Fiber	0.125 to 0.25 inches @90°	Δ 10 psid
Liner Wrinkles	Cylinder 0.5 inches @ 0° Sphere 0.5 inches @ 90°	Δ 25-50 psid
Fiber Bridging	0.25 inches @ 0°	Δ 25 psid

COPV Defect Detection Capability
Thermal Shearography

Defect Type	Typical Shear Vector	Typical Temperature Application
Composite-to-Liner Disbonds	0.25 inches @ 0°	$\Delta T=15°F$, RBH[1]
Fiber Bridging	Larger of 0.25 inches @ 0° or 3 times the composite overwrap thickness.	$\Delta T=10°F$, RAH[2]
Porosity, Voids & Poor Fiber Consolidation	0.12 to 0.25 inches @ 0°	$\Delta T=10°F$, RAH

Organizations Issuing Shearography Specifications

Designation: E 2581 – 07

Standard Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

This standard is issued under the fixed designation E 2581; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice describes procedures for shearography of polymer matrix composites, sandwich core materials, and filament-wound pressure vessels made entirely or in part from fiber-reinforced polymer matrix composites. The composite materials under consideration typically contain continuous high modulus (greater than 20 GPa (3×106 psi)) fibers, but may also contain discontinuous fiber, fabric, or particulate reinforcement.

1.2 This practice describes established shearography procedures that are currently used by industry and federal agencies that have demonstrated utility in quality assurance of polymer

specifications. It is recommended that an NDT specialist be a part of any composite component design, quality assurance, in service maintenance, or damage examination activity.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:* [2]

C 274 Terminology of Structural Sandwich Constructions

Organizations Issuing Shearography Specifications and Operator Certification

- **ASNT (2005) - Spec. TC1A for Shearography Level I, II & III**
- **ASTM (2007) – E2581- 07 Shearography NDT of Aerospace Composites**
- **AWS (2006) - C3.2 E3-WD1 Shearography & Holography**
- **AIA (2006) - Quality Sub. NAS 410 Rev 3 Shearography NDT**
- ***MIL STD 883 (2005) Optical Leak testing: Discrete Components and Assemble Modules.***

Quantitative Shearography NDT of COPV and CPV

Summary

1. LTI Shearography is highly cost effective, mature and widely accepted NDT technology.

2. Effective for the detection of COPV latent defects including:
   Fiber Bridging
   Porosity
   Broken Fibers
   Disbonds Composite to Liner

3. Effective for Damage visualization

Shearography
Nondestructive Testing

Thank you!

Laser Technology Inc.
1055 W. Germantown Pike
Norristown, PA 19403 USA

Tel**: 610-631-5043**

Continued Development of Meandering Winding Magnetometer (MWM®) Eddy Current Sensors for the Health Monitoring, Modeling and Damage Detection of Composite Materials

Rick Russell, NASA KSC
Russell Wincheski, NASA LaRC , Dr. Andy Washabaugh,
Dr. Yanko Sheiretov, Mr. Christopher Martin
and Dr. Neil Goldfine, JENTEK Sensors, Inc.

Composite Conference 2012
August 15, 2012
Las Cruces, NM

Agenda

- Background – Why MWM?
- Overview of MWM® Technology
- Historical application – Space Shuttle RCC
- Recent Developments for COPVs
  - Health Monitoring (Direct Stress Measurement)
    - Proof of concept study
    - Forward plan for 3 year study
  - NDE (Damage Detection)
- Design changes for miniaturization and high temperature applications

Background

- There are 3 mechanisms that affect the life of a COPV
  - The age life of the overwrap
  - Cyclic fatigue of the metallic liner
  - Stress Rupture life

The first two mechanisms are understood through test and analysis

- A COPV Stress Rupture is a sudden and catastrophic failure of the overwrap while holding at a stress level below the ultimate strength for an extended time.

- Currently there is no simple, deterministic method of determining the stress rupture life of a COPV, nor a screening technique to determine if a particular COPV is close to the time of a stress rupture failure.

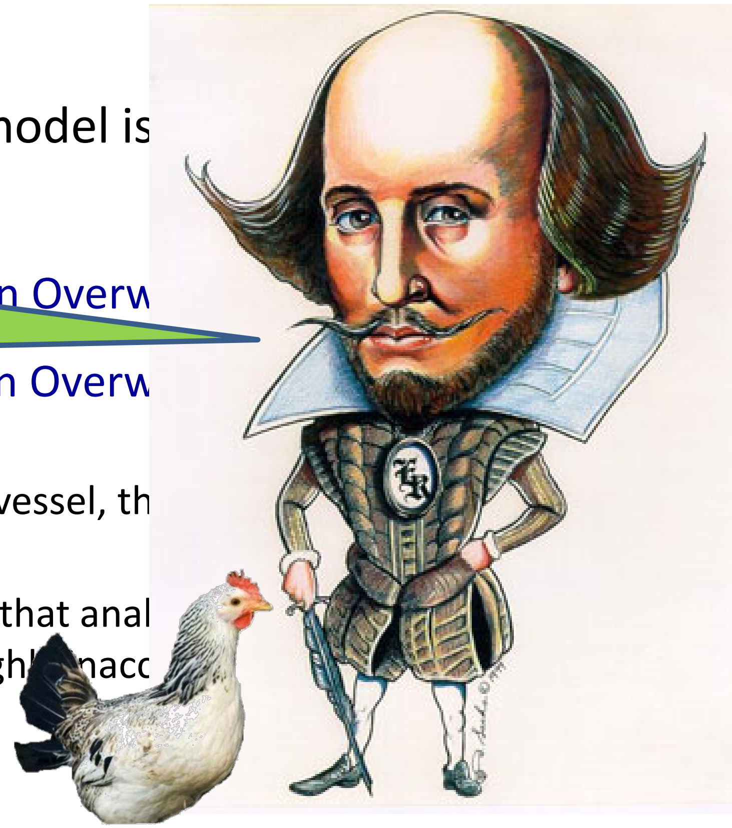
Stress Ratio

- A key f... eliability model is

To burst or not to burst.....

Stress in Overw

Stress in Overw

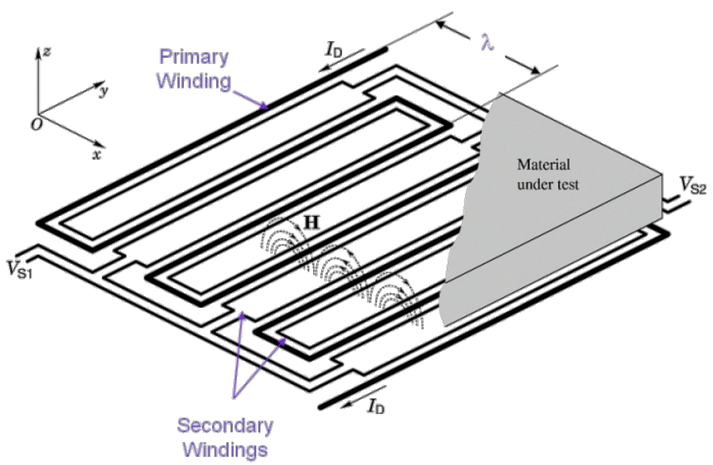


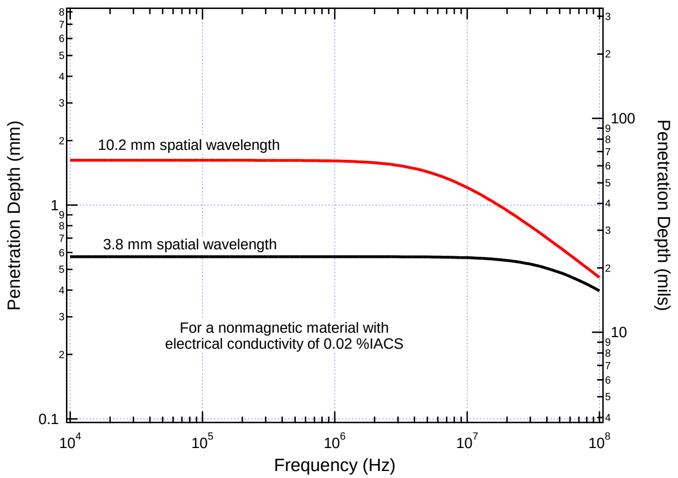
  - The stress at burst varies from vessel to vessel, th ... ries from vessel to vessel
  - Recent Orbiter COPV testing has proven that anal ... nd subsequent reliability modeling to be highl nacc
    - ~20% off

- Proposed technology would provide the ability to directly measure the stresses at various depths in the overwrap and potential directly calculate the Stress Ratio

MWM® Technology

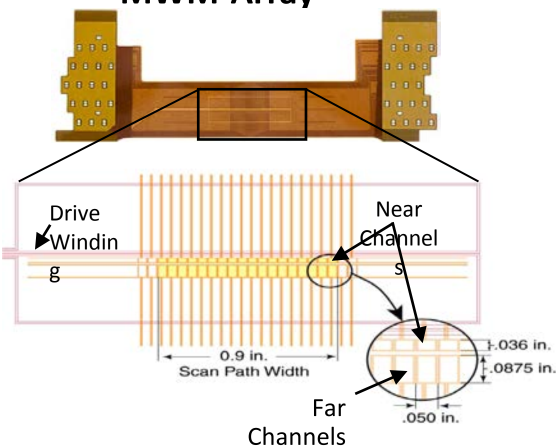
- What is a Meandering Winding Magnetometer (or MWM)?
  - Primary winding is a linear construct that can be aligned with fibers
  - Secondary windings for sensing the response
  - Fabricated on thin flexible substrate creating a conformable sensor
  - Can be manufactured in various array configurations
  - Depth of penetration varies with sensor wavelength (spacing) and frequency
  - Vendor has capability to perform computer simulations



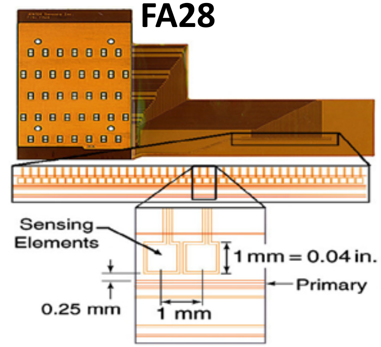


MWM® Arrays and Grid Methods

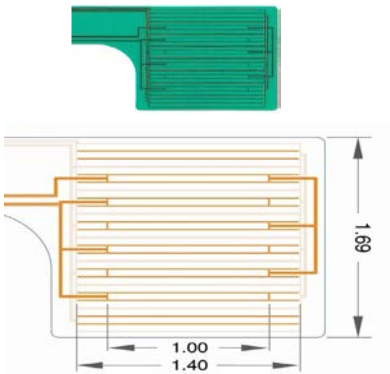
MWM-Array



MWM-Array FA28



MWM FS36

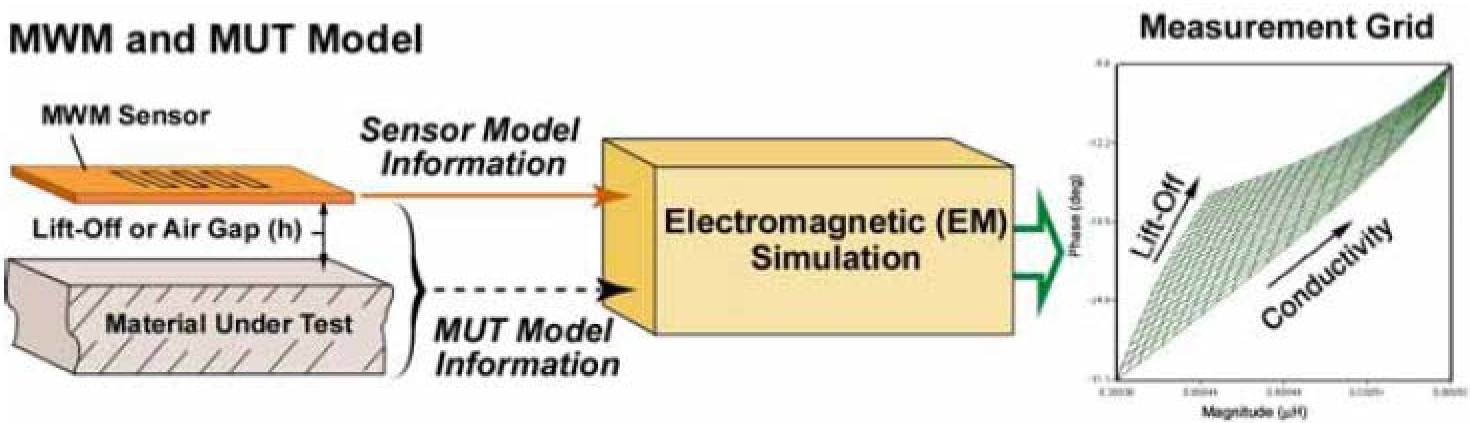


FA41 λ ≈ 480/190

FA28 λ ≈ 150 mils

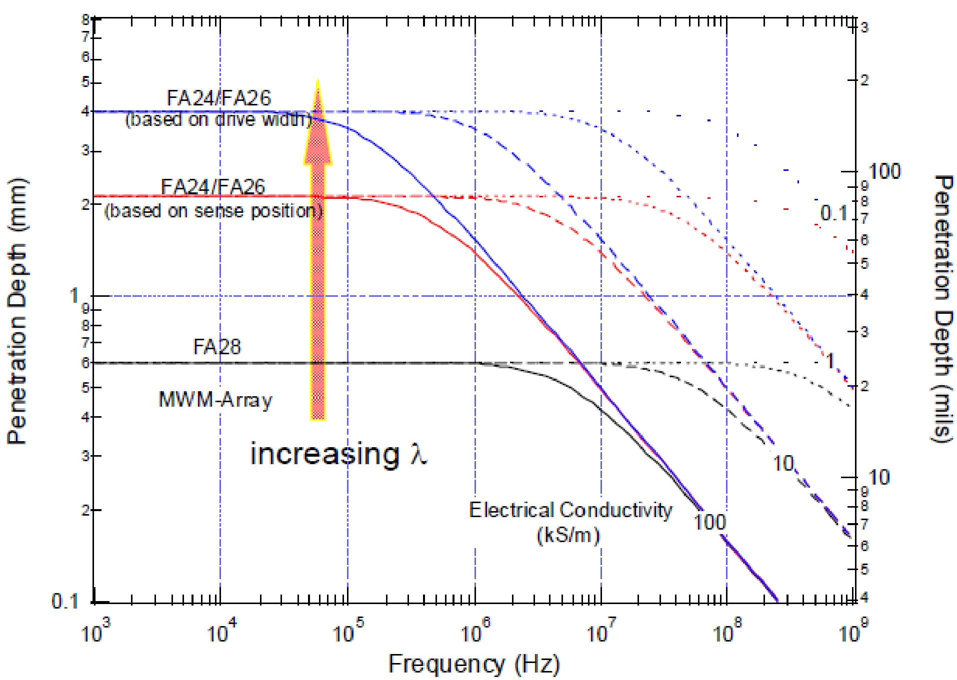
FS36 λ ≈ 400.0

JENTEK Grid Methods

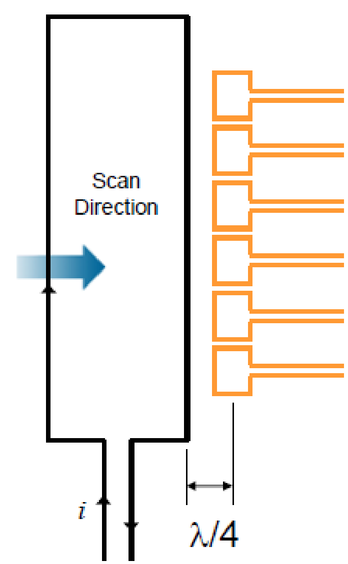


MWM Sensor Selection

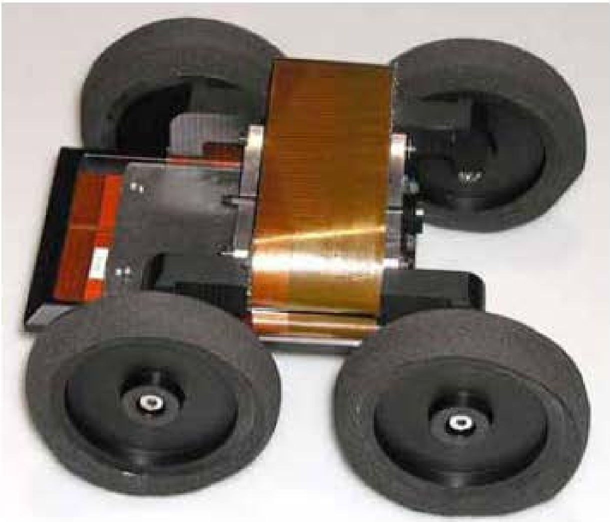
- Magnetic field Decays exponentially with distance away from the sensor
  - Decay rate determined by skin depth at higher frequencies and sensor dimensions at lower frequencies
- Higher frequencies needed to induce significant eddy currents
- Large dimensions needed for thick composites



Skin depth: $\delta = \sqrt{\dfrac{1}{\pi f \mu \sigma}}$

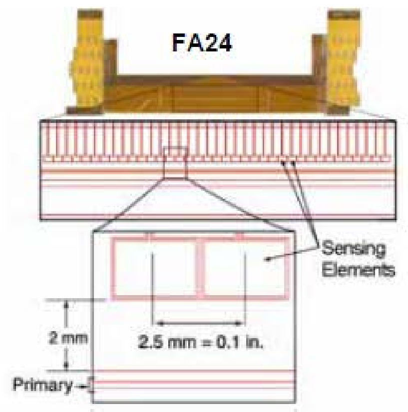


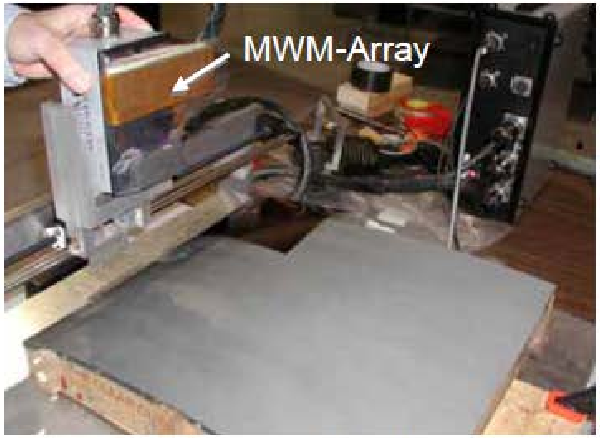
Application: Space Shuttle Orbiter RCC Panels



- Foam wheels protect surface
- Manual scanning for complex surfaces
- C-Scan images of wide areas built from multiple passes
- **Adapts automatically to varied curvatures**

Application: Space Shuttle Orbiter RCC Panels

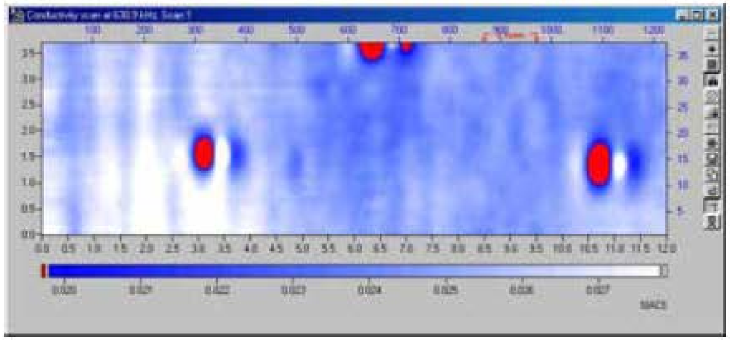




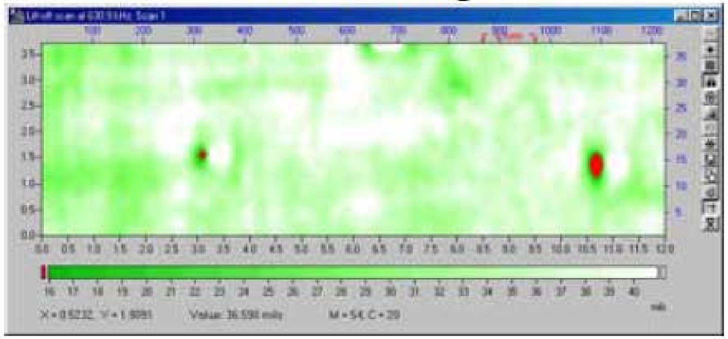
Blind Test RCC Sample Provided by NASA Langley Research Center

- Scan width = 37 sensing elements = 3.7 in.
- Scans performed at 1 in./sec.

Effective Conductivity Image



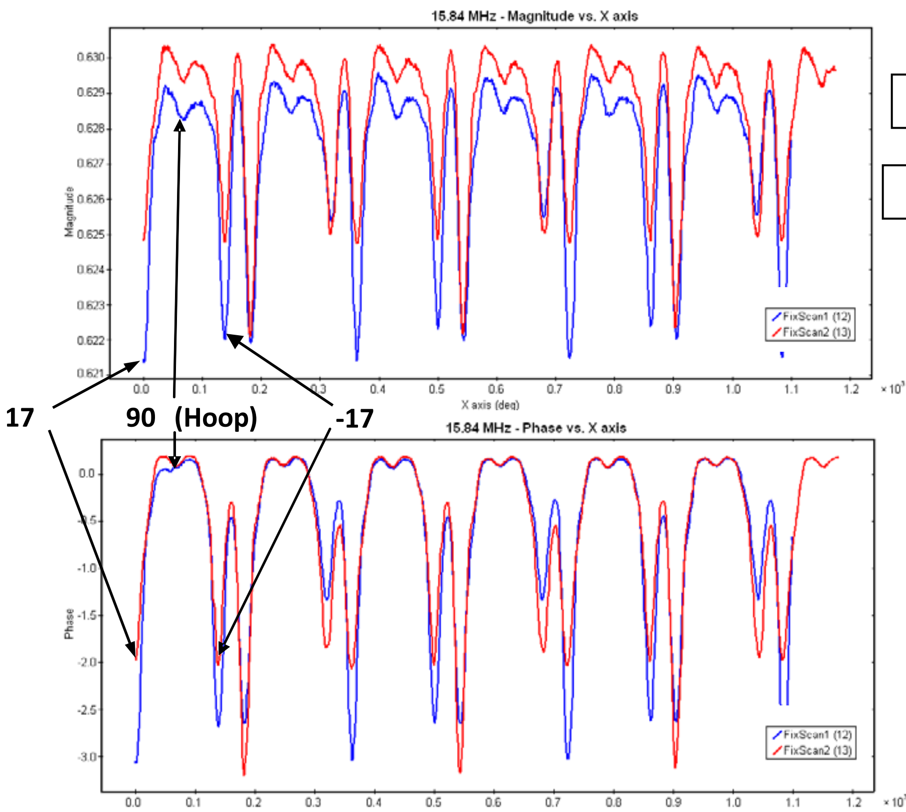
Lift-Off Image

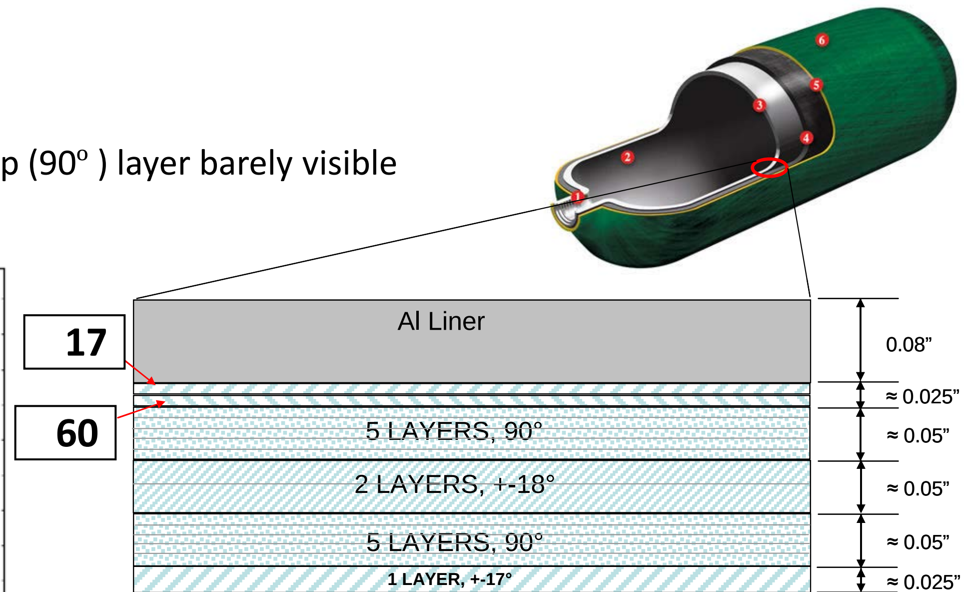


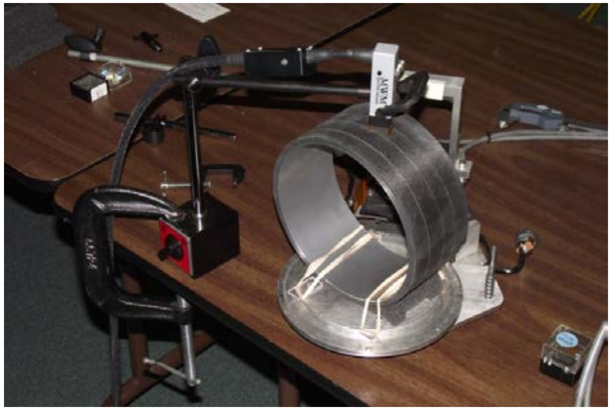
Throughput: 3.7 in. x 12 in. scan in 12 seconds = 3.7 sq. in./sec

COPV Testing – Effect of Fiber Orientation

- Multiple fiber orientations in several different layers
- Orientation measurements with FS33
  - 15.8 MHz data indicated
- Limited penetration depth of MWM so outermost hoop (90^{o}) layer barely visible

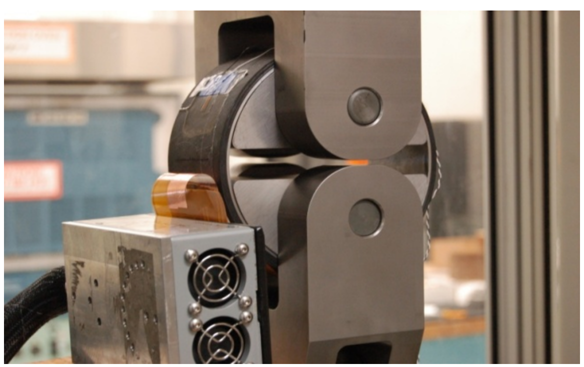






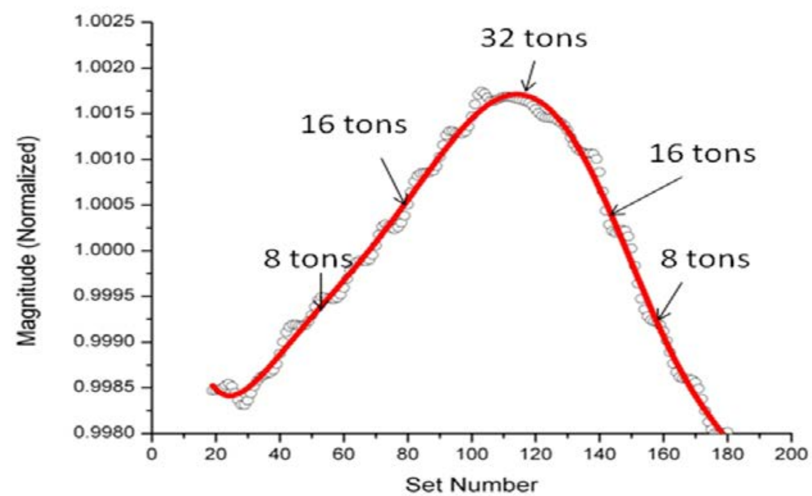
COPV – Health Monitoring
Proof of Concept Coupon Testing

Stresses produced by compressive loading of tapered wedges



Stresses produced by tensile loading of specially design test fixture

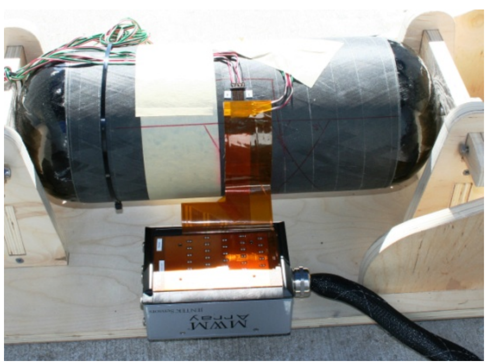
- Coupon cut from center section of COPV (~4" wide)
- Two test fixtures designed
- Due to cutting only hoop direction could be measured
- Several different sensor designs and orientations were tested

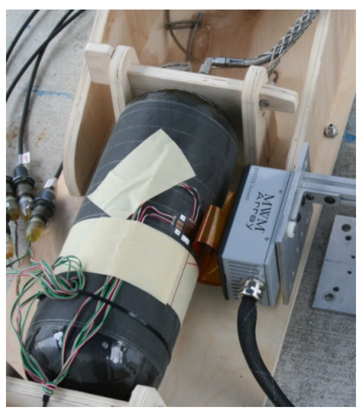


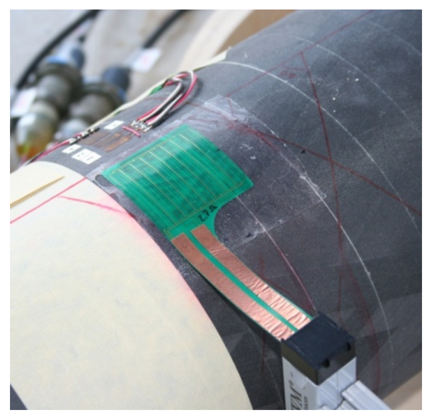
Example of results from compressive loading of tapered wedges test

COPV – Health Monitoring Proof of Concept Hydrostatic Test

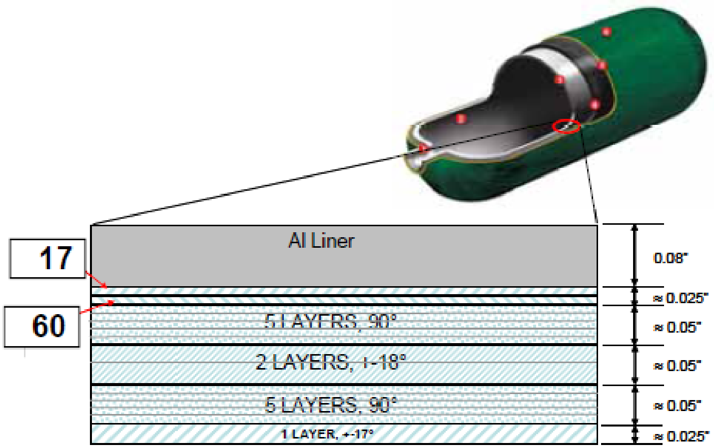
- Full COPV tested hydrostatically at KSC on February 5, 2011
- Vessel cycled to 8,000 psi and back to zero stopping at 2,000 psi increments
  - Pressure chosen to mimic MEOP
  - Estimated design burst pressure of COPV is 16,000 psi
- Based on coupon tests 3 sensor configurations were chosen
  - Different wavelength to obtain various depth of penetration
- Tests were performed with 3 sensor orientations
  - 90º, 60º and 17º to align sensor drive with fiber orientations



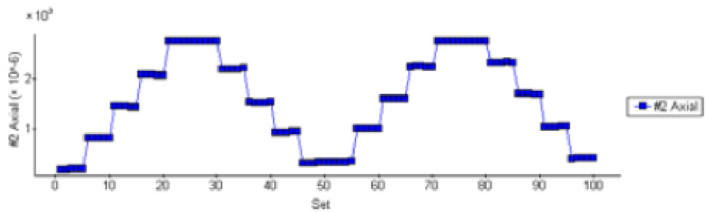




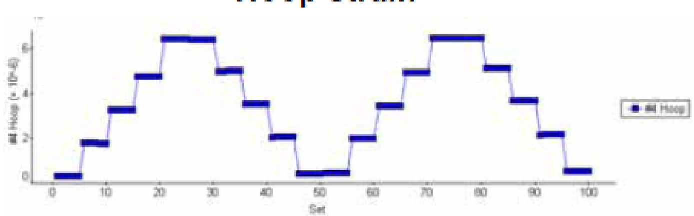
COPV – Health Monitoring Proof of Concept Hydrostatic Test

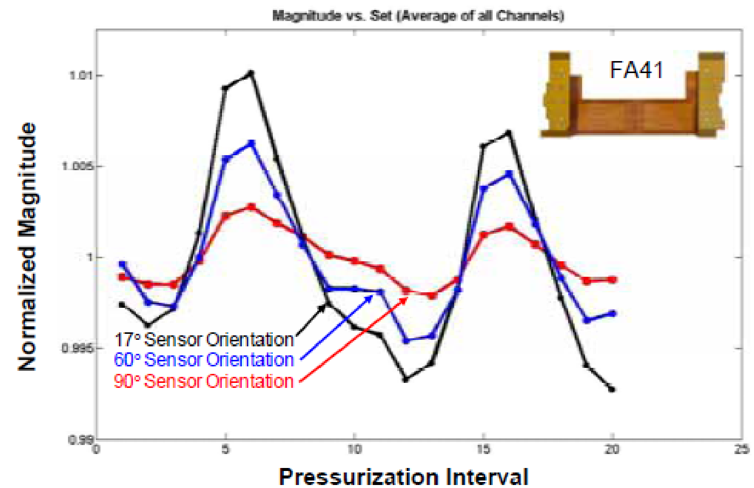


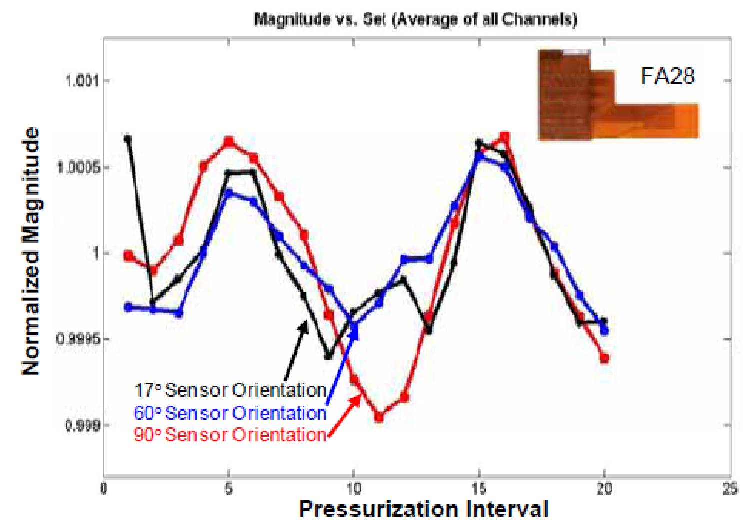
Axial strain



Hoop strain



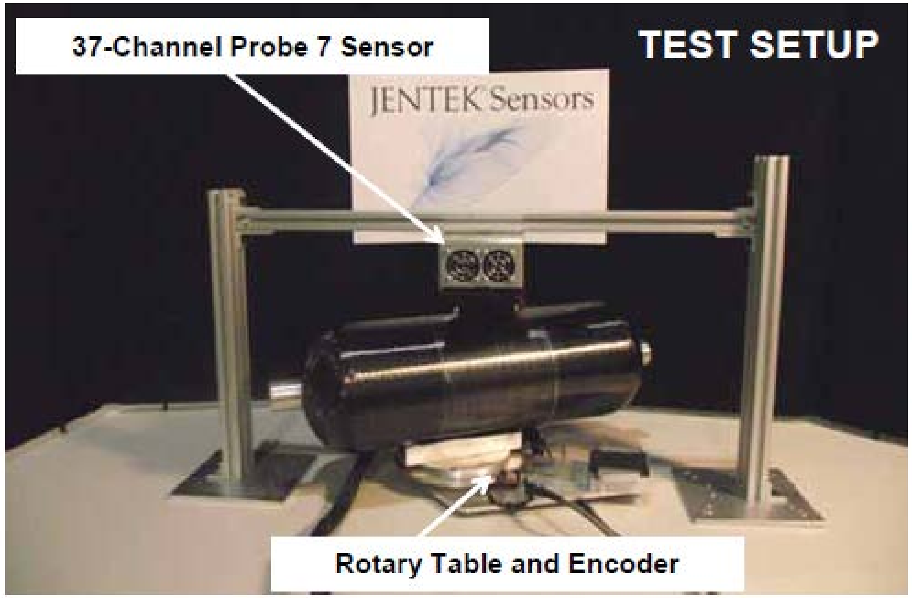


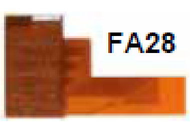


COPV NDE

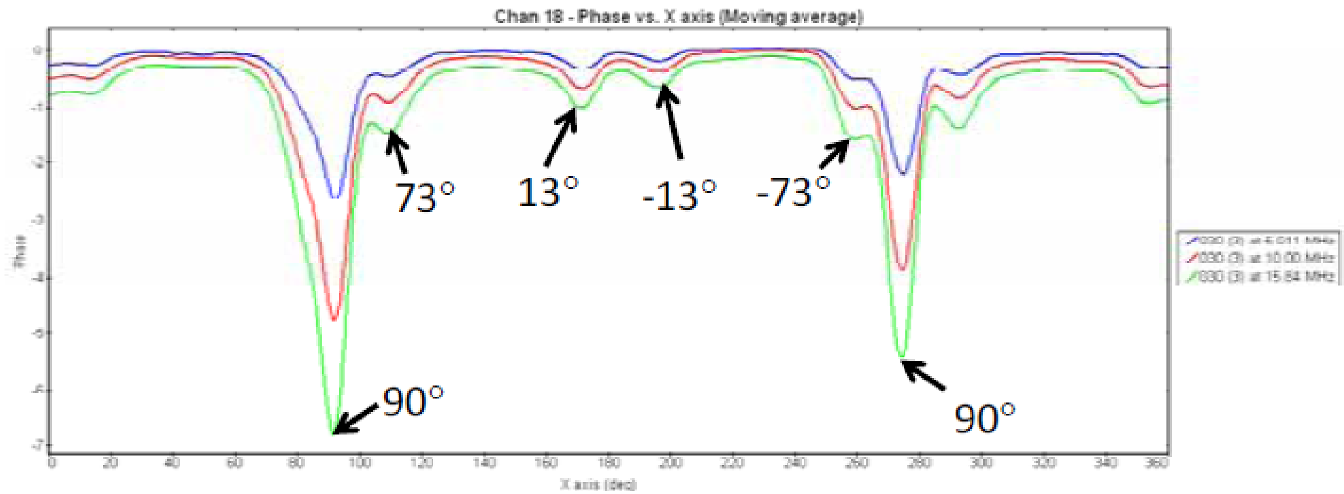
- Four COPVs selected from NASA White Sands inventory
- Scanned via MWM before and after impact testing

Rotation Scans

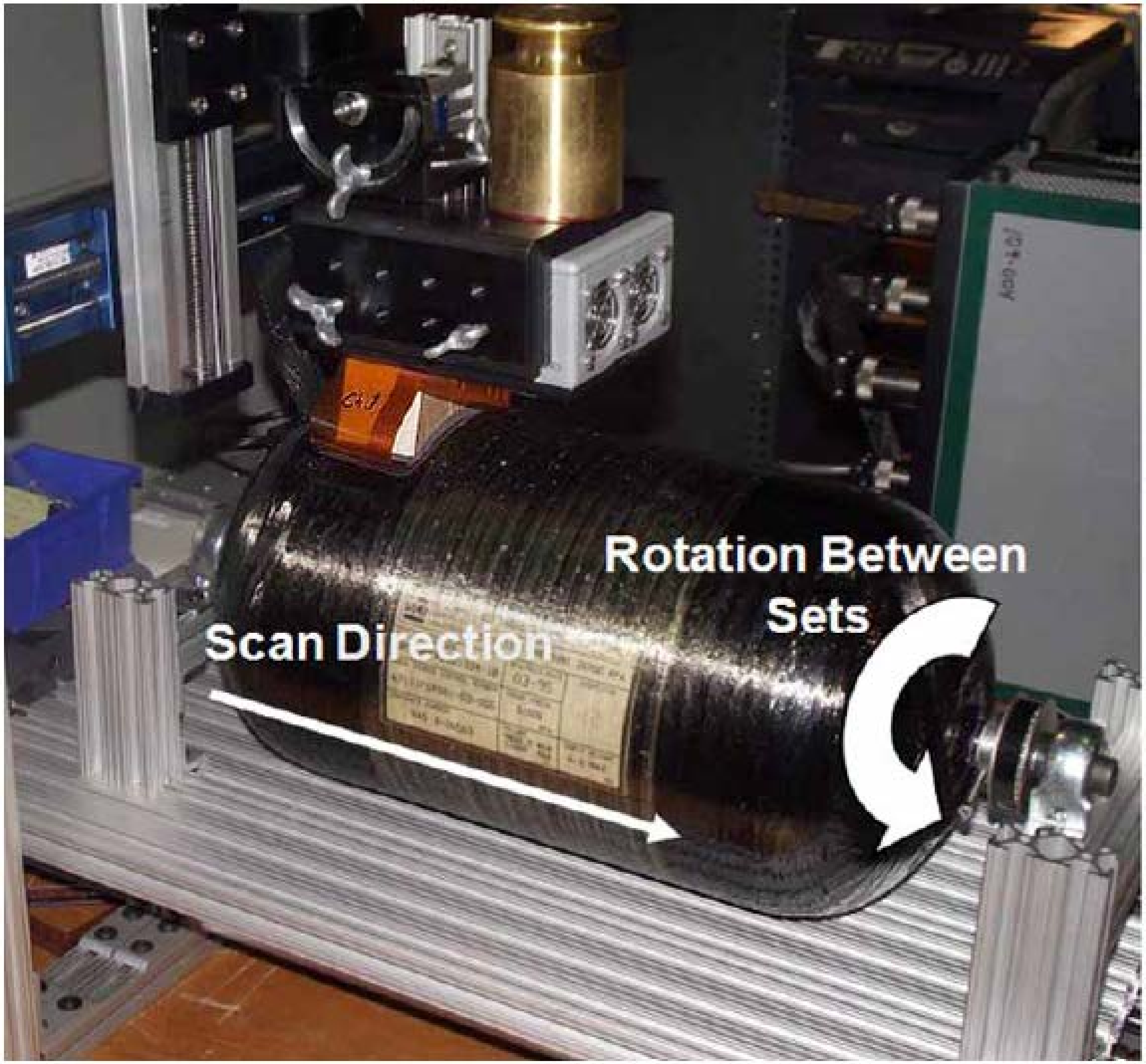


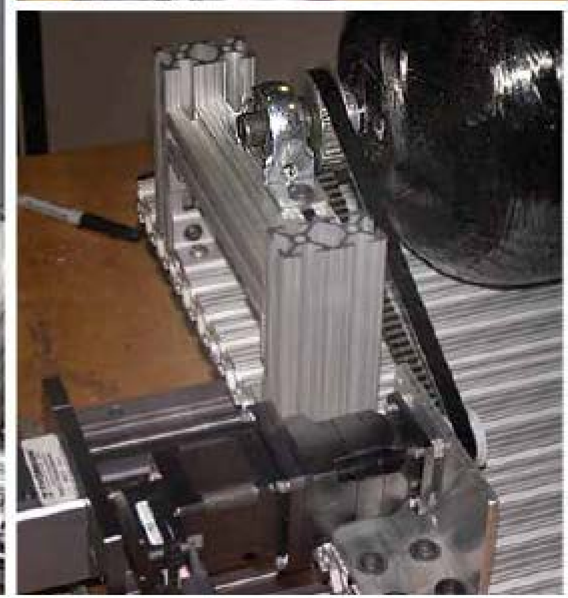


FA28 MWM-Array Scan

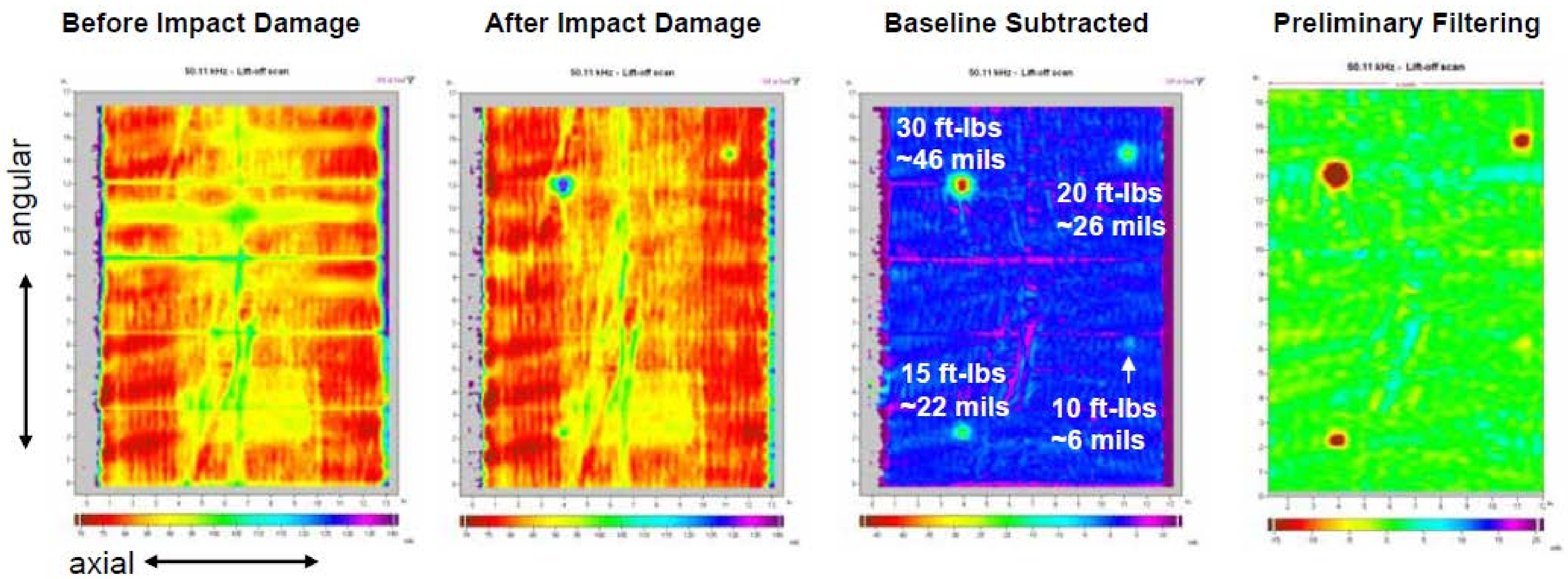


Test setup for hoop oriented fibers



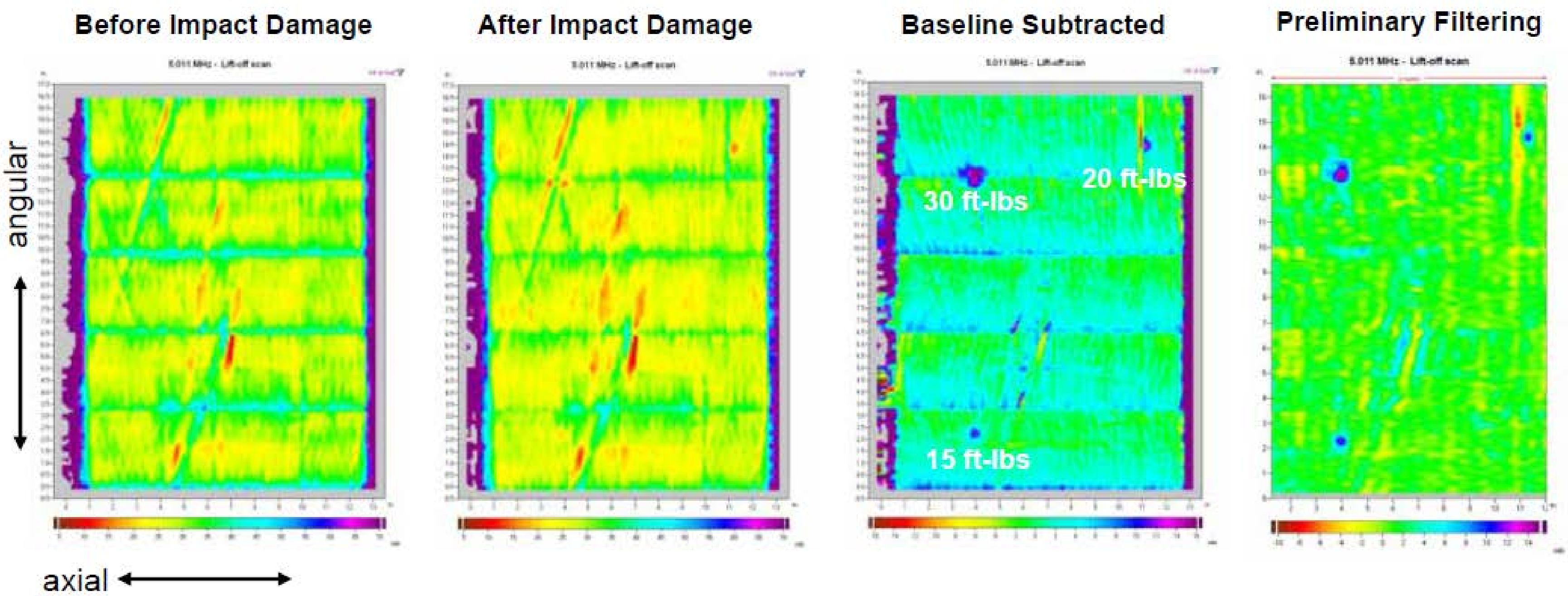


Lift-Off Image Low Frequency



- Sample AC5250-030; 90° Sensor drive orientation
- Higher impact energy results in larger dents in the aluminum liner
- Sensor: MWM-Array FA24
- 50.11 kHz

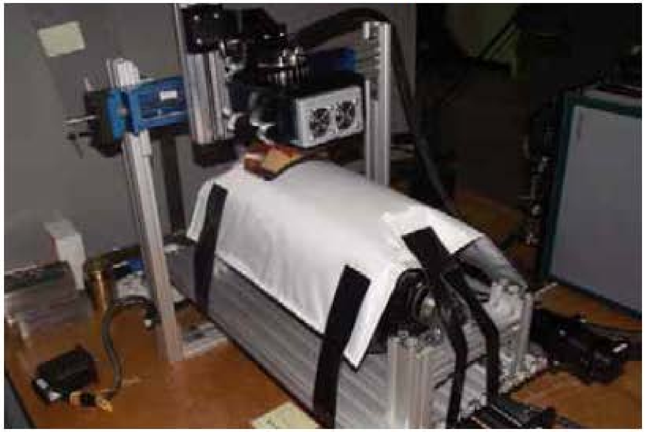
Lift-Off Image High Frequency



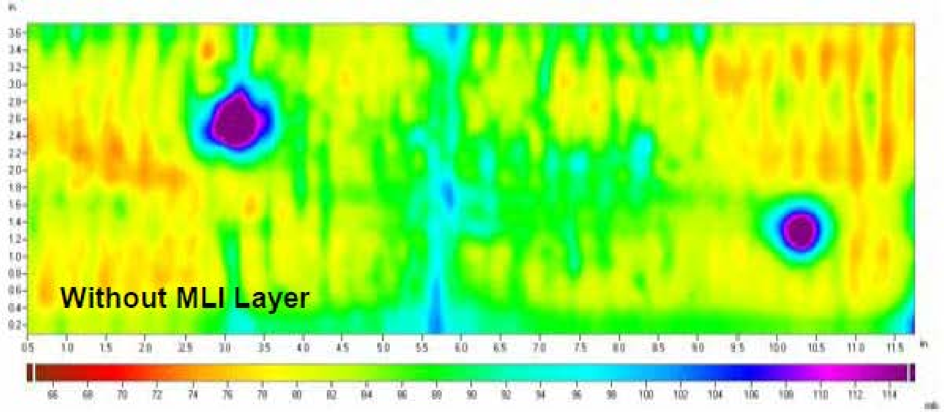
- Sample AC5250-030; 90° Sensor drive orientation
- Sensor: MWM-Array FA24
- 5.011 MHz

Scan of COPV with Insulation Blanket

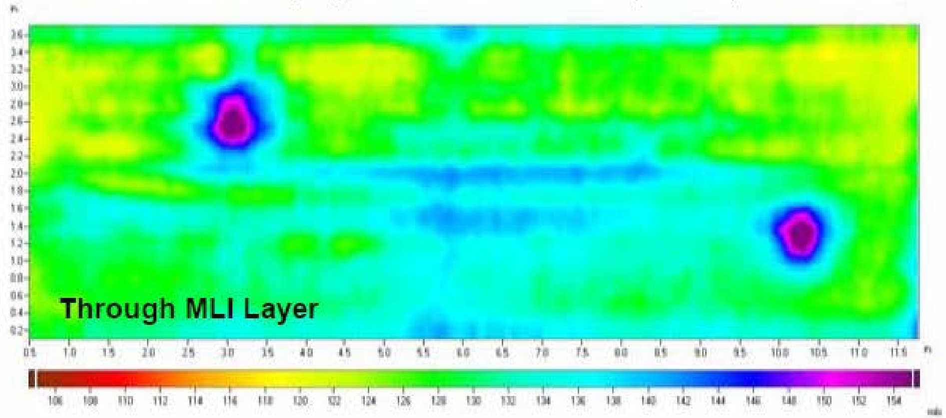
Test Setup



Lift-off C-scan for COPV AC5251-005 **without** an MLI layer (50 kHz)



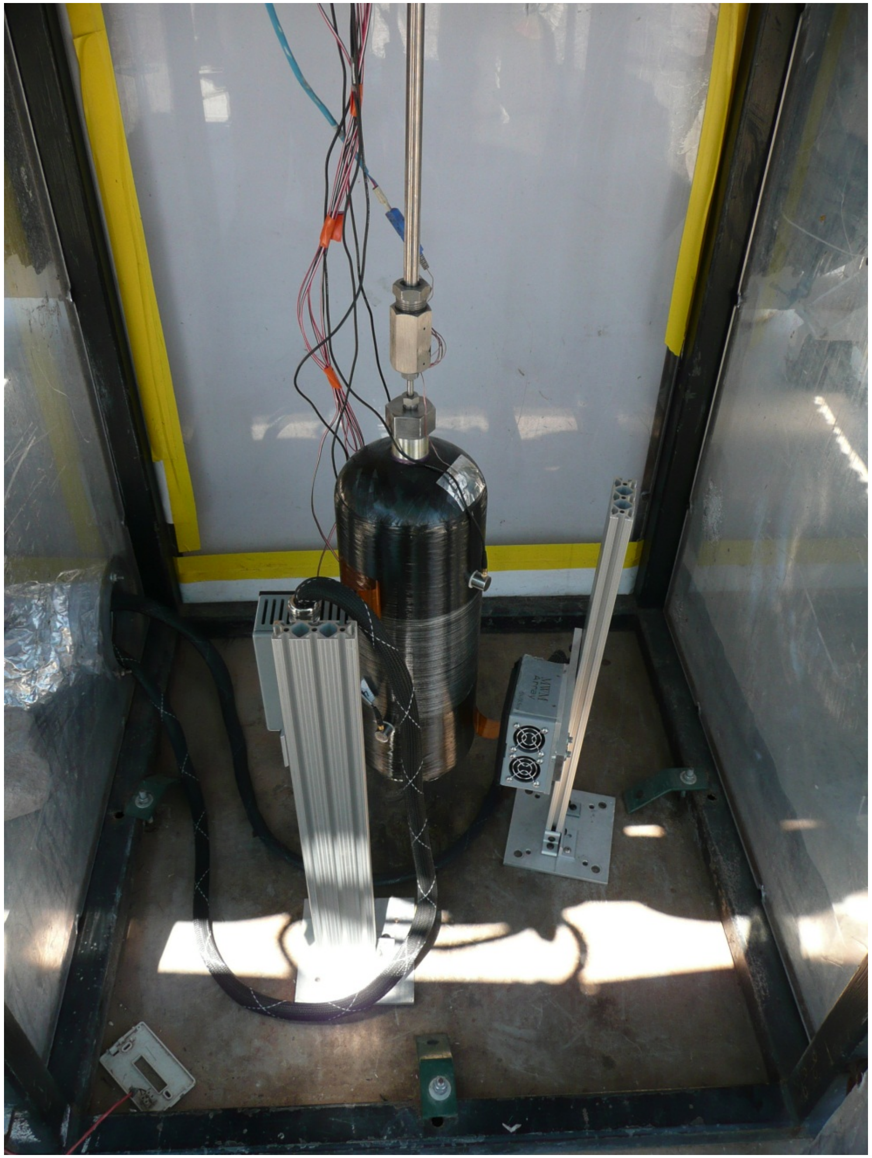
Lift-off C-scan for COPV AC5251-005 **with** a conductive MLI layer placed over the COPV (50 kHz)



3 year study

- Under the sponsorship of the NASA NDE Working Group (NNWG) a new 3 year project has just started
  - Test team includes JENTEK, NASA WSTF and NASA KSC
  - Further test and evaluate MSG networks for both SHM and damage detection
  - Coordinate results with Acoustic Emission (AE) data
  - Goal to bring technology level to TRL 7

Test Set-Up



3 year plan

- FY12 and FY13 will focus on adaption of the technology to enable coordination between MSG and AE measurements
  - 2 bottles will be tested in FY12
  - 3-7 bottles will be testing in FY13
    - Intentional damage will be introduced into some vessels
- FY13 will include a demonstration of a wireless capability within an embedded
- In FY14 an upgraded GSU and MSG network will be delivered that includes an embedded prototype GSU and wireless communications capabilities, including support for coordination with the AE data acquisition and analysis.

3 year plan

- FY14 will focus on a long duration (six month) test of a bottle with both MSG and AE networks
  - Coordinate both stress and damage tracking
  - Development of a detail plan for transition through flight qualification and testing

Development of a High Temperature MWM Array Sensor

- Designed for continuous use at 1000° C by proper selection of high temperature materials.
- Ceramic substrate and high-temperature metal deposited conductive winding constructs.
- Prototype 7-channel MWM-Array sensor built and tested at 850° C with no degradation observed.
- Demonstrated crack detection with prototype high temperature sensor.
- High temperature cabling issues require further development

Room Temperature MWM-Array Sensor

High Temperature MWM-Array Sensor