“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 Shuart - CoEx
- NASA LaRC/Eric Burke - SBIR SHM subtopic manager
- NASA MSFC/James Walker - CoEx ⇒ Composites for Exploration; CCTD ⇒ 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
“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.
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.
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
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
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
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

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

X-Y Coupon Scanner developed

Articulated sensor developed to inspect COPV domes in NORS Internal Profilometer
ISS NORS Dev. 4 Changes

Example Mean Cross Sectional Radius

Phase 1: Bare Liner  Phase 2: Wrapped Liner (COPV)  Phase 3: Autofrettaged

Delta Plots →

Axial Position (in)

Mean Radius (in)

0 5 10 15 20

2.82 2.84 2.86 2.88 2.9 2.92 2.94 2.96 2.98 3 3.02 3.04 3.06 3.08 3.1

Liner  Pre AF  AF
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
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: $\sigma, T$
  - Measure: $\varepsilon, t$
  - $t$ can be very long
  - $d\varepsilon/dt$ 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?

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

![Graph showing volumetric change over cycles](chart.png)
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)
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

New Input FY12
GRC: Translate Vendor Data Formats to NDF

Need Vendor Support
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
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
**Goals:**
Define Critical Damage Accumulation (CDA) in Composite Overwrap Pressure Vessel (COPV) before stress rupture occurs and corroborate (CDA) with a known NDE inspection standard: AE Felicity ratio; Additionally, 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.
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
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

- 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

Stresses produced by compressive loading of tapered wedges

Stresses produced by tensile loading of specially design test fixture

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Qtr</th>
<th>AE Method &amp; Sys Dev</th>
<th>AE Software Dev</th>
<th>Magnetic Stress Gage Dev</th>
<th>Embedded AO Dev</th>
<th>Embedded FBG Dev</th>
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<td>WSTF / LaRC / GRC</td>
<td>GRC</td>
<td>KSC / LaRC</td>
<td>MSFC</td>
<td>DFRC</td>
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<tr>
<td>FY12</td>
<td>Q1</td>
<td>Perform statistical analysis and down select burst prediction algorithms. Perform COPV AE feasibility studies and preliminary test method development.</td>
<td>Work with WSTF to outline AE updates to Acoustic Emission Analysis Applet (AEAA) software.</td>
<td>KSC: Test plan development and objective refinement for magnetic stress gage (MSG) application to COPVs.</td>
<td>Acousto-optic (AO) acoustic emission SHM sensor and method development.</td>
<td>Develop instrumentation plan and procedure development for in-situ structural strain monitoring of COPVs using FBGs.</td>
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<td>Q2</td>
<td>March: Hydrostatic tests of a GD COPV instrumented with FBG and AE sensors. July: Test w/ embedded and surface FBGs &amp; surface AE sensors.</td>
<td>Validate AEAA software performance using large COPV files.</td>
<td>LaRC: Demonstrate the ability of flight certified hardware to perform AE measurements in COPVs</td>
<td>Test selected AO sensors and systems</td>
<td>Develop analytical and experimental methods to reliably interpret strain measurements from embedded FBG sensors</td>
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<td>Q3</td>
<td>Direct AEAA algorithm development. Develop software for automated burst prediction. Investigate other techniques including extensional/flexural wave analysis.</td>
<td>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.</td>
<td>System integration efforts with WSTF/GRC automated AE monitoring software</td>
<td>Analytically model the embedded FBG sensors usingprofilometry data generated by WSTF</td>
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<td>Q4</td>
<td>Down select AE platform for hardware integration w/ DIDS incl. sensors. 2D laminate plate tests.</td>
<td>Add WSTF AE algorithms to AEAA</td>
<td>Comparative validation of AO AE to PZT AE sensors</td>
<td>Test to failure; correlate data at each step</td>
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<td>FY13</td>
<td>Q1</td>
<td>Develop test methods to match ISS pressure profiles. Addtl. COPV tests. Develop agency Accept/Reject criteria.</td>
<td>Structural health monitoring integration efforts for each technique as capabilities allow.</td>
<td>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.</td>
<td>System level testing with WSTF/GRC automated AE monitoring software</td>
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<td>Q4</td>
<td>Produce automated AE system with integrated alarms to meet robust flight hardware/ software requirements</td>
<td>System level Testing with Team-Selected Sensor Grids and SHM Equipment.</td>
<td>KSC: Provide input for Smart COPV SHM demonstration. LaRC: Support COPV level DIDS application.</td>
<td>System level testing with AO SHM Equipment.</td>
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<td>FY15</td>
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<td>Develop a robust &quot;early warning&quot; indicator of COPV catastrophic failure</td>
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<td>Q4</td>
<td>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.</td>
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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
**Goals:**
The goals of this study are (a) use 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

\[ y = -3E-07x^2 + 0.0007x + 0.912 \]

\[ R^2 = 1 \]
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:

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. Distributed 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. Energy (Measured area of the rectified signal envelope)
      ii. 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

Schedule/Plan/ Milestones:

<table>
<thead>
<tr>
<th>Year</th>
<th>Qtr</th>
<th>DFRC</th>
<th>GRC</th>
<th>MSFC</th>
<th>KSC / LaRC</th>
<th>WSTF</th>
</tr>
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<tbody>
<tr>
<td>FY12</td>
<td>Q1</td>
<td>Development of FBG sensors/methods for embedment in COPVs</td>
<td>Outline AE updates to NDEWIP software</td>
<td>Acousto-optic method and sensor development</td>
<td>Eddy current sensor and method development</td>
<td>Down select Felicity ratio algorithms; AE method development</td>
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<td>Q2</td>
<td>Feb. 27, 2012: Hydrostatic test of DFRC Bottle 2, Phase 2 instrumented with 800 FBG, 6 SG, and 6 PZ AE sensors</td>
<td>COPV-level test of selected FBG arrays</td>
<td>Add WSTF AE algorithms to NDEWIP</td>
<td>Test selected AO sensors and systems</td>
<td>COPV-level test of EC sensors</td>
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<td>Q3</td>
<td>Model validation of COPV FBG strain results</td>
<td>Validation of new NDEWIP AE modules</td>
<td>Comparative validation of AO AE to PZT AE sensors</td>
<td>Validation of EC and new NDEWIP AE modules</td>
<td>NDEWIP AE mods. software validation</td>
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FY13
   - 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.