

Composite Conference 2012

**“Smart COPV”
Composite Overwrapped Pressure Vessels
(COPVs) Integrated with Structural Health
Monitoring (SHM) Systems That Target Space
Exploration and ISS Needs**

*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
- NASA LaRC/Eric Madaras - Wireless Acoustic Emission (AE) detection systems
- NASA GRC/Don Roth - Acoustic Emission Analysis Applet
- NASA KSC/Richard Russell - Magnetic Stress Gage (MSG) SHM
- NASA DFRC/Lance Richards - Multiaxial Fiber Bragg Grating (FBG) grids
- NASA MSFC/Curtis Banks - OCT Composite SHM project tie-in using Fiber Optic Acoustic Emission (FOAE) (Los Gatos), piezoelectric sensors (Acellent Technologies and Métis Design Corporation), and polarization maintaining (PM) FBGs. Also will provide MSFC Resources (coupon development)
- WSTF Principal Investigators (real-time AE SHM):
- GeoControl Systems WSTF/Jess Waller - Polymer Science/AE
- NASA WSTF/Charles Nichols - AE Analysis, method development/automation
- NNWG HQ/Ed Generazio - Delegated Program Manager

Extended Agency “Smart COPV” SHM Team

- NASA JSC/Scott Forth - Manned Space Flight Pressure Vessel Analysis (i.e., ISS, MPCV)
- NASA JSC/Ajay Koshti - Manned Space Flight Programs NDE
- NASA JSC/George Studor - wireless instrumentation
- NESC NDE Fellow - Bill Prosser - NESC/NDE Fellow/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 Green - 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 Stuart - 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 other mission issues. 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
- This project is developing and plans to continue to update a “Smart COPV” Roadmap in coordination with the extended team and OCT Materials/Manufacturing Steering Committee/s where appropriate

Capabilities	2010	2015	2020	2025	2030					
	Selected	Exploration	WFIRST	LED Access	Propellant Depot	Radiation Protection	NEO/Mars Precursor	Heavy Lift	Advanced In-Space Propulsion	Space Platforms

2.1 Material
 2.1.1 Lightweight
 2.1.2 Computational
 2.1.3 Flexible
 2.1.4 Environment
 2.1.5 Special Materials

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

2.2 Structure
 2.2.1 Lightweight
 2.2.2 Design
 2.2.3 Reliability
 2.2.4 Test Tools
 2.2.5 Innovative

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

Example WBS Tables:

2.3 Mechanic
 2.3.1 Deployable
 2.3.2 Mechanisms
 2.3.3 Electro-mechanical
 2.3.4 Design
 2.3.5 Reliability
 2.3.6 Certification

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

2.4 Manufact
 2.4.1 Manufacturing
 2.4.2 Intelligent
 2.4.3 Electronic

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.**

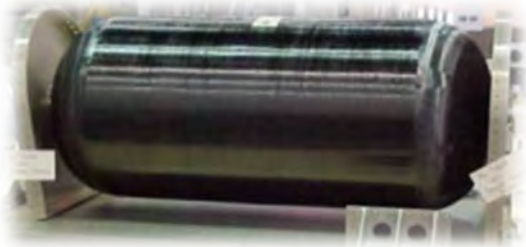
2.4 Sustainable Manufacturing	Workability-driven Technologies	Environmental Technologies	Green Production Processes	Advanced Energy Systems				
2.5 Cross Cutting	2.5.1 Nondestructive Evaluation and Sensors 2.5.2 Model-Based Certification and Sustainment Methods 2.5.3 Loads and Environments	Combined Environments Improved methods for Accurate Local and Global loads and Environments	Physics based design models Test Validation	Computational NDE Strategies for Critical Component Reliability Design for Monitoring Strategies	Combined NDE and Structural Analysis Damage Prediction Mission Loads & Environments Monitoring	Autonomous Inspection Integrated Life-cycle Analytical Tools Autonomous In-Flight Mitigation Strategies	Real-time Comprehensive Diagnostics Physics-Based Reliability Prediction, Mitigation, and Repair Mitigation-Processes for Virtual Fleet Leads	Virtual Digital Fleet Leader

Background (Cont'd)

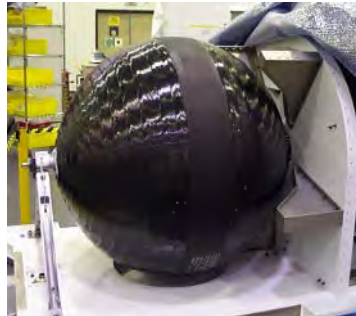
- Several promising SHM methods have been developed within the agency:
 - NNWG Stress Rupture NDE Development project
 - In-situ Carbon Fiber Micromechanics project
 - Multiaxial FBG Systems for Real-time NDE Inspection project plus Acousto-Optics project
 - Advancements have been made by team participants in coordination with NASA's Lightweight Spacecraft Structures & Materials (LSSM) and several other precursor programs, i.e., active ultrasound (UT) methods, Acellent and Metis structural health monitoring)
 - Magnetic Stress Gage (MSG) Health Monitoring of COPVs, KSC project keys off of a SBIR
- In process manufacturing NDE methods such as Profilometry, automated Eddy Current (EC) and UT scanning methods can provide data necessary to screen liners and COPVs for defects understand mechanical response variations
 - These tools may help produce more consistent structures which better follow models and better conform to design criteria and evolve COPVs.
 - Resulting structures and with implemented monitoring systems create “Smart COPVs” capable of monitoring critical structural response (health) and alerting crew to hazards.

Background (Cont'd)

- As discussed in the roadmaps this type of SHM is critical to nearly all future long duration NASA missions
- Potential near-term needs include carbon-epoxy (C/Ep) COPVs used on ISS, ISS Nitrogen-Oxygen Recharge System (NORS) if reused, the Orion crew and service modules, and as nearly all future long duration NASA spacecraft missions
 - Incidental but direct benefits also exist 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 (the latter include composite structures being developed under NASA's Composites for Exploration program plus several precursor programs (i.e., LSSM, both wet and dry structures), especially where cyclic loading is experienced



Nitrogen Tank Assembly
(45"Lx19.7"D)



High Pressure Gas Tank - Oxygen
HPGT COPV (37.89"D)



Overall Project Objectives

- Better COPVs: evaluate mechanical response, reduce risk and improve reliability of COPVs to support NASA missions
- Evaluate, down-select and integrate the most promising NDE technologies from NNWG, LSSM, and other projects into COPVs
 - Using a multidisciplinary team approach, generate and provide a “Smart COPV” SHM map (linked to the OCT Roadmaps where applicable)
- Further develop down-selected technologies, raising the TRL level such that an integrated end-to-end “Smart COPV” demonstration is accomplished
- Current center focus areas are shown on following slides
- Seek other program synergy to help provide the resources to accomplish objectives and meet needs

Smart COPV Development Areas

1. Damage quantification through AE Monitoring (WSTF, LaRC, GRC)
Measures transient elastic stress waves emitted by new and growing composite flaws
 - a. Felicity ratio and Dunegan's corollary used to ascertain severity of composite damage
 - b. Waveform analysis used to characterize type and extent of composite damage
 - c. Passive real-time detection of MMOD impacts demonstrated by LaRC (ISS DIDS system)
2. FOAE and Strain Monitoring Technology (MSFC)
Simultaneous measurement of strain and acoustic emission activity
 - a. Anomalous strain growth or deflection detected
 - b. Strain correlated with AE activity thus assessing proximity to catastrophic failure
3. Multi-axial FBG Strain Mapping and Trend Analysis (DFRC)
Maps the localized strain fields relative to principal overwrap lay-up directions using optical sensors
 - a. Hundreds strain readings taken in near real time over a COPV surface allow for FEA-like measurements
 - b. Tensor analysis of embedded and surface strains possible for failure prediction modeling
4. MSG Sensing Technology (KSC)
Measures real-time stress in the COPV's layers and may spot preferential wrap angle failures due to design or tow tension issues
 - a. Measures stresses in the metallic liner through composite overwrap
 - b. Discerns liner wall thinning processes at localized stress/strain sites
5. Active - Passive Piezoelectric Sensing (SBIR developed-COTS)
Remote real-time or on-demand detection of impact damage
 - a. Active or passive-active piezoelectric sensors integrated into a "SMART" layer
 - b. Uses AI techniques to estimate Magnitude & location of damage determined

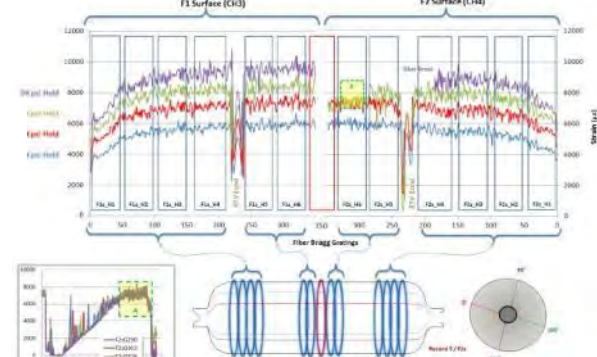
GRC AE Analysis Applet



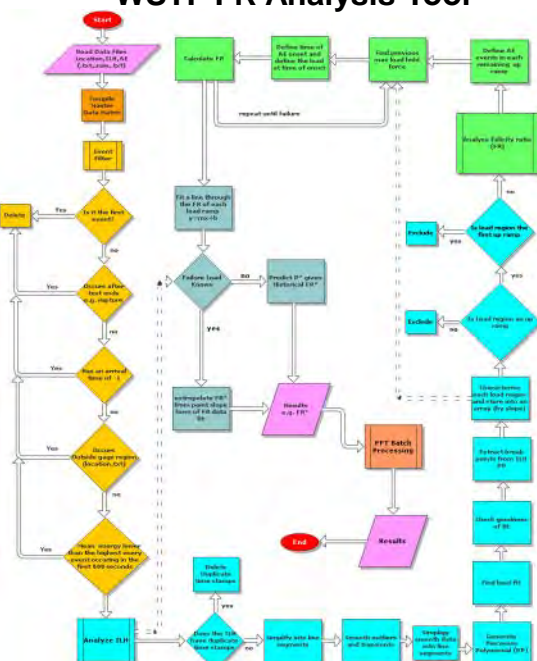
LaRC DIDS AE



DFRC FBG strain measurement



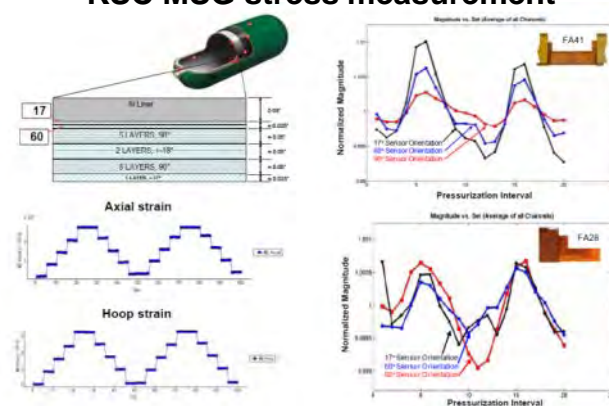
WSTF FR Analysis Tool



Smart COPV



KSC MSG stress measurement



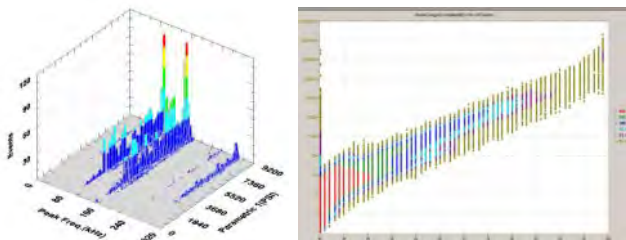
WSTF/LaRC Profilometry and Eddy Current



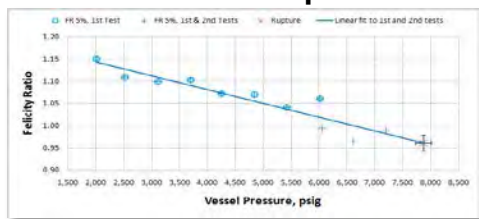
MSFC FOAE



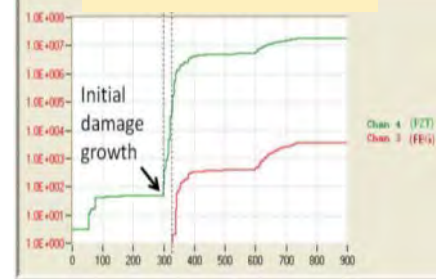
AE waveform analysis



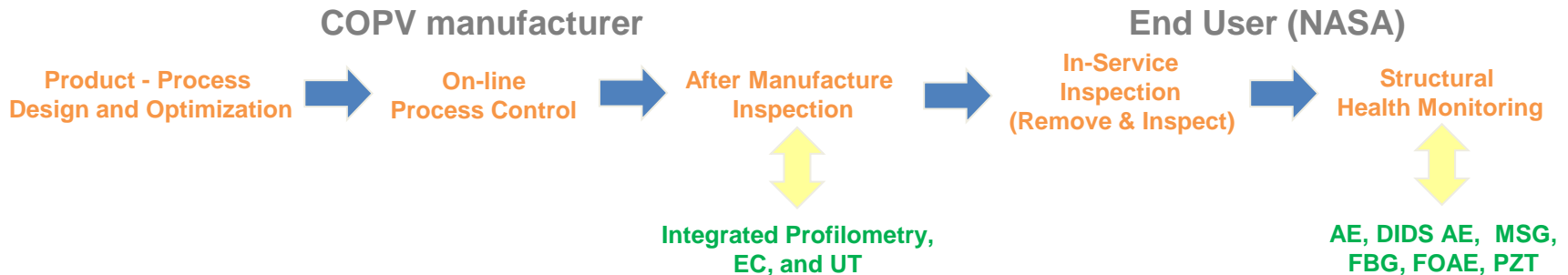
WSTF COPV burst prediction



Las Gatos COPV Results



COPV Life Cycle Considerations



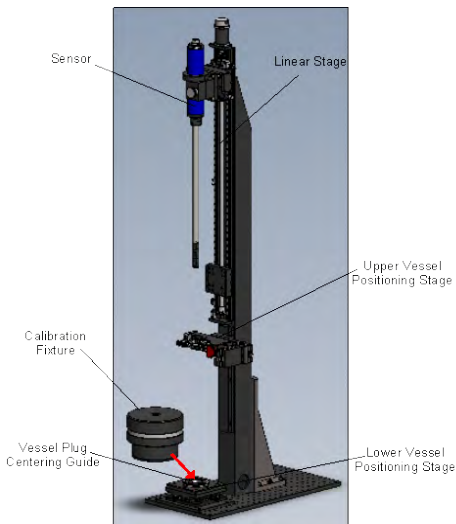
- COPV variability is an ongoing issue, necessitating implementation of complementary non-SHM NDE during the manufacturing phase
 - Profilometry has proven to be useful:
 - Evaluate mechanical response through manufacturing: wrapping and autofrettage (plot each together)
 - Mapping liner buckling and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

The graphic features a central circular porthole with a metallic frame and four bolts. Inside the porthole is a bright, starburst-like light effect. To the left of the porthole is a blue grid pattern. To the right is a blue and yellow striped background with a metallic texture. The text "Composite Conference 2012" is overlaid in a bold, white, sans-serif font with a blue drop shadow.

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Sub-project Details by Center

WSTF COPV Profilometry and Eddy Current Scanners



Original Internal Profilometer



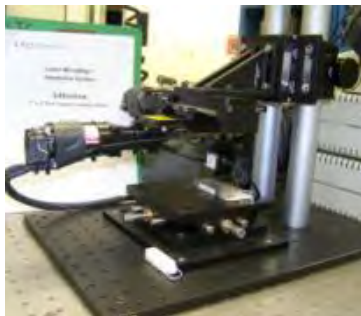
External Profilometer added to Original Scanner



External Eddy Current (EC) Probe added



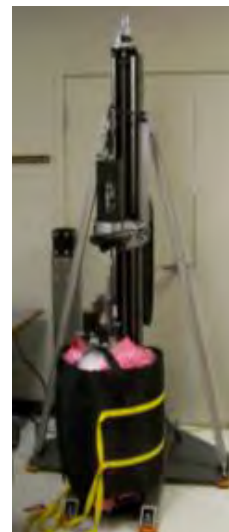
12-foot Orion Internal Profilometer developed and verified on simulator vessel



X-Y Coupon Scanner developed

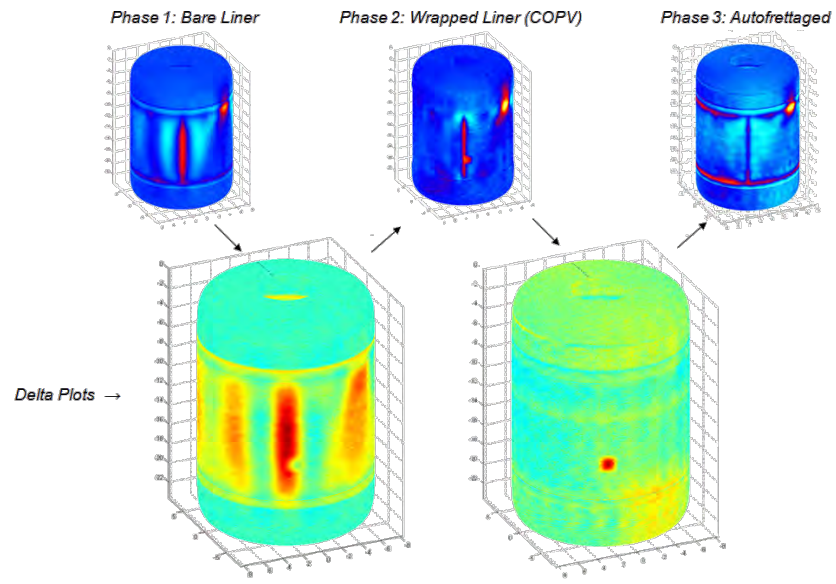


Articulated sensor developed to inspect COPV domes in NORS Internal Profilometer

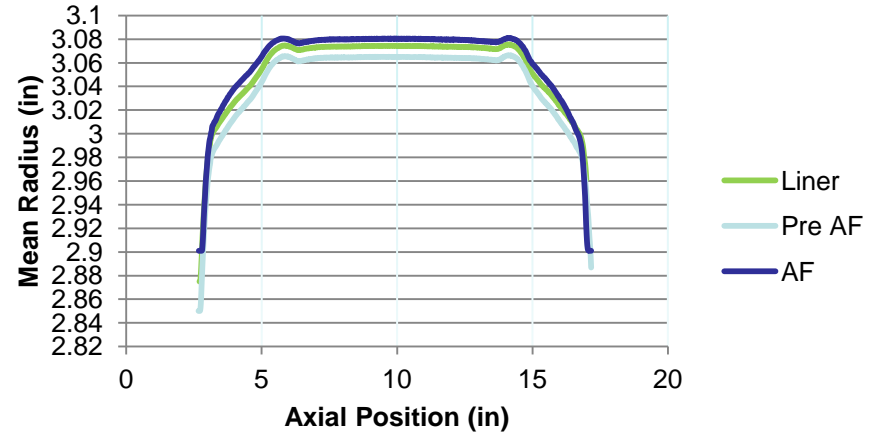


7-foot NORS Internal Profilometer developed, verified and actively being used by the ISS NORS Program

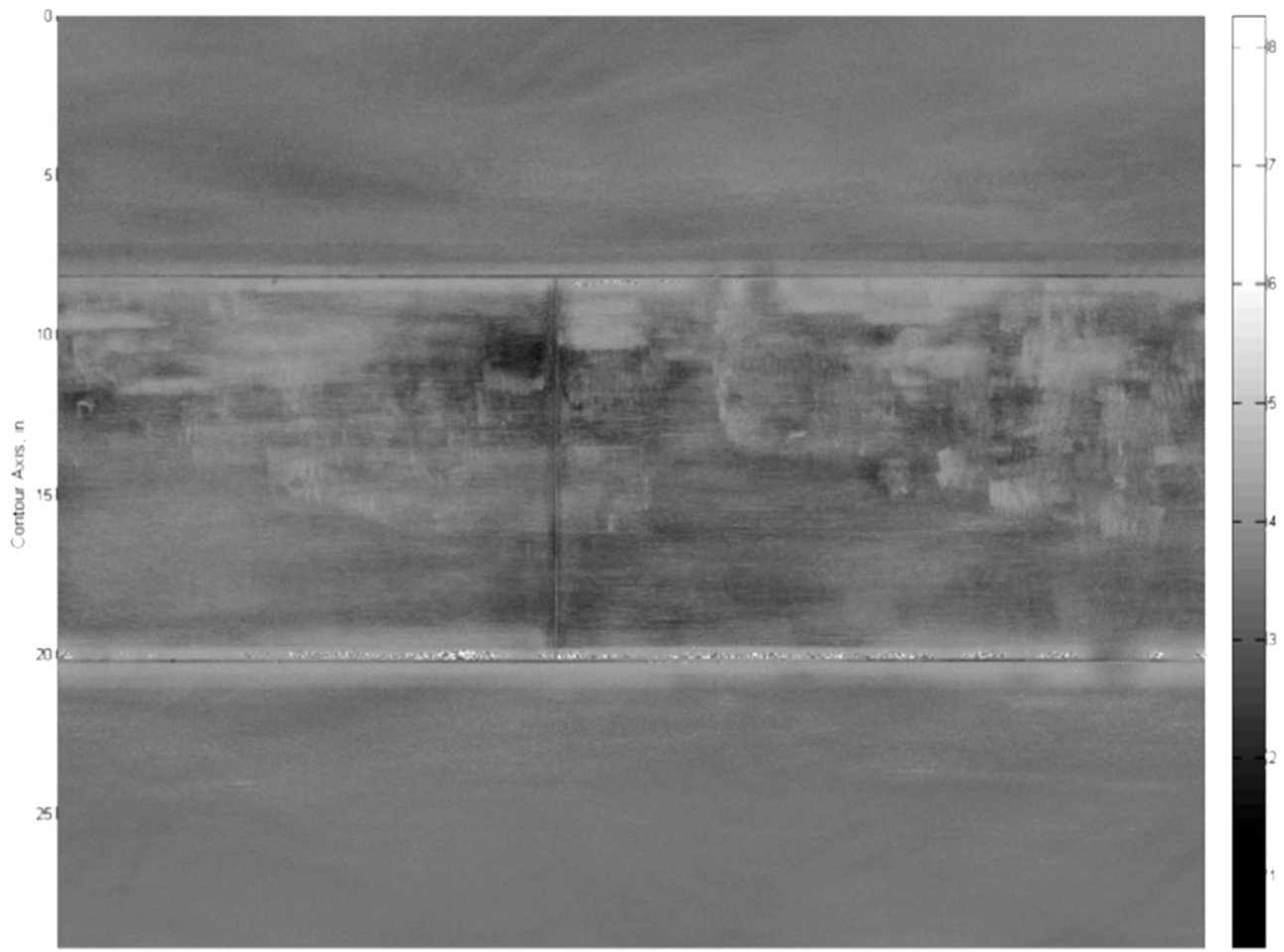
ISS NORS Dev. 4 Changes



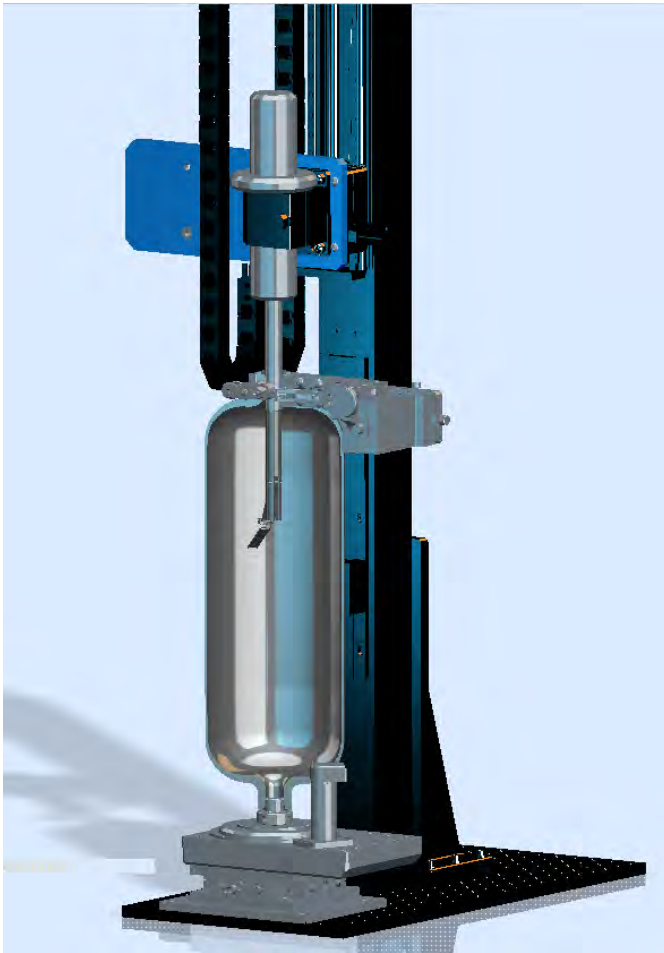
Example Mean Cross Sectional Radius



ISS NORS Dev. 4 Laser Video



NESC Assisting with Internal EC Scanner Being 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

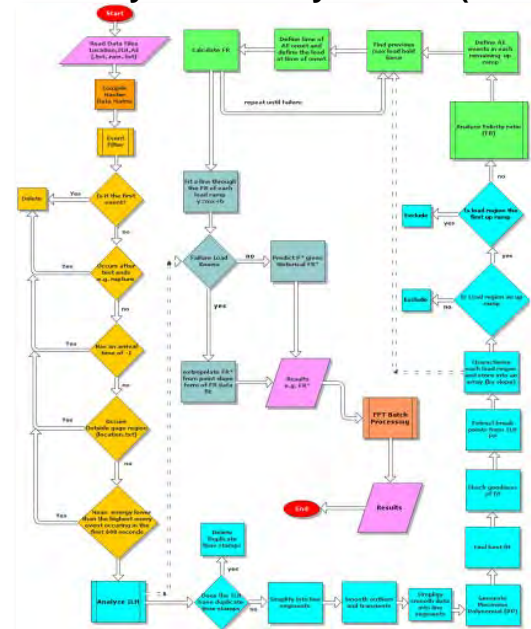
Approach: Statistical Physics vs. Stochastic model used

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

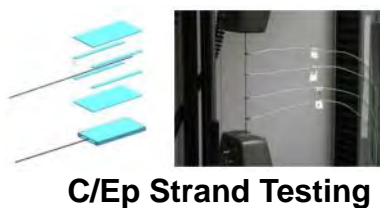
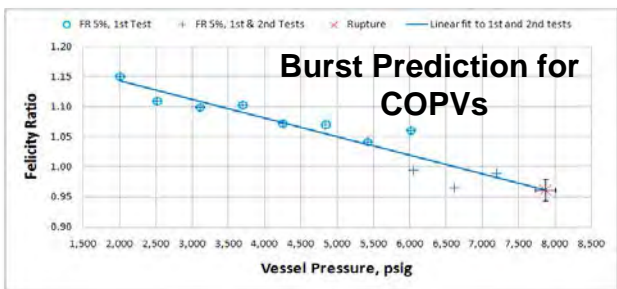
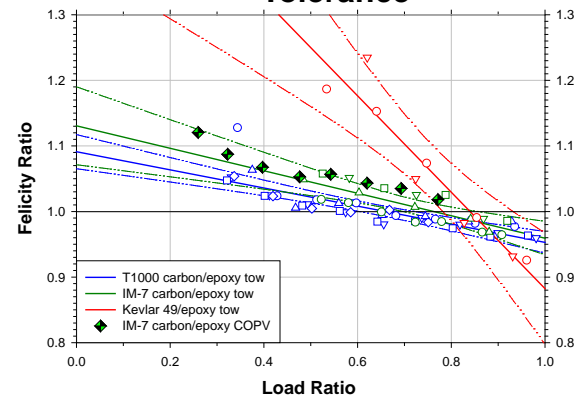
Status: In-house software & AE methods developed

- FR analysis software developed
 - 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)



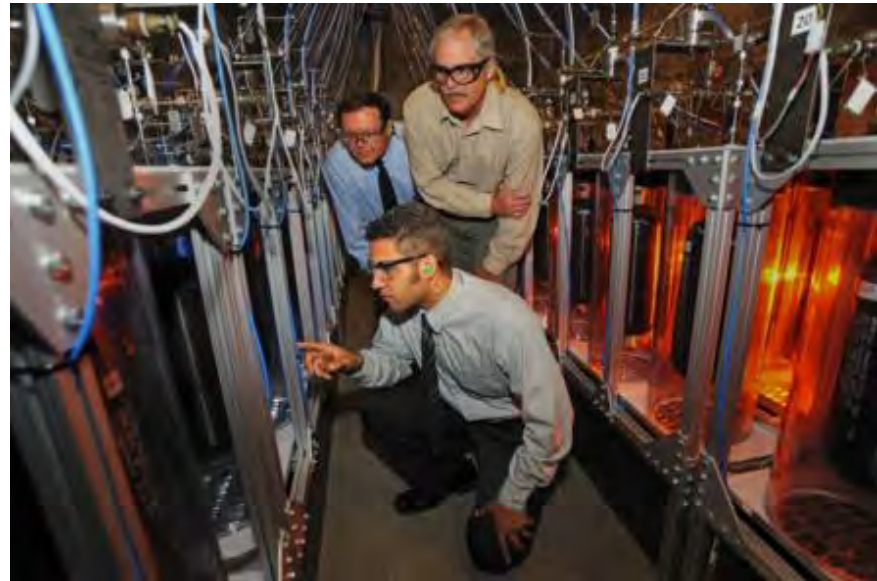
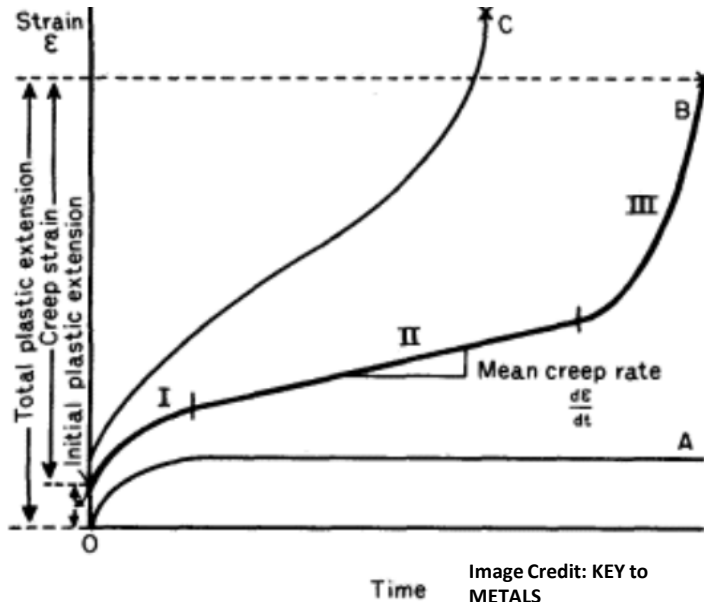
C/Ep Comparative Damage Tolerance



WSTF: Supporting Activity – FY12

- Tests used to better define AE signal feature trends and AE-based COPV burst pressure models:
 - NASA-JSC Innovations, Research, and Development, FY11-12
 - Provided additional COPV and composite strand data for assessing method efficacy using statistical trends
 - Large-scale ISS COPV Stress Rupture Programs, FY11 on
 - Strain, pressure, temperature, and AE data were collected from ISS flight-like COPVs during long-term tests
 - 20 General Dynamic COPVs tested in the NNWG Gen 1 Stress Rupture (SR) Test System
 - 60 General Dynamic COPVs under test in a new, larger SR Test System
 - More to be cycled through testing (~160 available)
 - Trying to evaluate trends indicative of impending failure using improved noise reduction and data acquisition techniques

Monitoring of ISS Stress Rupture Testing Do Carbon Fiber CPV Exhibit Stress Induced Failure?



- A, B or C? How to determine this experimentally?
 - Load, measure, wait
 - Constant: σ , T
 - Measure: ϵ , t
 - t can be very long
 - $d\epsilon/dt$ in region II may be very small and get lost in the noise and drift

Monitoring of ISS Stress Rupture Testing (Con't) Can Sensitivity to Small Changes Answer This?

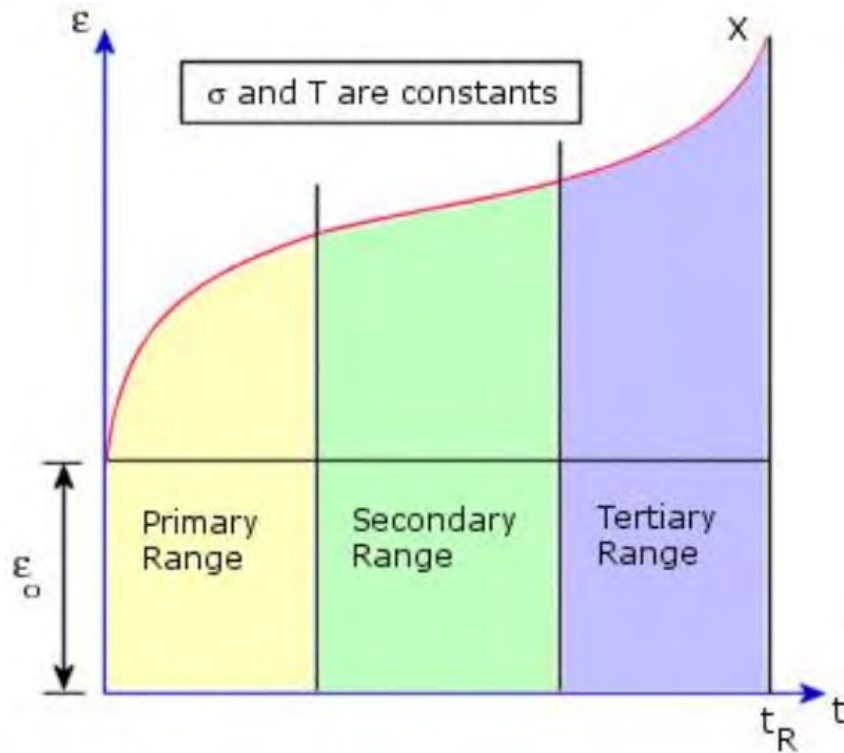


Image Credit: Graphic Systems Corp.

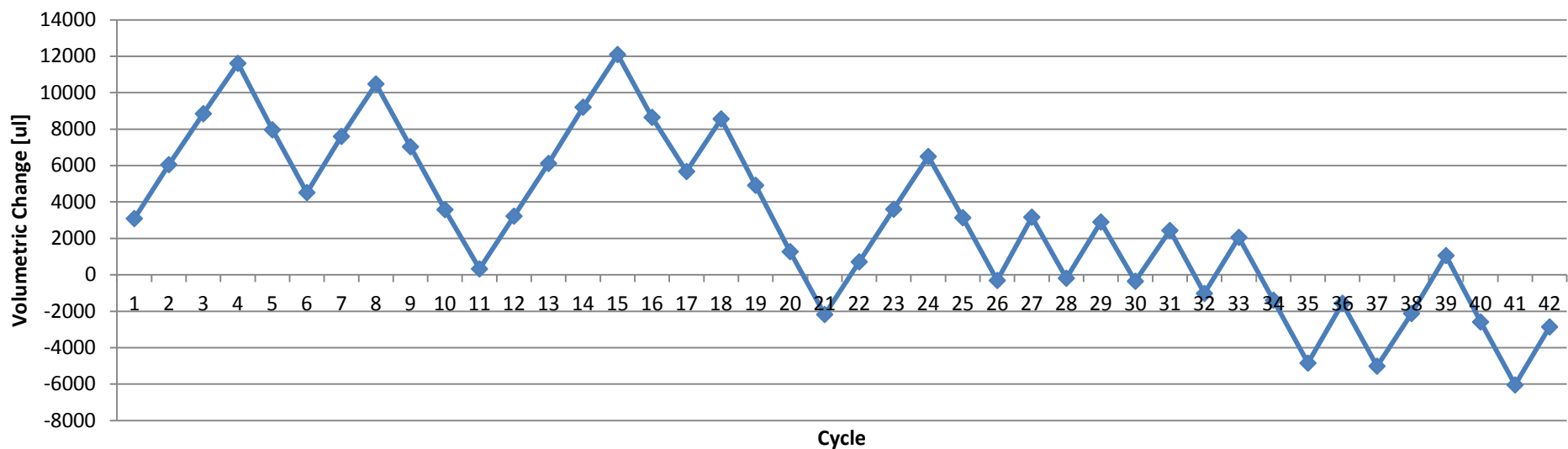
- Currently, resolution, noise and drift limit detection of small $d^2\epsilon/dt^2$
- Alternate Methods?
 - Volumetric Tracking
 - Measure $E(t)$ more directly
 - Accelerated Time ?



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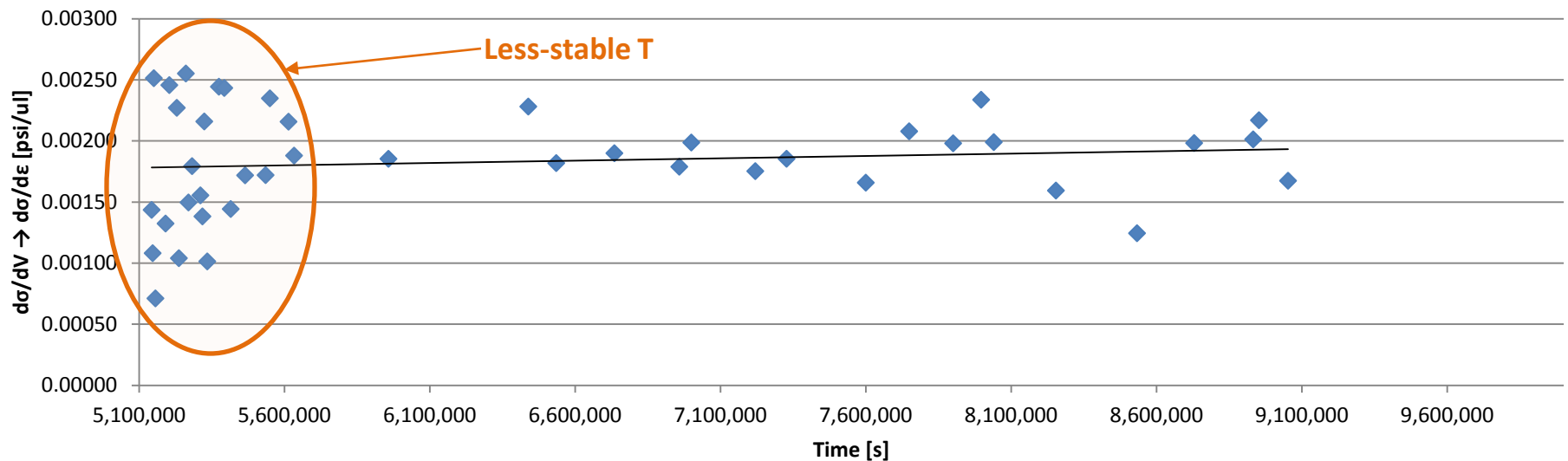
Monitoring of ISS Stress Rupture Testing (Con't) Can Sensitivity to Small Changes Answer This?

- Track dV during pressure control cycles or cycles compensating for vessel growth during stage 1
 - High accuracy in dV, need very stable control over Temp.



Monitoring of ISS Stress Rupture Testing (Con't) Can Sensitivity to Small Changes Answer This?

- Measure $E(t)$ [creep modulus] more directly
 - Correlate to physical models of viscoelastic behavior
 - Need to sort out temperature effects (solvable)
 - Progress possible over longer times (in work)



Monitoring of ISS Stress Rupture Testing (Con't) Can Sensitivity to Small Changes Answer This?

- Plans:
 - Tight test controls
 - Separate effects as far a possible
 - Identify direction and relative magnitude of effects
 - Focus first experiments on what is indeterminate
 - Fiber testing can determine a basis for accelerated ageing

WSTF: FY12 Plan

Overall Project Management

- Technical Approaches and Goals from each contributing Center and are being evaluated and revised in weekly planning meetings and a detailed plan tied to the TA12 roadmap is under development
 - Meetings been held with the Core Team at this point; will involve an extended Agency Team when a draft plan is established to stimulate broader input and consensus
 - Adjusting plans to current funding, but plan to leverage extended Agency Team involvement to attract extended Agency Team interest and synergistic co-funding and involvement

Software and Method Refinement and Integration

- Continue and complete WSTF-GRC-AE vendor software integration which has been in development to suit the purposes of real-time Felicity ratio analysis, batch processing, and pattern recognition
 - Batch processing of AE event features has been integrated into GRC's AE Analysis Applet (AEAA)
 - Current features: energy, counts, peak amplitude, rise time, amplitude RMS, and duration.
 - In-house code written at WSTF will be integrated into AEAA and AE equipment vendor software packages
 - Targeted feature: autonomous, real-time capability with user-specified accept-reject
 - AE analytical protocols will be developed for current and anticipated on-orbit COPV pressure profiles (collaboration with JSC and S. Forth)

WSTF: FY13 Plan

Hardware Refinement & Integration

- Down select AE platform for hardware integration w/ DIDS incl. sensors.
 - WSTF and GRC developed software that must tie into the LaRC wireless DIDS by FY14
- For the purposes of modal AE analysis on coupons and COPVs, both DWC and MGI hardware will be used
 - Merits of using conventional resonant sensor parameter (RSP) versus broadband sensors for performing Felicity ratio (FR) trend line analysis will be assessed and an optimized choice made

Coupon Shakedown Tests

- Apply the real-time autonomous AE system to laminate coupons in preliminary shakedown tests to demonstrate software and hardware functionality, reliability, and accuracy
 - Layup geometries will be tested, and damage progression monitored by AE
 - Source location inaccuracies caused by structural anisotropy in the composite lay-ups (involves collaboration with M. Hamstad of Univ. of Denver)
 - Attenuation characterization of high frequency (fiber breakage) events and the minimum detectability distance determinations will also be performed and the relevant findings implemented
 - Coupon-level method refinement for DIDS array AE, embedded FGB grids, Acousto-Optic NDE, and Magnetic Stress Gages will be performed as necessary prior to component level COPV tests (synergistic/antagonistic concurrent data collection attributes assessed)

WSTF: Plans for FY14

Bottle Testing of Automated AE System

- Once software and hardware function has been verified in preliminary shakedown tests on composite laminate coupons, pressure testing will be performed on COPVs (already procured by the NNWG during the NDE of COPV Stress Rupture project)
- Setup test system alarms using selected Pass/Fail criteria
- Provide automated remaining lifetime predictions using a semi-empirical approach using AE, stress and strain data
 - Damage progression, e.g., the cumulative amount of fiber breakage, will be quantified by FFT batch processing
 - Evaluate merits of pattern recognition and pass-fail criteria using waveform analysis based the extensional/flexural characteristics
 - COPV-level method refinement for modal AE, DIDs array AE, embedded FGB grids, acousto-optic NDE, PZT, and Magnetic Stress Gages will also be performed
 - Implement parallel integration of modal AE, DIDs array AE, FGB strain, acousto-optic NDE, PZT, and magnetic stress gages on COPVs as feasible

WSTF: Plans for FY15

Single and Multiple COPV Testing of Automated Acoustic Emission System

- Select and test Target COPVs
 - COPVs on ISS or other at-risk COPVs to be targeted first using customized accept-reject criteria
 - Work to develop autonomous AE SHM capability for ISS evaluation can also have direct implications for detection of MMOD impacts and other similar applications (e.g., structural composite applications)
 - AE (conventional and DIDS) data collection and reduction is laborious and time consuming.
 - Automated software critical to real-time analysis
- Accomplish System Demonstration and Project Reporting with inputs from all centers

GRC: Acoustic Emission Analysis Applet

Goal:

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

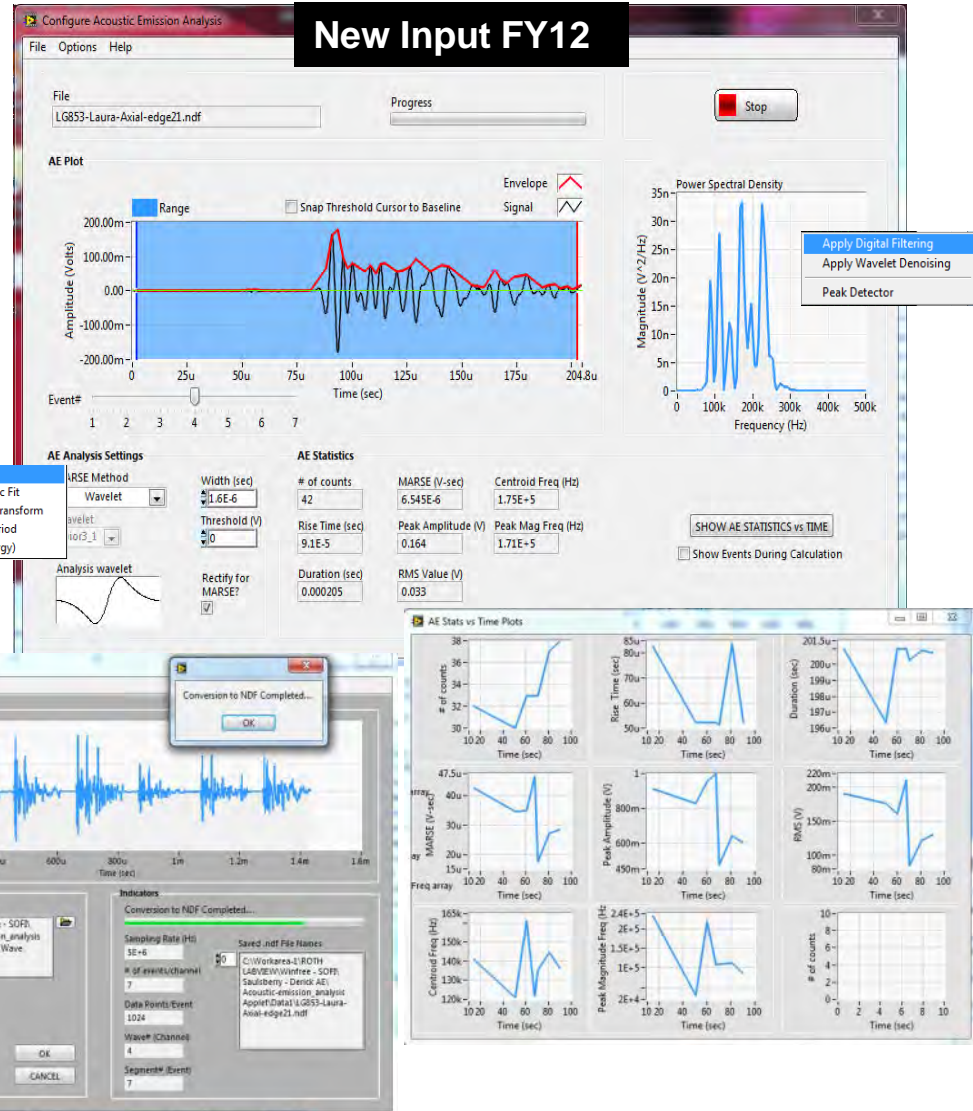
Approach:

- 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





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GRC: Translate Vendor Data Formats to NDF

Need
Vendor
Support

Digital Wave AE Data --> NDF Translator

Help

Channel Data

Amplitude (V)

Time (sec)

Conversion to NDF Completed...

OK

Settings

File to Translate

C:\Workarea-1\ROTH LABVIEW\Winfree - SOFI\Saulsberry - Derick AE\Acoustic-emission_analysis\Applet\Data1\LG853-Laura-Axial-edge2.Wave

Limit Wave Segments to 2048 Points

Create .txt file for Event/Time

OK

CANCEL

Indicators

Conversion to NDF Completed...

Sampling Rate (Hz)

5E+6

of events/channel

7

Data Points/Event

1024

Wave# (Channel)

4

Segment# (Event)

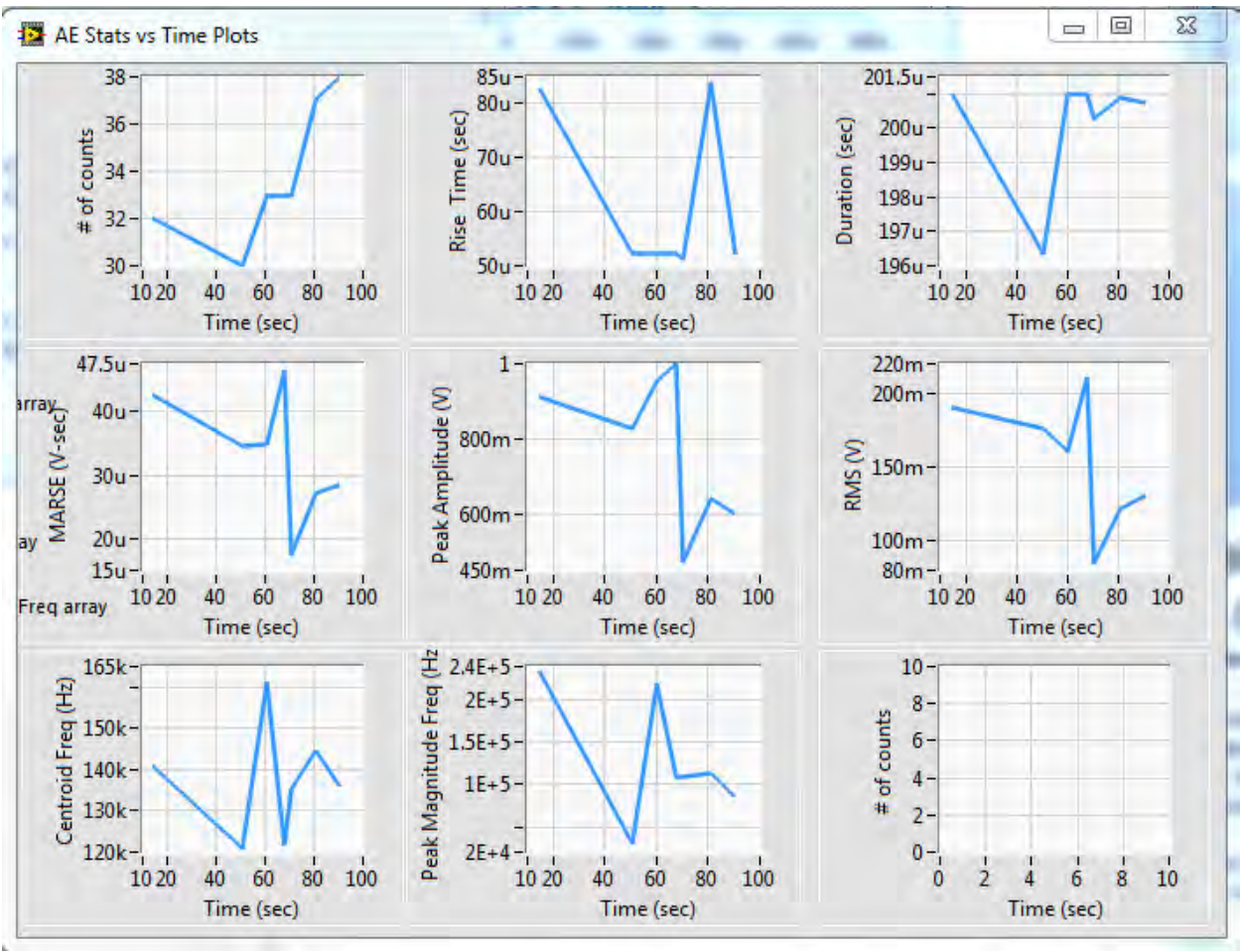
7

Saved .ndf File Names

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GRC: AE Statistics vs Time Plots



LaRC - Application of DIDS Hardware to COPVs

Goal:

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

Approach:

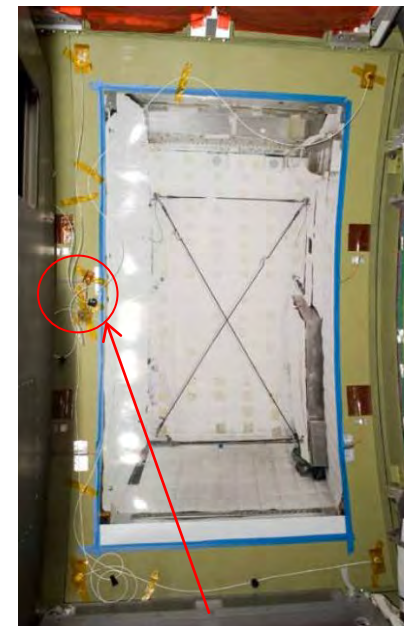
- Evaluate the ability of the Distributed Impact Detection System (DIDS) to capture AE events during testing
- Evaluate system's throughput vs. the requirements of a measuring a COPV
- Assess the DIDS' ability to function as an IVHM system

Status:

- DIDS hardware has been certified for on-orbit application and is currently on orbit, being used to support the SDTO project UBNT



DIDS system with sensors and short cables



DIDS system installed behind rack in Node 2

LaRC: FY13-15 Plans

- FY13
 - Develop the potential of the integration of the wireless Distributed Impact Detection System (DIDS) as an Integrated Vehicle Structural Health component for COPV structures
 - Support the integration of the DIDS output into the software refinement integration task
- FY14
 - Support the application of the DIDS hardware to C/Ep coupon testing
 - Support the application of the DIDS hardware to COPV level demonstration
 - This assessment will help to address the sensitivity, bandwidth, and gain levels required of the DIDS system when applied to these structures
- FY15
 - Support COPV level demonstration
 - The advantage of utilizing the DIDS system is that it has been certified as a flight system and was selected in part because of its wireless capability, low power consumption, and small mass

MSFC: Smart Layer for Smart COPV

Goals:

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

Approach:

1. Perform cycle testing of COPV until Keizer effect is violated. At reduced loading, damage index will be measured.
2. Leverage funding from OCT and Composite for Exploration

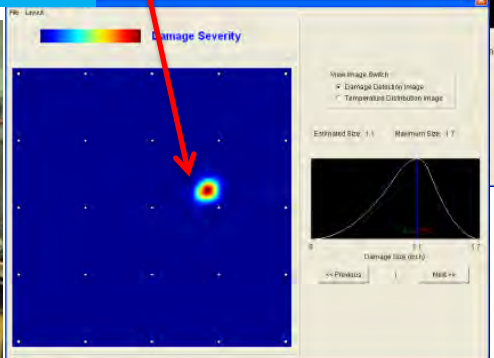
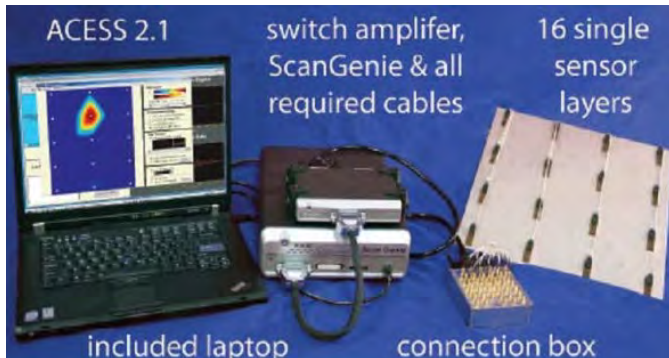
Status:

1. Tested composite laminate with foam core.
2. Currently have three 18" COPV that will be tested at MSFC and possibly one at WSTF.



COPV integrated Smart layers

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

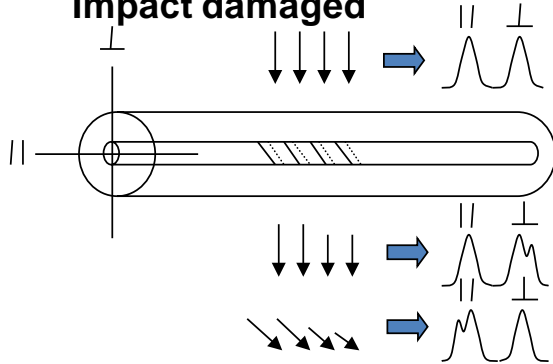


MSFC: Fiber Bragg Strain Sensors Embedded in Composite Bottle

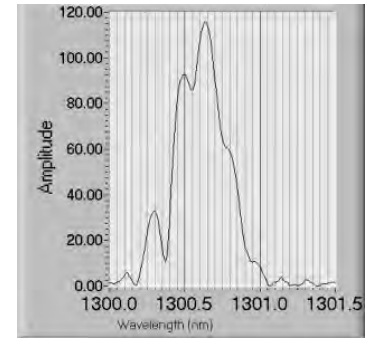
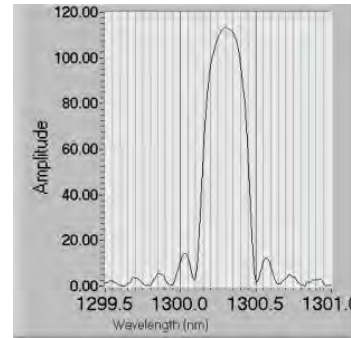
Fiber Bragg strain sensors embedded in composite bottle

Multiple sensors per fiber

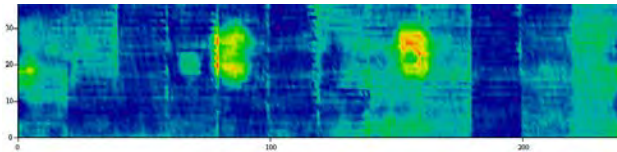
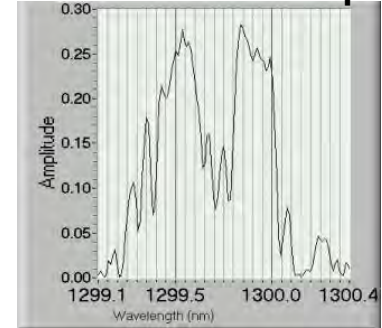
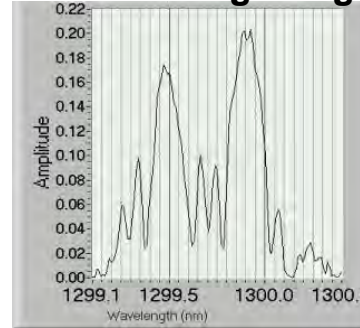
Impact damaged



Single-axis gratings before and after cure



Multi-axis gratings before and after impact



DFRC: Embedded Fiber Bragg Gratings

Objectives

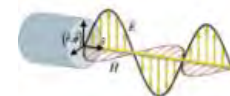
- Perform real-time in-situ structural monitoring of COPVs by acquiring 100s of fiber Bragg grating measurements from sensors embedded within the composite structure of the COPV
- Develop analytical and experimental methods to reliably interpret strain measurements from embedded FBG sensors
- Develop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

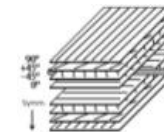
- Hypercomp COPV Testing Complete
 - Instrumented COPV with 1600 FBGs (800 embedded and 800 surface mounted)
- GD T1000 Bottle – Surface sensor testing complete
- Bottle being overwrapped this week (4/27)
- Final burst tests planned for June 2012 at WSTF



Theoretical development



Coupon testing



Analysis and Modeling



Sensor Installation



Embedding / Fabrication



Failure Testing

KSC: Magnetic Stress Gages (MSGs)

Project Objectives

- Design and demonstrate the ability of NDE sensors to measure stresses on the inner diameter of a COPV overwrap.
- Results will be correlated with other NDE technologies such as acoustic emission (AE)
- Project will build upon a proof-of-concept study performed at KSC 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
 - Applicable to essentially all future flight programs

KSC: Proof of Concept Coupon Testing

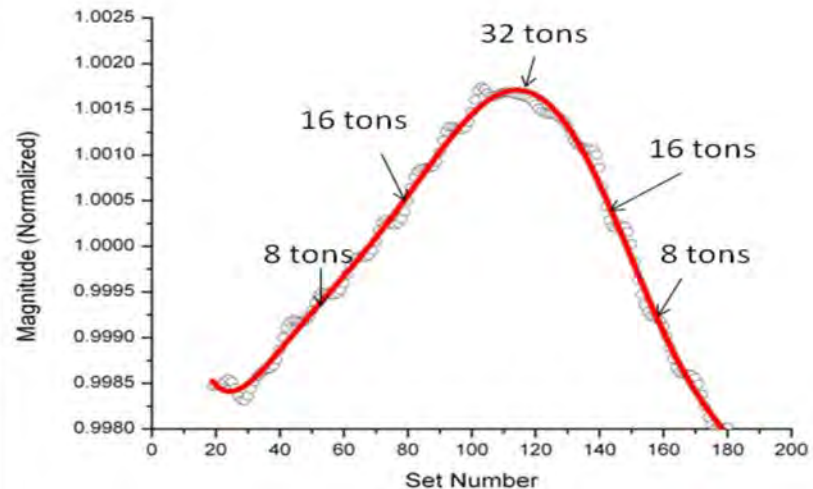


Stresses produced by compressive loading of tapered wedges



Stresses produced by tensile loading of specially design test fixture

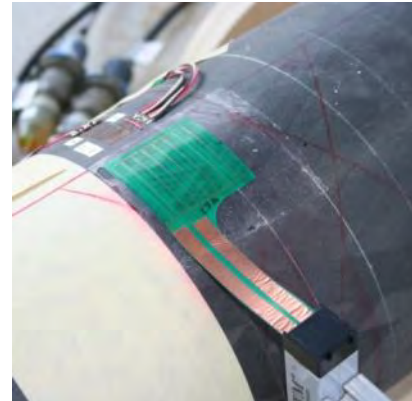
- Coupon cut from center section of COPV (~4" wide)
- Two test fixtures designed
- Due to cutting only hoop direction could be measured
- Several different sensor designs and orientations were tested



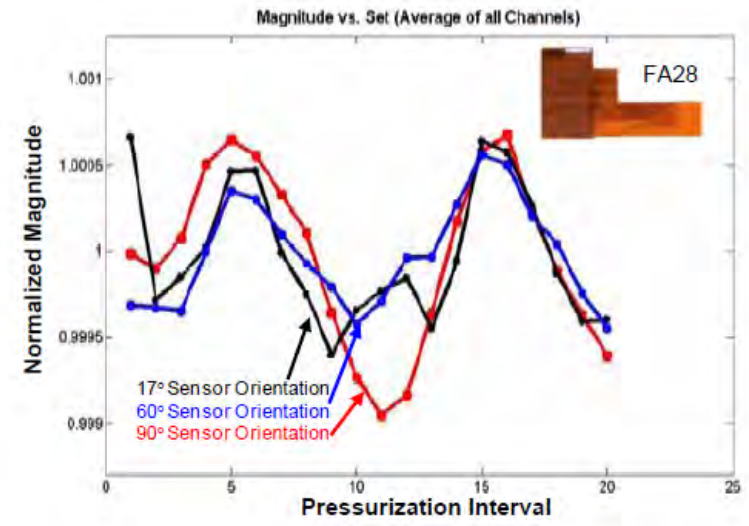
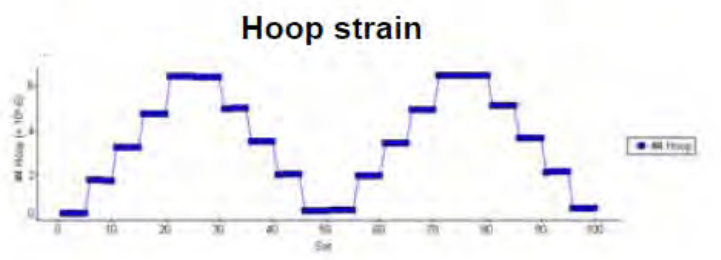
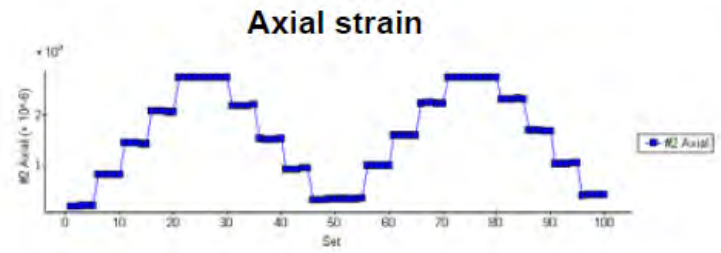
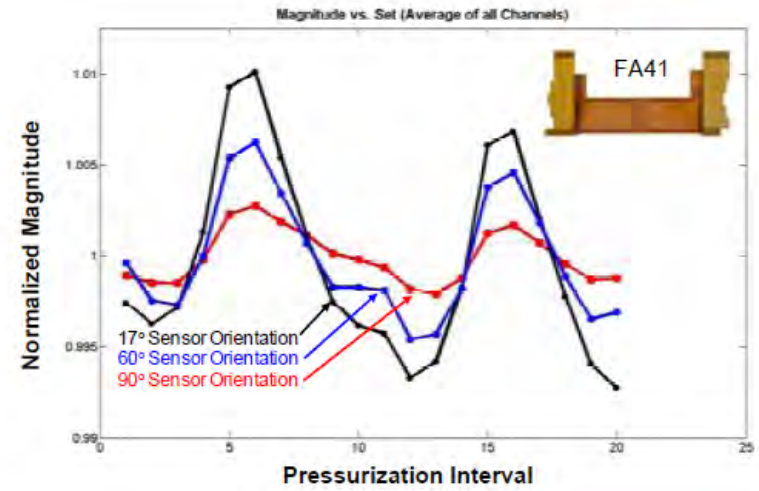
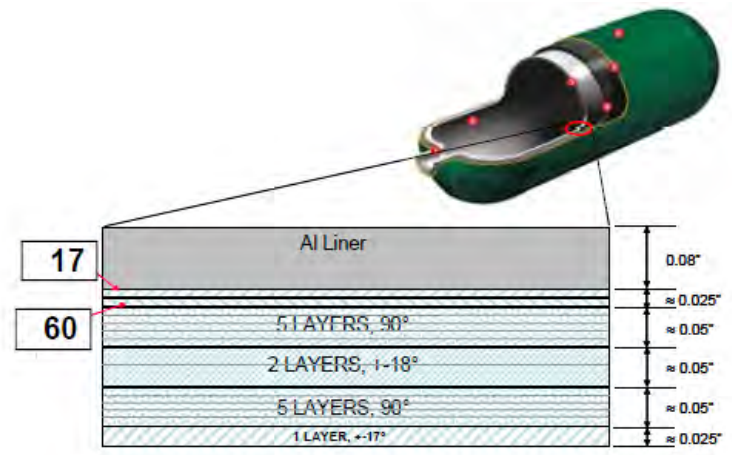
Example of results from compressive loading of tapered wedges test

KSC: 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
 - 90°, 60° and 17° to align sensor drive with fiber orientations



KSC: Proof of Concept Hydrostatic Test



KSC: FY12 Plan

- Test Plan Development and Objective Refinement:
 - Detailed training and test plans shall address the location of MSG and AE sensors, the loading progression and range, and the type and location of damage to be induced (e.g. impact) and location of damage for each test
 - This task shall also include a refinement of the stress and damage monitoring objectives to ensure alignment with NASA mission objectives
 - AE sensor locations and all AE efforts will be directed by WSTF
- Select MSG Sensors:
 - A minimum of three MSG sensors shall be selected based on previous COPV coupon testing
 - These sensors shall support initial testing
 - All sensors will remain the property of JENTEK
- System setup for COPV including GridStation Unit (GSU) and first generation Multiplexing (MUX) Network:
 - JENTEK shall set up a 7-channel (or more) GSU and a multiplexing sensor network or parallel architecture cable configuration with support for between 5 and 50 channels
 - The system setup shall be determined based on input from NASA and results of previous NASA funded COPV coupon testing
 - The MSGs selected under Task 2 shall be supported by this system. Note that if parallel cabling is selected, the channel number may be limited to 7
 - Delivery of this unit pushed to FY13 due to budget cuts

KSC: FY12 Plan Cont'd

- Refine Measurement and Calibration Procedures:
 - JENTEK will refine the measurement and calibration procedures
 - These first two tests are designed to adapt the MSG methods for stress tracking and to begin the effort to coordinate with the AE data acquisition.
 - The goal is to provide reliable stress tracking using the MSGs.
- COPV Testing:
 - Two COPV bottle tests will be performed for up to three days each test
 - These tests will be a learning experience designed to enable the PI and NASA to refine the measurement and calibration methods, test the basic prototype MUX and MSG sensors and evaluate initial performance capabilities and limitations.
 - The contractor will be responsible for the placement of sensors and data acquisition during these tests
 - WSTF personnel will be responsible for the COPV test facility operations including pressurization
- Annual Report

KSC: FY13-15 Plans

- FY13
 - Refine test plan
 - Upgrade and delivery of GSU
 - Additional training and system integration
 - Develop integrated stress and damage tracking methodology
 - Testing of 3-7 bottles (at least one with damage)
 - Annual Report
- FY14
 - Finalize long duration test plan
 - Upgrade and delivery of GSU
 - Additional training and system integration
 - Develop capabilities for long term testing
 - Long duration test of approximately 6 months instrumented with both MWM and AE
 - Annual Report
- FY15
 - Participate in Smart COPV SHM system demonstration
 - Provide input to Smart COPV Final Report

Overall Project Schedule & Milestones

Year	Qtr	AE Method & Sys Dev	AE Software Dev	Magnetic Stress Gage Dev	Embedded AO Dev	Embedded FBG Dev
		WSTF / LaRC / GRC	GRC	KSC / LaRC	MSFC	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 .	<u>KSC</u> : 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, 3	<u>March</u> : Hydrostatic tests of a GD COPV instrumented with FBG and AE sensors. <u>July</u> : 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.	<u>LaRC</u> : 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	Down select AE platform for hardware integration w/ DIDS incl. sensors. 2D laminate plate tests.	Add WSTF AE algorithms to AEAA	<u>KSC</u> : Develop MSG system and test plan for COPV applications. Test 3-7 COPVs. <u>LaRC</u> : 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
	Q4					
FY14	Q1	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.	<u>KSC</u> : Develop capabilities and plan for long term testing. <u>LaRC</u> : 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
	Q4					
FY15	Q1	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.	<u>KSC</u> : Provide input for Smart COPV SHM demonstration. <u>LaRC</u> : Support COPV level DIDS application.	System level testing with AO SHM Equipment.	Develop a robust "early warning" indicator of COPV catastrophic failure
	Q3					
	Q4	Demonstrate Smart COPV SHM syste 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)
- Manufacturing NDE systems: EC to screen for liner flaws and Profilometry characterize COPV mechanical response
 - More development and validation of EC 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 for all techniques selected: high resolution strain maps, liner stress measurements, acoustic emission test results, and profilometry scan data.
- Real-time AE automated software incorporated into an automated monitoring system based on the GRC AEAA and WSTF AE software
 - Includes a ~TRL5-6 hardware platform developed on which the software is incorporated for “black-box” diagnostic and predictive capabilities (minimum breadboard level) requiring little to no astronaut interaction excl. alarms.
- A working concept of a ‘Smart COPV’ with an end-to-end demonstration of real-time COPV SHM system developed, includes end-to-end demonstrations:
 - of the developed real-time embedded FBG SHM System
 - of real-time AE/ wireless AE failure prediction
 - of real-time composite layer stress evaluation using by sensing unique stress in different angles with MSG sensors

Questions?



Smart COPV - Path Forward

- Tool is currently a post-processing tool but will be adapted as SHM tool
 - AE Stats vs. Time/Pressure updated as events occur
- Import pressure profile data to plot and track AE stats vs. pressure (and time)
- Create Condensed NDF 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

MSFC: Acousto-Optic NDE

Goals:

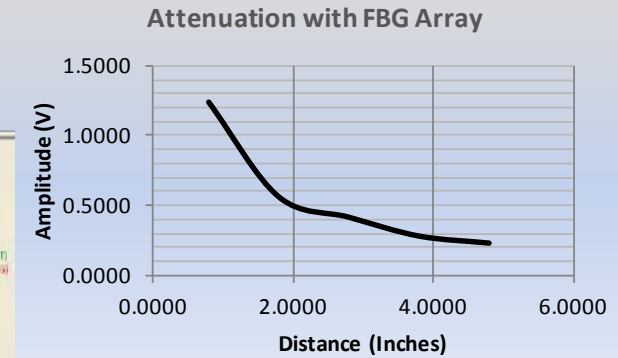
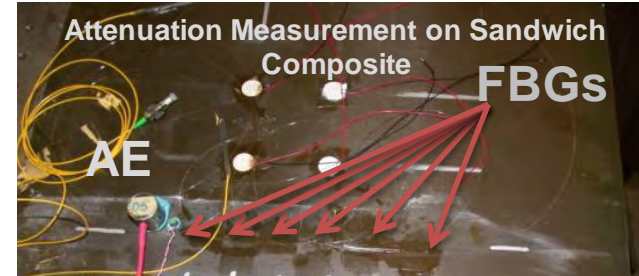
The goals of this study are (a) see the small size and wide acoustical bandwidth of Fiber Bragg Gratings (FBGs) to measure transient acoustical signature, and (b) investigate the possibility of incorporating strain and temperature measurement as well

Approach:

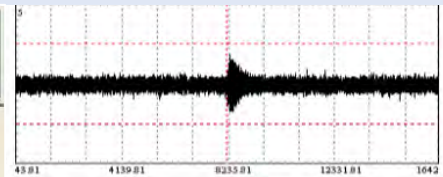
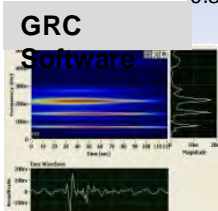
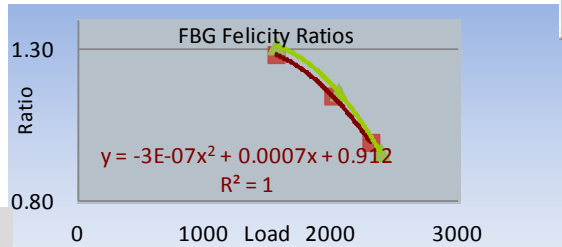
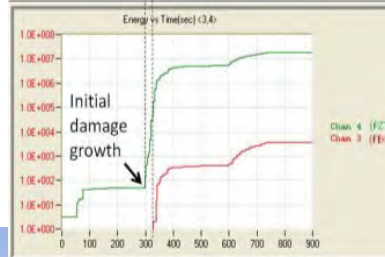
- Compare FBG-AE to PZT-AE in laboratory pitch/catch
- Compare FBG-AE Felicity ratio with PZT AE
- Measure FBG-AE on multiple-composite structure
- Test multiple FBG-AE sensors

Status:

- Tested & compared FBG-AE to PZT-AE
- Performed Felicity measurements
- Leverage OCT and CoEx funding.
- Need better multi-FBG-AE approach




Las Gatos COPV Results



IFOS Multi-FBGs on COPV Result

FBG#1
FBG#2
FBG#3
FBG#4

The graphic features a central circular porthole with a metallic frame and four bolts. Inside the porthole is a bright, starburst-like light effect. The background is a horizontal band with a blue grid on the left, a yellow and blue diagonal stripe, and a blue textured surface on the right. The text 'Composite Conference 2012' is overlaid in a bold, white, sans-serif font with a blue drop shadow.

Composite Conference 2012

Backup

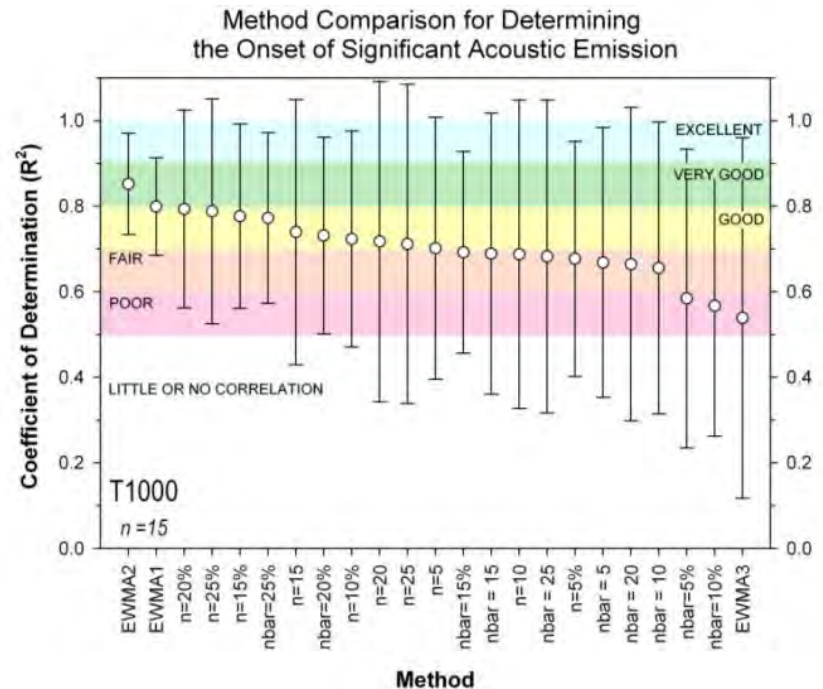
WSTF – USRP and Coop Student Supported Progress

- 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 Structures*, 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

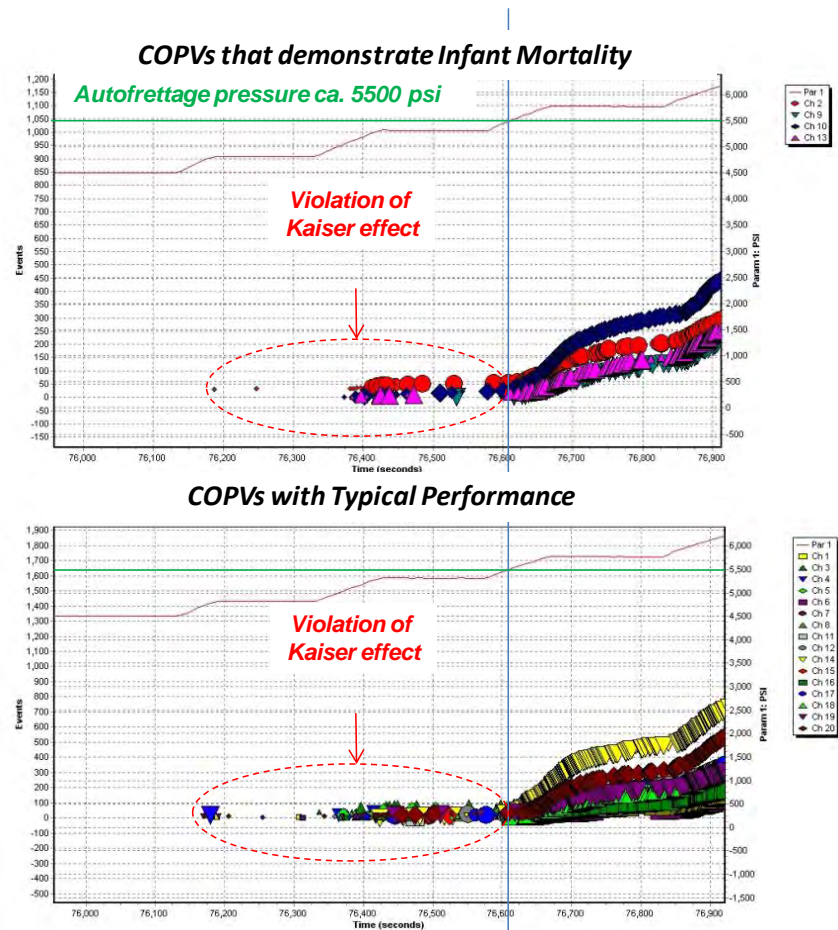
- Preliminary acoustic emission trends:
 - Infant mortality linked to significant energy levels reached prior to reaching the previous pressure state
 - Significant damage accumulation evidenced by AE response w/out stimulus
 - Statistical methods show potential for accurate burst pressure prediction
 - 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



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
	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
FY12	Q2	Feb. 27, 2012: Hydrostatic test of DFRC Bottle 2, Phase 2 instrumented with 800 FBG, 6 SG, and 6 PZ AE sensors				
	Q2	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.
	Q3					
	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.