NDE for Advancing COPV Quality Assurance and Assessing MMOD Impacts

Project Active 2015 - 2018

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Technical Leads: Larry Hudson, David Lubas, Eric Madaras, & Regor Saulsberry

ASNT In Space Inspection Workshop 2017

Approved for public release.
Overview

• To date, three fatalities due to composite overwrapped pressure vessel (COPV) failures have occurred in the U. S. transportation sector [1, 2, 3]. Two COPV failures resulting in injury have occurred; namely, during a U. S. Air Force program in 2003, and at Kennedy Space Center in 2008.

• More recently, two commercial spacecraft launches carrying commercial payloads were scrubbed in 2014 due to COPV related failures [4, 5]. The Sept 2016 on-pad explosion was also traced to a COPV failure; the details of which will not be discussed in this presentation. [6, 7]

• This project targets the top inspection and monitoring needs of NASA and Commercial Spaceflight partners. State of the art manufacturing systems need to be developed. COPVs flying in an unshielded configuration may need to be monitored for MMOD impacts, however impact signatures needed to be determined.
Falcon 9 rocket set to take a satellite into space on Labor Day weekend exploded during testing days before. [http://wapo.st/2c8fQVP](http://wapo.st/2c8fQVP)
Composite Overwrapped PVs

Nomenclature

- Ported Boss
  ("Blind" when there is no inlet/outlet)
- Dome Section
  (High angle helical fiber wraps)
- Transition
- Barrel or Cylindrical Section
  (Helical wraps under hoop wraps)
- Shoulder
- Composite Overwrap
  (Carbon Fiber & Epoxy)
- Metallic Liner

NASA-JSC White Sands Test Facility
Las Cruces, New Mexico
Needs Expressed by COPV Experts

- **R1:** Statistically validated and automated COPV inspection system for the identification and sizing of liner cracks\(^1,2,3\) and thickness\(^3\) measurements, esp. in domes (ground-based system).
  - Outer-surface liner flaw detection accomplished. Results are better than special penetrant.
  - Electromagnetic liner thickness mapping included and demonstrated, as is ID/OD contour mapping.
  - Through-wall detection of flaws was requested\(^1,2\) and is in work.
  - UT inspections of liner-composite bond lines from liner interior is a newer request. \(^1\)

- **R2:** Statistically validated detection of space debris impacts during spaceflight.\(^1,2\)

- **R3:** Validated characterization of composite damage including cut fibers (ground-based system).\(^1,2\) Special-NDE validation with composites poses unique challenges.
  - Special NDE validation on composite specimens may not be feasible due to manufacturing variations.
  - This requirement is broad and, as such, is more difficult to define.

- NASA COPV Points of Contact Surveyed (commercial entities omitted)
  1. NASA CPV Working Group Lead: Lorie Grimes-Ledesma
  2. NASA Engineering & Safety Center NDE Technical Discipline Lead: Bill Prosser
  3. NASA Human Spacecraft Pressure Systems Lead: Nate Greene
  4. NASA Pressure & Energetic Systems Safety Manager: Owen Greulich
Sites Advancing COPV NDE
Multipurpose COPV Scanners – WSTF (Co-f: NESC)

- EC flaw maps for an X-oriented sensor scanning L-R

DIDS AE SHM tests planned for COPV impacts - LaRC

- S/N 030, Vertical Flaw #5
  - Target size .015” x .006”
  - Noise Floor (σ) = .125V
  - 8.6 SNR

FOSS/FBG Strain Measurement – AFRC (Co-f: CPVWG)

- Exterior Surface & Embedded FBG tech demonstrated. Higher density Liner-Interior FBG instrumentation in work with partner Samtech.

Near-surface ET POD study inspections complete. Will propose dome ET POD to NESC. Through-wall ET crack detect probe in development.

Magnetic Stress Gage System – KSC

- Tests completed to identify signatures of subsurface composite damage supported by AE. Analyses and reporting underway.

We are advancing DIDS IVHM for SLS/ICPS COPV MMOD applications by supporting hypervelocity impact tests with the NESC. Scanner sppts.
Multipurpose Pressure Vessel Inspection System
R1: Ground-based inspections supporting manufacturing qualifications.

✓ Multipurpose Pressure Vessel Inspection System

Collaboratively funded by both NESC & OSMA

- Supported Boeing/ATK production of NORS COPVs with ID/OD 3D surface maps.
- Now has ID/OD dome and cylinder EC crack, EC thickness, and profile sensors.
- Smaller variant supporting simulated orbital debris impact testing on pressurized and empty COPVs during a NESC risk assessment.
- ET flaw POD complete for cylinder OD. Through-wall POD now required.

Manager: Regor Saulsberry, NASA JSC White Sands Test Facility (WSTF)

- Technical Leads at NASA Langley, Uniwest, and Laser Technique Co.

* Acellant smart strips were down selected in FY15 during an annual RIF aligned with COPV SME priorities.
COPV Scanner: General System Overview

- Multipurpose Scanner
- Internal Laser Probe (EC Probe Similar)
- Internal End Effector Articulation
- External End Effector Articulation
- Internal End Effectors
- External End Effectors
- Large OD EC Thickness Sensor (Validation Required, Proposed for FY17)
Internal profile measurements of an early NORS composite vessel through all manufacturing phases (left). Intensity map collected during profile measurements showing typical indications (right). Areas in red have a smaller internal radius. Delta plots show interphase measurement shifts. A thin, 0.010-in. thick skin-to-core debond simulated with a Teflon® PTFE insert was easily detected (right Delta plot).
Extraordinary detection capabilities were demonstrated and verified in accordance with MIL-HDBK-1823a, *NDE System Reliability Assessment*.

- The eddy current test (ET) probe liner scan and analysis procedure produced an estimated 90/95 POD at a detectable flaw size of .0094 in x .0047 in (L x D) for fatigue cracks despite challenging surface finish conditions.

Limitations of the most prevalent alternative: penetrant testing.

- Standard Penetrant

- Special Penetrant, sampling of a few examples observed across NASA/industry
  - PT detection of 0.0500-in x 0.0250-in has been used as a special NDE crack size.
  - PT POD of 0.0300-in x 0.0150-in has also been demonstrated.
R2: Detection of impacts during spaceflight.

✓ **Distributed Impact Detection System – DIDS AE**

- System is currently aboard the *International Space Station*, Node 2
  - Also being used to monitor a low mass, high volume inflatable habitat: the *Bigelow Expandable Activity Module* (BEAM).
  - Originally developed for Shuttle wing leading edge impact monitoring. George Studor and Bill Prosser were co-developers.

- FY16 saw the first application of DIDS to simulated orbital debris impact testing on pressurized and empty COPVs.
  - Supported by a NESC SLS MMOD risk assessment.

- Manager: Eric Madaras, NASA Langley

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Application of DIDS Acoustic Emission Hardware to Orion-like COPVs

Background: COPVs shown aboard Orion’s European Service Module
Generalized Overview of Acoustic Emissions
LaRC - Application of DIDS hardware to COPVs

**The Goal:**
- Demonstrate the ability of flight certified hardware to perform AE measurements in COPVs

**The 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 measuring a COPV
- Assess the DIDS’ ability to function as an IVHM system

**Status:**
- Two of four DIDS systems have been procured
- Hardware has been certified for on-orbit application and is currently on orbit, being used to support the SDTO project UBNT
Distributed Impact Detection System (DIDS)
Detection of Impact and Detonation of Impacted Pressurized COPV

Impact at $T \approx 0 \text{ ms}$
Picture frame time at $T = +0.782 \text{ ms}$

$T$ = Detonation Time at Sensor Location

Impact location at COPV wall
47-degree impact of a 1 mm Al ball at 7.41 km/s on a COPV pressurized to ~4300 psi. HITF 16159

Suspect that the first 50 µs of AE signal may be from the ply delamination process.

Impact at T ≈ 0 ms

Hypervelocity Impact resulting in severed fibers and ply delamination.
Direct impact of a 1.5 mm Al ball at 7.24 km/s. COPV was pressurized to ~4300 PSI. HITF 16166

Gas venting noise is decreasing during the 2 ms of measurement. Some of the early noise levels are probably due to the initial ply failing near the impact location. Venting noise is greater than the impact noise seen in HITF 16159.

Impact at T ≈ 0 ms
Direct 1.72 mm Al ball impact at 7.01 km/s. COPV was pressurized to ~4300 PSI. HITF 16167 = Detonation Time at Sensor Location

Impact at T ≈ 0 ms

HVI with Penetration and COPV Rupture
General Observations

- AE spectra for HITF 16159 and 16166 are similar, with abroad peaks near \( \sim 100\text{KHz} \) and \( \sim 450\text{KHz} \).

- HITF 16159 had a smaller 100KHz peak and higher 450KHz peak signal than HITF 16166, suggesting that the vent noise was adding signal in the 100KHz regime.

- HITF 16167 had less defined peaks at 100KHz and 450KHz, probably because the null parts of the data weren’t windowed out.
R3: Ground-based characterization of composite damage.

✓ Balanced array of maturing NDE technologies

**Fiber Bragg Grating (FBG)**
Optical Strain Measurement System
Larry Hudson – NASA Armstrong Flight Research Center

**Magnetic Stress Gage (MSG)**
Sensing System
David Lubas – NASA Kennedy Space Center

Exterior Surface & Embedded FBG tech demonstrated. Higher density Liner-Interior FBG instrumentation in work with partner Samtech, a COPV liner manufacturer.

Tests completed to identify signatures of subsurface composite damage supported by acoustic emission (AE). Impact damage site locus resulted in subsurface fiber conductivity shifts and high frequency AE.

* Acellant smart strips were down selected in FY15 during an annual RIF aligned with COPV SME priorities.*
Fiber Bragg Grating (FBG)
Optical Strain Measurement System
Generalized Overview of Fiber Bragg Gratings

\[ \lambda_{\text{Bragg}} = 2n\Lambda \]

Unstrained FBG

\[ \lambda'_{\text{Bragg}} = 2n'\Lambda' \]

Strained FBG
The Goal: Characterize the ability of fiber Bragg grating sensors to detect failure in COPVs
- COPVs have been experiencing random failures for unknown reasons
- Continuous grated fiber being used to identify residual strain in COPV metallic liner resulting from autofrettage process which may be failure mechanism

The Approach: Install continuous grated fiber on COPV metallic liner inner surface
- Install fiber during the metallic liner fabrication process
- Modify dome with 10K psi fiber-optic feedthrough
- Complete composite overwrap
- Perform autofrettage process while monitoring FBG output

Accomplishments:
- Completed installation of optical fibers in two metallic liners
- Liners returned to vendor to close open end

Upcoming Activities:
- Composite overwrap liners
- Perform autofrettage process
- Testing March 2017
Magnetic Stress Gage (MSG) Sensing System
KSC - NDE for Advancing COPV Quality Assurance and Assessing MMOD Impacts

KSC - Eddy Current Health Monitoring

**Objectives:** Demonstrate that Magnetic Stress Gages (MSG) can effectively measure stresses in internal overwraps and is synergistic to AE and other successful methods being used by the “Smart COPV” team

**Goal:** Integrated this technology with other “Smart COPV” technologies for synergistic health monitoring of COPVs used for all future flight programs
Accomplishments

- Completed test 1 cyclic testing, long term hold and system update verification
  - Cyclic tests completed and consistent with previous round of testing
  - Long term hold readings and thinning consistent with previous round of testing
  - No significant damage detected with either Jentek sensor, strain gage, or AE sensors
  - Encountered drift and data loss during calibration and testing
- Jentek system sent out to repair drift due to cable, and software data loss
- Completed FY 16 annual report

KSC - NDE for Advancing COPV Quality Assurance and Assessing MMOD Impacts

COPV set up in pressurization cell instrumented with MWM sensors, AE sensor, and strain gages.

Sensors

Thickness measurements (mils) from 4/15/2016 – 7/8/2016 with 5 minute intervals.
KSC/MSG: Recently Completed Testing

• An larger COPV is being investigated as an additional data point to compare to the previous two rounds of testing

  • Perform cyclic testing to determine undamaged tank response
  
  • Impact COPV to cause fiber damage
  
  • Conduct long term hold on newly impacted COPV to determine damaged tank MSG response

• Correlate MSG data with AE and strain gage sensor
Benefits & Infusion
Anticipated Benefits

• The aerospace industry will continue favoring composite pressure vessels in their designs because they provide a 50 to 75 percent reduction in weight over metallic pressure vessels. Manufacturers continue developing lighter, higher performing composite pressure vessels that pose significant inspection challenges to quality assurance and nondestructive inspectors.

• In many cases, weight savings are limited by flaw detectability. As we move into the exploration of deep space and manned missions to Mars, where weight savings will take on greater importance, inspection systems that reduce or eliminate human error such as these will take on expanding and important roles to assure mission success.

• From the manufacturer perspective, all systems developed are turn-key, relatively easy to apply, and produce data that is simple to interpret. A graphical user interface provides an intuitive view of flaws with sensitivity enhanced well above visual detection limits.
Infusion Paths

- Commercial spaceflight partner expressed interest in the **Multi-Purpose COPV Scanner**. Also received an inquiry from another commercial entity.

- The **DIDS AE** system for MMOD impact detection and mapping has been installed on the **International Space Station**. Plans to expand system coverage with multiple DIDS are being discussed.

- Composite thickening has been noted by **MSG**, as have reductions in conductivity, at high stress levels. This suggests that fiber breakage has occurred. The sensors can be used on the bench to scan vessels for mechanical damage. In theory, fiber breakage may be characterized and identified at various ply depths for the entire COPV.

- Liner manufacturer expressed a desire to know to what extent, if any, the COPV manufacturing process has on developing weak points in the metallic liner. **Fiber Bragg grating (FBG)** sensing can be used to determine if weak points arise at any point in the COPV manufacturing process. Liners will be randomly selected for monitoring during COPV manufacturing. FBG sensors will also be installed on the outside of the COPVs to advance technologies for **in-situ** Structural Health Monitoring (SHM) of COPVs during operation.
Q & A

- Points of Contact:

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  KSC\Dave Lubas: 321.867.5310, david.l.lubas@nasa.gov
  LaRC\Eric Madaras: 757.864.4993, eric.i.madaras@nasa.gov
  WSTF\Regor Saulsberry, 575.524.5518, regor.l.saulsberry@nasa.gov
Backup Charts
## Technology Overview

<table>
<thead>
<tr>
<th>Technology Being Advanced</th>
<th>Engineering parameters measured by the technology</th>
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<tbody>
<tr>
<td><strong>NESC/NNWG COPV Scanner - WSTF</strong></td>
<td>Eddy current (EC) thickness measurement up to 0.120&quot;±0.001&quot; and EC crack detection demonstrated better than 0.015&quot;x0.030&quot;. Interior and exterior 3D laser profile ±0.003&quot; w/ 0.3&quot; range. Limited to liners shorter than 48&quot; and narrower than 22&quot;.</td>
</tr>
<tr>
<td>Providing manufacturers tools for identifying inconsistently produced liners and COPVs.</td>
<td></td>
</tr>
<tr>
<td><strong>DIDS AE System - LaRC</strong></td>
<td>Power-efficient, Flight-qualified system passively monitors and alerts to high-energy, narrowband acoustic emissions. This makes it ineffective at general structural monitoring, other than MMOD, tool strikes, or perhaps for leak detection.</td>
</tr>
<tr>
<td>Alerting COPV users to space debris impacts, tool strikes, and leaks in Flight systems.</td>
<td></td>
</tr>
<tr>
<td><strong>FBG Strain Measurement SHM - AFRC</strong></td>
<td>High linear density (better than 1 cm) optical uniaxial and biaxial strain arrays, demonstrated successful for 1600+ exterior measurements on 6.5L tanks. Newer continuous grating technology further enhances spatial resolution. Surface techniques have been validated with conventional sensors and are very promising for ground/flight applications. Ruggedized system developed and flown. A Flight-qualified system is 90% complete. Interior liner instrumentation during manufacturing is feasible and is being investigated.</td>
</tr>
<tr>
<td>Providing users with FEM-like strain maps of COPVs in real time for acceptance testing, requalification, and SHM.</td>
<td></td>
</tr>
<tr>
<td><strong>Magnetic Stress Gage Sensors - KSC</strong></td>
<td>Tailorable printed eddy current arrays provide thickness, conductivity, and stress data at multiple ply depths. Surface-mounted measurement of metallic liner thickness has been demonstrated. Wireless SHM applications will be investigated.</td>
</tr>
<tr>
<td>Providing multi-layer measurements of ply stress, confirming orientation, and determining ply thickness above and below sensors.</td>
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</table>
## NDE Application - Life Cycle Considerations

Color Key:  
- **Good Support of the Requirement**
- **Needs Work**
- **Not Effective/Unknown**

<table>
<thead>
<tr>
<th>Technology Being Advanced</th>
<th>Product and Process Design and Optimization</th>
<th>On-Line Process Control</th>
<th>After Manufacture Inspection</th>
<th>In-Service Remove and Inspection</th>
<th>In-Situ (SMART) Structural Health Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>NESC/NNWG COPV Scanner</td>
<td>YES</td>
<td>YES</td>
<td>YES (MEOP baseline)</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Surface FBG Strain Measurement SHM</td>
<td>NO</td>
<td>NO</td>
<td>YES (MEOP baseline)</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>DIDS AE System</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Magnetic Stress Gage Sensors</td>
<td>NO</td>
<td>NO</td>
<td>YES (MEOP baseline)</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
# Requirements Matrix

**Color Key:** Good Support of the Requirement, Needs Work, Not Effective/Unknown

<table>
<thead>
<tr>
<th>Technology Being Advanced</th>
<th>Liner Cracks$^{1,2,3}$</th>
<th>Liner Thinning$^1$</th>
<th>MMOD Impacts$^{12}$</th>
<th>Composite Damage$^{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIDS AE System SHM</strong></td>
<td>N/A, sensor frequency unlikely to detect metallic crack growth.</td>
<td>N/A, thickness cannot be measured.</td>
<td>SHM. Flight system is onboard ISS, demonstrated effective at identifying MMOD, but needs to be tested on COPVs (attenuation; POD study).</td>
<td>N/A. Power-efficient system passively monitors and alerts to high-energy, narrowband acoustic emissions. This makes it ineffective at global structural monitoring.</td>
</tr>
<tr>
<td><strong>FBG Strain Measurement SHM</strong></td>
<td>N/A, unless evidenced by local dissimilar strain field</td>
<td>N/A, although liner growth through autofrettage and use can be tracked.</td>
<td>Evident by loss of connection w/ sensors or irregular strain hot spots.</td>
<td>Demonstrated by COPV testing, strain hot spots (bulging) appeared in weakened areas. Composite crack identification demonstrated in one test. Signals and accept/reject anticipated to be design/materials dependent.</td>
</tr>
<tr>
<td><strong>Magnetic Stress Gage Sensors (Remove and Inspect)</strong></td>
<td>N/A - Agree with this for what we are doing now but the technology could go here.</td>
<td>Eddy current based system is sensitive to metallic liner thickness. A POD study needs to be performed and system refined for SHM.</td>
<td>N/A - Not the primary use for this technology. Multiple sensors placed in strategic areas could aid for this.</td>
<td>Composite thickening has been noted, as have reductions in conductivity, at high stress levels. This suggests that fiber breakage has occurred. The sensors can also be used on the bench to scan vessels for mechanical damage.</td>
</tr>
</tbody>
</table>
## Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
<th>Location</th>
<th>Center(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Team activities revised and lower priority/TRL items discontinued</td>
<td>2/15</td>
<td>-</td>
<td>All</td>
</tr>
<tr>
<td>COPV Scanner Demonstration at Laser Techniques Co</td>
<td>2/15</td>
<td>Redmond, WA</td>
<td>WSTF, NESC</td>
</tr>
<tr>
<td>Provide a COPV Scanner status report to the NESC Review Board and an overview presentation</td>
<td>3/15</td>
<td>-</td>
<td>WSTF</td>
</tr>
<tr>
<td>Refine single mode FBG data reduction algorithms; test real-time liner interior sensor installation on domes and hoops.</td>
<td>3/16</td>
<td>AFRC</td>
<td>AFRC</td>
</tr>
<tr>
<td>Add LaRC filtering algorithms to the ET system and completion of final preparation items for POD study</td>
<td>3/16</td>
<td>WSTF</td>
<td>WSTF, NESC</td>
</tr>
<tr>
<td>Adapt MWM eddy current arrays to curved vessel geometry and complete FY14 data reduction</td>
<td>4/16</td>
<td>KSC</td>
<td>KSC</td>
</tr>
<tr>
<td>TRL4 determine feasibility of MWM fiber breakage, overwrap thickness, or volume growth PASS/FAIL criteria, proof-of-concept test at WSTF</td>
<td>5/16</td>
<td>KSC</td>
<td>KSC</td>
</tr>
<tr>
<td>TRL5 DIDS AE field test @ WSTF, MMOD impact and leak test PASS-FAIL, repeatability test</td>
<td>6/16</td>
<td>WSTF</td>
<td>LaRC</td>
</tr>
<tr>
<td>Eddy Current POD Study complete (9/2016) and report to the NESC Board</td>
<td>10/16</td>
<td>TBD</td>
<td>WSTF</td>
</tr>
<tr>
<td>Complete TRL4 standalone off-the-shelf MWM technology for COPV Pass-Fail</td>
<td>9/16</td>
<td>KSC</td>
<td>KSC</td>
</tr>
<tr>
<td>Testing and validation of large ID eddy current thickness probe and development of an ID eddy current through-wall (ECTW) flaw/crack detection probe.</td>
<td>10/16</td>
<td>WSTF</td>
<td>WSTF, LaRC</td>
</tr>
<tr>
<td>Develop DIDS Data Translator**, validate with AE or other NDE or DA as necessary</td>
<td>1/17</td>
<td>LaRC, WSTF</td>
<td></td>
</tr>
<tr>
<td>FY16 Status Reports (two pagers) presented by all centers (teleconference). COPV SMEs will be pulsed and reallocations/cuts made if needed.</td>
<td>1/17-9/17</td>
<td>All</td>
<td></td>
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<tr>
<td>Overall SHM integration efforts – new software development as needed</td>
<td>1/17-9/17</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>TRL5 FBG field test w/ PASS-FAIL threshold &amp; gradient alarms; repeatability test</td>
<td>3/17</td>
<td>WSTF</td>
<td>AFRC</td>
</tr>
<tr>
<td>Begin integration of FBG, DIDS AE</td>
<td>5/17</td>
<td>AFRC, LaRC, MSFC</td>
<td></td>
</tr>
<tr>
<td>FY17 Status Reports (two pagers) presented by all centers (teleconference). COPV SMEs will be pulsed and reallocations/cuts made if needed.</td>
<td>1/18</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>Integrate selected SHM systems and inter-relational COPV diagnostics. Start POD and calibration studies.</td>
<td>6/18</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>Optional flight test (additional funding required).</td>
<td>7-9/18</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>Integrated SHM systems demonstration in a relevant space environment preparations and testing</td>
<td>8/18</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>Collect and integrate Final Report</td>
<td>9/18</td>
<td>All</td>
<td></td>
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Background

This NASA Office of the Chief Engineer (OCE) and Office of the Chief Technologist (OCT) have established discipline steering committees (SCs) and these SCs had been busy developing roadmaps. These roadmaps are indicated as central to the planning and development of NASA space technologies critical to space exploration.

- Further, to ensure these roadmaps are properly focused and targeted, the National Research Council (NRC) peer reviewed and commented on them.

This project directly targets the Reliability/Life Assessment/Health Monitoring in OCT Roadmap TA12, Materials, Structures, Mechanical Systems and Manufacturing 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 systems health management (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 will develop, maintain, and continue to update an SHM Roadmap in coordination with the Materials/NDE SC, and Discipline SC Coordinators.
“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 Structural Health Monitoring (SHM) methods have been developed:

- NNWG Stress Rupture NDE Development project
- In-situ Carbon Fiber Micromechanics project
- Multi-axial FBG Systems for Real-time NDE Inspection project
- 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 UT methods)
- Eddy Current Health Monitoring of Composite Overwrapped Pressure Vessels has (KSC Project) just started

Profilometer and Eddy Current inspection have produced methods that can help reduce COPV variability and make better COPVs as a foundation for adding necessary sensors and creating truly “Smart COPVs”
• Future NASA missions may not be successful without SHM (ref. OCT Roadmaps)

• Current needs and applications include carbon-epoxy (C/Ep) COPVs used on ISS, new ISS Nitrogen-Oxygen Recharge System (NORS), the Orion Crew and Service Modules, and as planned for application to nearly all future 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