

**NASA Prototype All Composite Tank Cryogenic pressure tests to Failure with
Structural Health Monitoring**

September 2015

Rudolph J. Werlink MS PE

NASA Fluids and Technology Branch NE-M5c

Kennedy Space Center, FL 32899

Francisco Pena

Aerostructures Branch (RS)

NASA Armstrong Flight Research Center

ABSTRACT

This Paper will describe the results of pressurization to failure of 100 gallon composite tanks using liquid nitrogen. Advanced methods of health monitoring will be compared as will the experimental data to a finite element model. The testing is wholly under NASA including unique PZT (Lead Zirconate Titanate) based active vibration technology. Other technologies include fiber optics strain based systems including NASA AFRC technology, Acoustic Emission, Acellent smart sensor, this work is expected to lead to a practical in-Sutu system for composite tanks.

BACKGROUND

NASA future goals include investigating the solar system by traveling beyond low Earth Orbit with manned missions. The large amount of energy required and available resources necessitate new technologies to reduce weight.

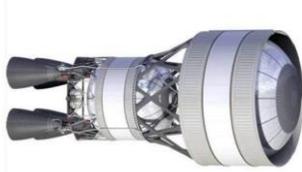


Figure 1 Proposed SLS upper stage with 5.5 meter LOX and 8.4 meter diameter LH2 tanks

The technology will require new materials of high strength and low weight likely made of carbon composites. Failure modes must be understood to provide reliability. Health monitoring Technology is being developed for both structural members and propellant tanks to understand the mechanics and provide an in-Sutu warning system to prevent unexpected catastrophic failure. The current plan is to develop 100% composite liquid oxygen and liquid hydrogen tanks for the upper stage of NASA's Space Launch System (SLS) Rocket (figure 1). A 500 gallon all Composite Tank test to failure, filled with LN2 and with similar health monitoring technology was reported in a prior conference.¹ This paper will report on the initial results on 100 gallon Composite tanks filled with liquid nitrogen (LN2) and pressurized to failure with health monitoring technologies installed. This report will present the NASA Kennedy Space Center (KSC) PZT vibration and NASA Armstrong Flight Research Center (AFRC) Fiber Optic Sensing System (FOSS) initial analysis. The test tanks were filled with liquid nitrogen (LN2) prior to applying increasing pressure steps using gaseous nitrogen in the top ullage until burst. Health Monitoring Technologies gathered data during the test. The testing took place on February 19th 2015 for the Scorpius tank, May 13th for COPV1 and May 15th for COPV2. The test site was NASA Marshall Space Flight Center (MSFC).

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Test Description: Test Tank setup mechanical components are shown below (Figure 2)

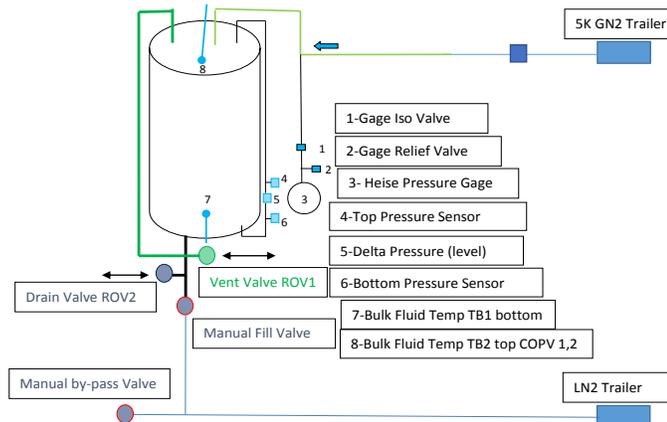


Figure 2 Test Tank Setup Main Components



Figure 3 Test Site Layout

Background on the three test tanks:

- Scorpius 100 gals all composite fabricated in 2008 by Scorpius Space Launch Company, Hawthorne, CA and delivered to MSFC, unused until now.
- 100 gal COPV #1,#2 composite overwrap manufactured at MSFC Oct-Nov 2014
- Tank Dimensions 59” End-to-end length and 24” Diameter, 0.170 “thick
—~100 gal Volume —composite cylindrical tanks —attached at top and bottom flanges to frame with 2 inch and 1 inch Stainless Steel tubing
- Testing prior to delivery: Scorpius: 14 psig Helium leak down and LN2 fill
COPV #1,#2: Hydrostat to 1872 psig (autofertague), this is to yield the Aluminum linear into the composite wrap, minimizing linear separation during cryogenic temperatures

TABLE 1 Test Tank Fabrication details and expected burst pressure

description	materials	Layup/thickness	Expected burst pressure (Model)
Scorpius all composite	The hoop and axial fiber filament fibers were carbon IM7 carbon The resin was CTD 7.1,	Linear 0.0375, 2 helical Wrap Thickness 0.0990” (based on Model 2 predictions) 6 Hoop Wraps Thickness 0.0385” (balances total overwrap thickness)	1600 psig
COPV 1 NASA MSFC	AL T6061 linear 0.155 with composite: T-800 S Dow 383 Epoxy w/ Huntsman T403	4 x hoops 0.011 in 2 x 9 degree helical, 0.011 in 2 x hoops 0.011 in over-wrap	3200 psig
COPV 2 NASA MSFC (repaired center section)	AL T6061 linear 0.155 with composite: T-800 S Dow 383 Epoxy w/ Huntsman T403	Same as COPV 1 except outer hoop wrap was repaired by adding 2 hoop wraps to the center 4”, and one hoop each for an over wrap layer 6” and 10” wide.	3300 psig

General Instrumentation

The customized software used for control and data collections is written using Labview which will allow continuous recording at 2 Hz and at high data rates (to 50 KHz) to a 10 second buffer. Since the failure point is unpredictable, high speed data will be saved to disk by the computer operator selection just after the event. This method keeps the

database file sizes reasonable. The control and data can be considered in two Categories, standard sensors /data and advanced Health Monitoring Technology.

Standard (Facility) Measurement system (Labview program):

- 24 strain gages 12 hoop and 12 axial
- 14 Thermocouples on outside tank walls, 2 inside tank probes top/bottom
- 8 Free field over-pressure Piezo-resistive sensors (Scorpius) replaced with 8 free field PCB piezoelectric sensors for COPV 1 and 2 burst tests.
- three high definition cameras (IP real time), Three High Speed cameras-triggered for burst events
- Fill and drain Electro actuated cryogenic valves control and feedback
- Ullage GN2 pressurization accurate feedback control (stable pressure steps)
- Top ullage pressure, bottom tank pressure, delta Pressure for fluid height

Advanced Health Monitoring technologies installed on 100 gallon test tanks:

TABLE 2 Summary of Health Monitoring Technology

Health Monitoring Systems	Description	Details
Acoustic Emission	Passive Ultrasonic Mistras OEM	11 sensors passive, continuous listens for ultrasonic cracks can locate
FBG MSFC Optical Strain	high fidelity strain Micron OEM	28 Strain sensors passive, continuous 1-2 HZ
FBG NASA Armstrong Research Center Optical Strain	high fidelity, High sensor count strain/temperature customized Custom NASA Technology	4000 Strain (hoop, axial) sensors 2000 temperature sensors
Smart sensor PZT system	active vibration reflected pulses Acellent OEM	64 sender/receivers , active serially scans (1 min scan duration) at intervals based on time of reflections, amplitude for severity and location in grid.
NASA KSC PZT health monitoring System	active vibration modal based frequency analysis NASA KSC unique RJW	6, 1 active white noise, detects frequency mode stiffness changes continuously overall Health, used at intervals , 5-20K HZ

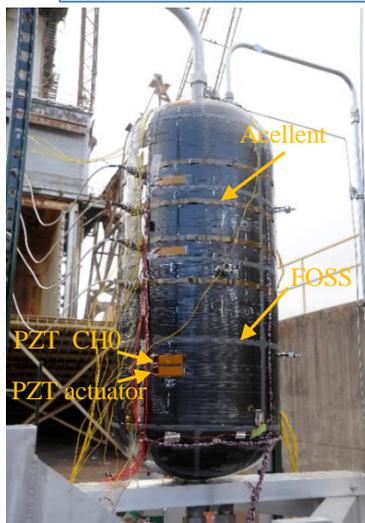


Figure 4 Scorpius Composite Tank 2/19/15

Figure 5 COPV 1 Tank 5/13/15

Figure 6 COPV 2 Tank 5/15/15

Figures 4-6 above show the test tanks and installed sensor layout on the Primary side for the PZT actuator and sensors. The AFRC FOSS was only installed on the Scorpius Tank and COPV 1 due to the schedule delay from the Hydrostat damaged outer mid hoop fibers which were repaired with a hoop overwrap (Table 1). The cause of the fiber breakage under only 1850 psig was due to over sanding on the surface prep for sensors

installation. Shown below (Figure 7) is the details of the pressure profiles and health monitoring data gathering.

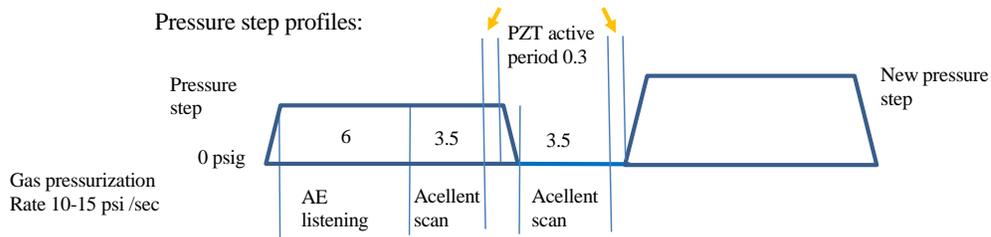


Figure 7 Pressure Step Profiles

Shown below are the before and after pictures along with High Speed Frames of the failure initiation area for the three test tanks. The overpressure data was measured at the locations shown in the Test Site setup (Figure 3) A secondary Test objective is to record the overpressure wave at failure for comparison to Safety TNT Equivalent Equations and fragmentation distances from the bursts.ⁱⁱ



Figure 8 Scorpius Tank in test site just prior to LN2 fill



Figure 9 Beginning of burst, 1230 psig top of Scorpius tank

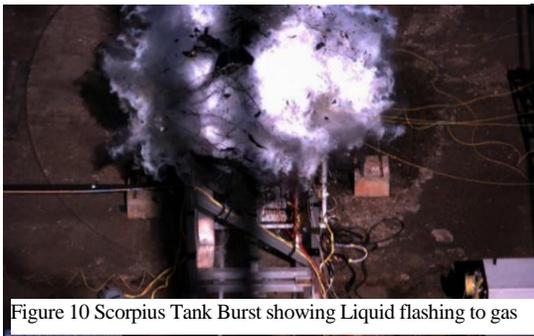


Figure 10 Scorpius Tank Burst showing Liquid flashing to gas



Figure 11 test stand and Scorpius tank half after the burst



Figure 12 COPV 1 in test stand



Figure 11 COPV 1 at burst mid- hoop 3150 psig



Figure 14 test setup after COPV1 burst May 13 2015



Figure 15 COPV 1 main fragment in trench under tower after burst



Figure 16 COPV 2 (center section was repaired) in test stand



Figure 17 COPV 2 at burst lower- hoop 3370 psig



Figure 18 test setup after COPV2 burst May 15 2015



Figure 19 after burst Main fragment -upper part of COPV 2 landed approx. 300 ft. from setup

Strain Gage results:

The strain gage system worked well with the cryogenic temperatures and very high strains the adhesive system sometimes failed, as expected, However much data has been obtained, and indications are that the max strain at failure was over 14,000 micro strain,

the failure locations show by the high speed video often had disabled gages presumably due to the very high strains. See Table 3 below for a summary. The low and high strains at the same vertical location can be explained by a bending force due to the contraction of the cold upper vent piping vs. the warm pressurization gas line. These constraints cause axial bending forces on the tank. The strain gage data was periodically zeroed before important pressure steps, so absolute strains were not plotted on the screen. This was to remove temperature effects from the strain data, but it also removed some real strain such as the discussed bending. The data set has all the information.

TABLE 3 Burst Test results and Strain gage summary

Test Tank 100 gallon volume	Burst date	Pressure steps prior to each step pressure was 0 psig for data gathering	Description of failure	Strain gage's active at failure Hoop (H), Axial (A)	Max micro strain at failure Hoop (H) Axial (A)	Min microstrain at failure Hoop (H) Axial (A)
Scorpius	2/19/15	250,500,750,1000,1100, 1230 burst	Dome, top half of tank	H 8/12 A 2/12	H 11,811 A 10,112	H 1,000 A 8,640
COPV 1	5/13/15	1000,1500,1800,2000,2200,2400, 2600,2800,3000, 3150 burst	Center hoop, all	H 9/12 A 1/12	H 13,699 A 11,578	H 6,137 A 11,578
COPV 2	5/15/15	1500,1800,2000,2200,2400,2600, 2800,3000, 3200, 3370 burst	Bottom hoop, all	H 8/12 A 5/12	H 12,792 A 6,779	H 7,364 A 4,612

Health Monitoring Systems Results:ⁱⁱⁱ

NASA Armstrong Flight Research Center (AFRC) designed (FOSS): The concept involves the distribution of fiber optic sensors adhered to the surface of composite structures in a network analogous to the nervous system in the human body. The FOSS, developed at NASA AFRC is used to interrogate the continuous Fiber Bragg Grating (FBG) optical fiber and to provide strain and/or temperature data. It is capable of simultaneously and continuously interrogating up to eight 40-foot optical fibers at 0.25-inch spatial resolution for a total of 16,000 sensors per system. The systems can operate in stand-alone mode, which is used for flight applications, or remote control

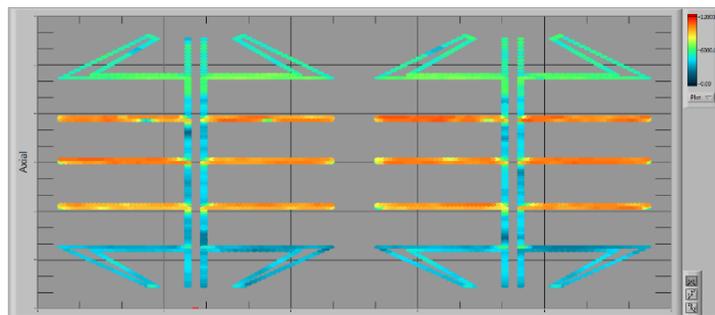


Figure 20 COPV 1 FOSS-2D micro strain surface plot during 2,600 psig of internal pressure (the tank is full of LN2 with gaseous nitrogen

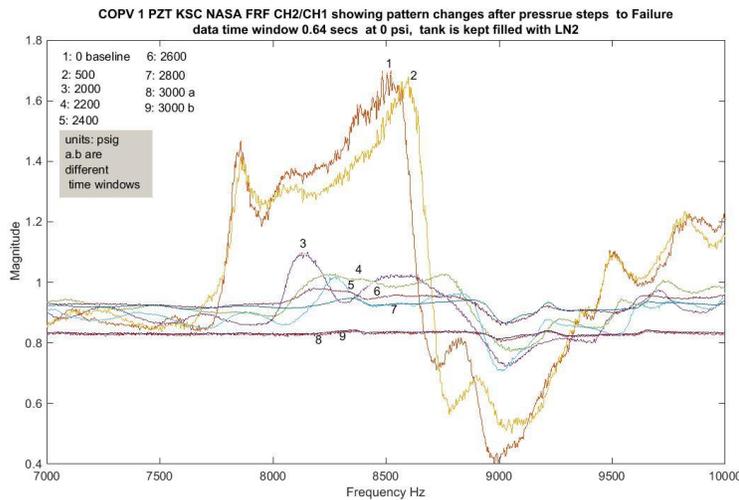
mode, where a laptop is connected to provide monitoring and control. Each of the 16,000 sensors can be sampled up to 100 samples per second simultaneously, and a centralized software interface combines all functions into a suite of application to fully exercise

the FOSS.. The high spatial resolution enables engineers to develop dense strain contours which may enable the development of real time Factor of Safety assessments, and measurements could potentially be used as a pre-burst strain indicator to avoid catastrophic failure. The figure shows the continuous grating fiber optic sensors that were installed in a serpentine pattern on the pressure vessels to characterize strain gradients along the axial length of the COPV as well as along the hoop orientation of the COPV. The outer most layer of composite wrap was aligned in the hoop direction. Sensors orientated in the hoop direction were able to directly monitor the tensile

strength of the composite tow due to their parallel alignment. Though the hoop strains were generally of larger magnitude than the longitudinal direction for all-metal vessels (due to vessel geometry), equal sensing area was dedicated to longitudinal direction. Sensors running in the longitudinal direction could potentially evaluate whether composite wrap in the hoop direction separates. The widening of the tow spacing can be used as a precursor to rupture since the results of widening tow may cause there to be a region of unsupported metallic liner.

NASA KSC PZT active vibration Health Monitoring Results:

Frequency Response Function (FRF) from the input and response accelerometer



COPV1 TTF May 13 2015	Standard Deviation for FRF's over 1-25600 HZ					
	Frequency response functions (FRF)					
	ch0ch1	ch0ch2	ch0ch3	ch1ch2	ch1ch3	ch2ch3
After pressrue steps (psig)						
comb1sbas	0.394298	0.42845	0.687158	0.250916	0.358735	0.389905
comb1saf500	0.284316	0.33105	0.472983	0.241558	0.316847	0.356271
comb1saf2000	0.243102	0.224546	0.312303	0.095529	0.113137	0.131837
comb1saf2200	0.121989	0.119856	0.162475	0.073394	0.08188	0.091484
comb1saf2400	0.090212	0.075685	0.091766	0.061226	0.08389	0.097179
comb1saf2600	0.029519	0.03493	0.042775	0.033095	0.056563	0.075431
comb1saf2800	0.012414	0.017066	0.018147	0.016326	0.030223	0.03417
comb1saf3000	0.045644	0.071535	0.039625	0.0272	0.028907	0.068029

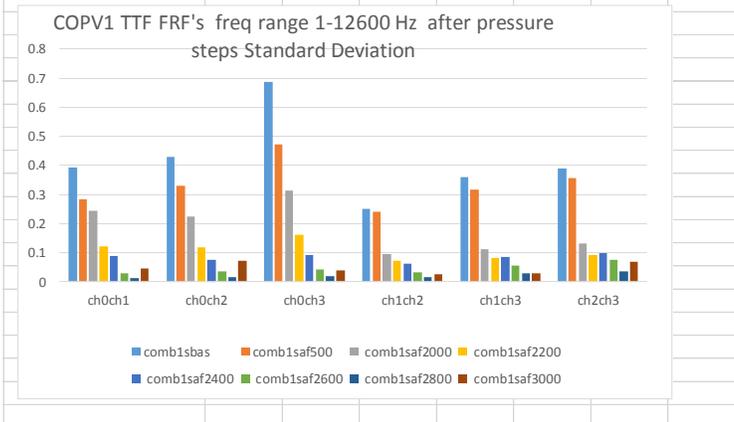
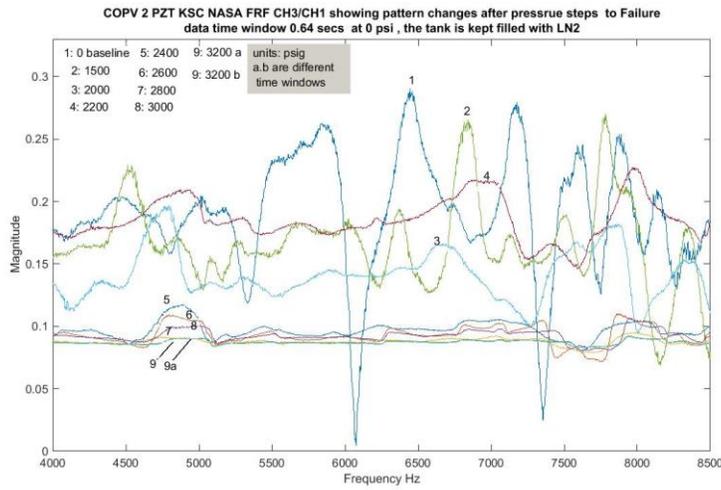


Figure 21 FRF plots showing the effects of increasing Pressure steps on the modal signatures and Standard deviations plot directly above for COPV 1.



COPV2 TTF May 15 2015	Standard Deviation for FRF's over 1-25600 HZ					
	Frequency response functions (FRF)					
	ch0ch1	ch0ch2	ch0ch3	ch1ch2	ch1ch3	ch2ch3
After pressrue steps (psig)						
comb2sbas	5.677951	1.913549	1.221844	0.030099	0.068592	0.228772
comb2saf1500	1.533109	0.486287	0.379201	0.044064	0.056631	0.199532
comb2saf2000	1.532659	0.589517	0.237518	0.19084	0.02368	0.081262
comb2saf2200	0.835633	0.530409	0.176204	0.01325	0.020397	0.029509
comb2saf2400	1.222877	0.239062	0.253959	0.01072	0.052267	0.051806
comb2saf2600	0.637375	0.121404	0.08356	0.012428	0.011085	0.033942
comb2saf2800	0.423887	0.066238	0.035373	0.036389	0.018472	0.028852
comb2saf3000	0.249069	0.053262	0.082082	0.008373	0.015479	0.043305
comb2saf3200	0.247044	0.065158	0.19568	0.010679	0.025334	0.041459

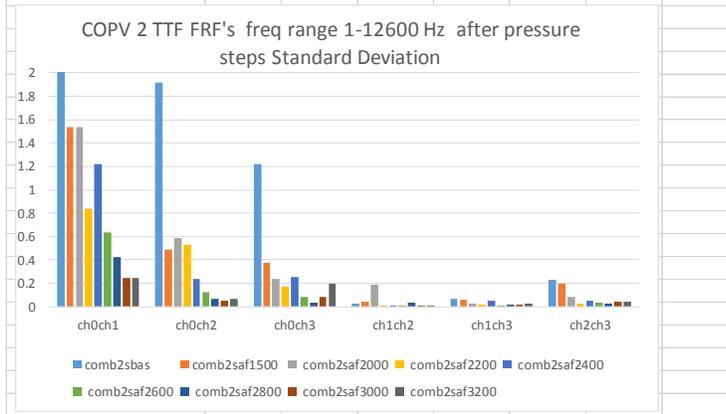


Figure 22 FRF plots showing the effects of increasing Pressure steps on the modal signatures and Standard deviations plot directly above for COPV 2.

Discussion: the system uses a PZT actuator to supply a consistent random input while recording PZT sensor responses on the tanks. Because pressure affects stiffness, the data is compared at near 0 psig following a new pressure step, (Figures 21 and 22). The Graphs show the relative frequencies transferred between two sensors with differences due to the tanks stiffness changes which affect the frequencies and magnitudes of the responses. The basic equation is:

$$\text{Frequency} = \sqrt{\frac{K}{M}}$$

Where K is the material stiffness which is affected by the type, geometry, temperature of the material and external stress such as pressure, M is the modal mass of the system. The data shows these effects as expected. The all composite Scorpius tank

was tested on an extremely cold day (<20 Deg. F) and the PZT front end data system containing a battery and disk drive temporary froze, therefore there was no vibration data during burst pressurizations for the Scorpius tank. The COPV 1 and 2 data however clearly show the effects of the tank damage most noticeably with decreasing modal peak amplitudes. Just prior to failure there is usually an increase in peaks at lower frequencies. The tables show that standard deviation clearly predicts the failure in these tests. With reference to the before condition (baseline) any changes which are significant can be detected and a software program developed to automatically flag the damage. Sensor Installation methods are still being developed for this extreme application (temperature under -310 Deg. F and very high strain levels well over 1.5%) These conditions often exceed the capabilities of the adhesives used to attach the sensors.^{iv} This an area of development to provide a robust technique, also quicker installation methods will need to be developed for example, applying sensors as the last step in manufacturing an integrated health monitored tank. Scaling up from medium size tanks (100-750 gallons) to very large tanks such as to be developed for the SLS is a problem for health monitoring systems. The current Acellent system sensor spacing was 5-6 inches with a maximum of 360 sensors, thus limiting coverage for large tanks. The FOSS from NASA AFRC has promise in covering large tank surface areas with several thousand sensors. For a practical In-Sutu system, the FOS methods require lower cost and temperature sensitivity of the electronics. AE data sets are large because the sensors must be ‘listening’ at all times to detect events and require expertise in interruption. Software algorithms need to be developed for faster analysis without intervention. The KSC PZT system shows the ability to measure changes in the tank stiffness as compared to a baseline signature. This system is a practical and relatively inexpensive system that can be developed for detection of serious structural changes, while not determining locations and type of flaw. The PZT needs refinements such as amplifier optimization, and will benefit from FE modeling^v to predict theoretical frequencies and automate mode shapes to aid in developing go/no go software.

CONCLUSION

One composite and two COPV prototype tanks were evaluated by testing to failure filled with LN2 and using experimental Health Monitoring Technology. The test data from the COPV tank bursts demonstrated the viability of the NASA KSC modal method for these COPV tanks when pressurized to failure. Health monitoring technologies must be evaluated with known defects including handling damage in the future testing programs before implementation. The project results are advancing knowledge in predicting composite tank failures under realistic conditions these tests advance the Health monitoring technology to a goal of providing in-Sutu, embedded, noninvasive Health monitoring technology. These results are highly important in progressing with the NASA goals of extending manned and unmanned spaceflight beyond Low Earth Orbit with lower weight, safer technology. This project is highly collaborated with NASA centers and is highly efficient utilizing a large percentage of NASA Civil Servant Scientists, Engineers and Technicians.

ACKNOWLEDGEMENTS

Those listed below have made it all possible: Jimmy Sisco MSFC Engineering Test Site Lead and his great team, Gerald Neal MSFC Safety Engineering, Dr. Curtis E. Banks MSFC, Claude Chris Conn MSFC, James Walker, MSFC, Tom Delay MSFC,

William Hastings, MSFC, Rush Elkins, and MSFC. GRC NASA Dr. John Thesken and Eric Baker, AFRC NASA Team including Anthony Piazza, Dave Parker, Frank Pena. The KSC Test Team including Kevin Jumper lead Engineer, Jared Sass NASA KSC, Mike Guthrie, Jeff Wall, Mark Velasco Technicians, WA Crawford Lead electrical technician, Jeff (George) Garrison video, Geof Rowe Lead electrical engineer and software programing, Thanks very much to Jason Crusan Director NASA Headquarters AES and Richard McGinnis, Program Manager AES, Robert Johnson NASA KSC Project Manager APL,

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ⁱⁱ WSTF-WP-12-0025 *Cryogenic Pressure Testing of a 515 Gallon Composite Vessel (FAST)* Laboratories Office NASA White Sands Test Facility
Chris Keddy, NTEC, Nathanael Greene, NASA, Harold Beeson, NASA Office Chief White Paper November 30, 2012

ⁱⁱⁱ The Micron fiber Optic Strain (FOS), Mistraes Acoustic Emission (AE) and Acellent Smart Sensor analysis results along with complete AFRC FOSS results are to be reported in a later document.

^{iv} Adhesives used for the sensors attachments: **Vishay AE10** Two-component epoxy, Elongation Capabilities: 1% at -320°F [-195°C]; 6% to 10% at +75°F [+24°C];
HBM X60 2-component fast curing adhesive, Elongation Capabilities: to 10% at +75°F [+24°C];

^v NASA GRC will report on the Modeling results in a later Document