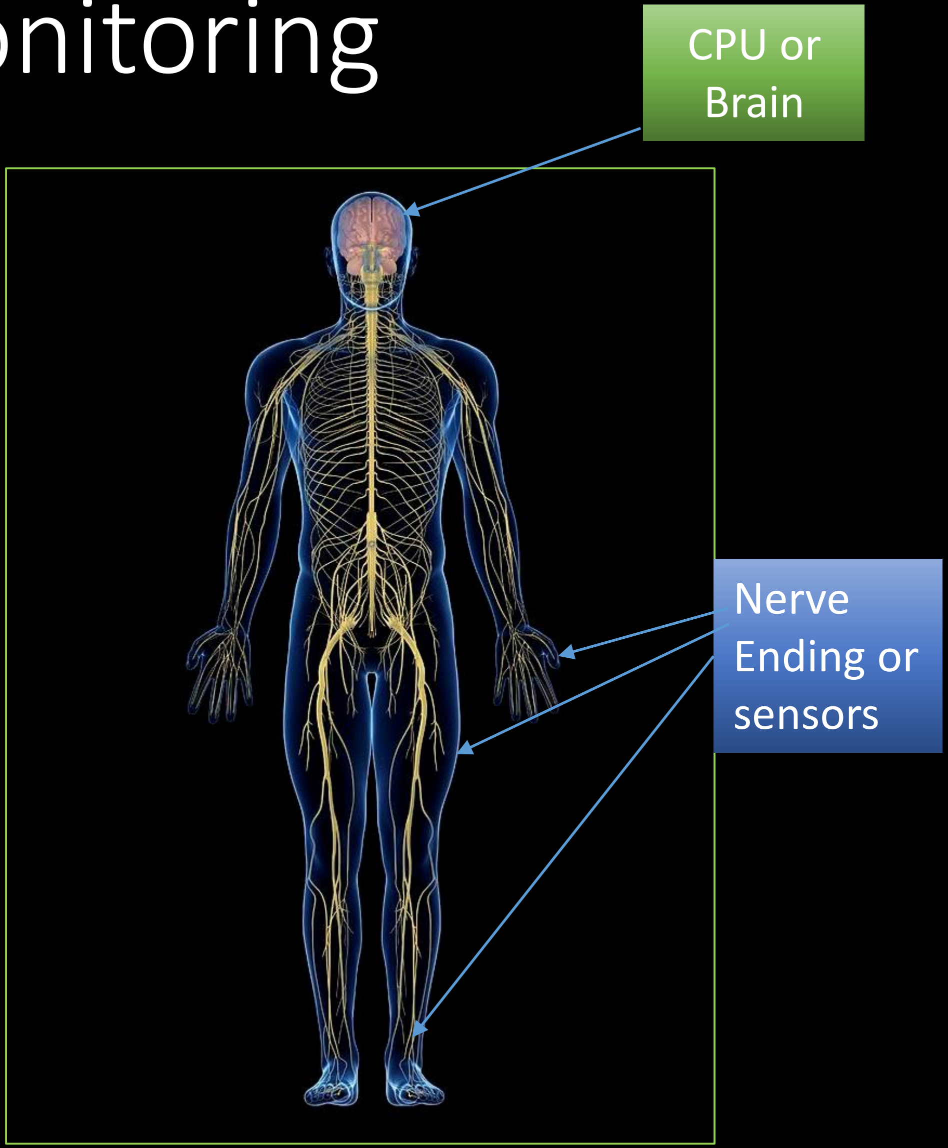
Stress to Failure Testing of Pressure Vessels with SHM Sensors at Liquid Nitrogen (LN_2) Temperature

Structural Health Monitoring

- As the nerves in a human body detects touches and pain, a series of SHM sensors can detect structural defects or changes.
- The nerve endings carry information to the brain for processing via the central nervous system. The brain tells the body to react accordingly.
- The sensing element of a SHM sensor transmit electrical or optical signals to be processed by a central processing unit that are compared to a baseline reading.



Structural Health Monitoring

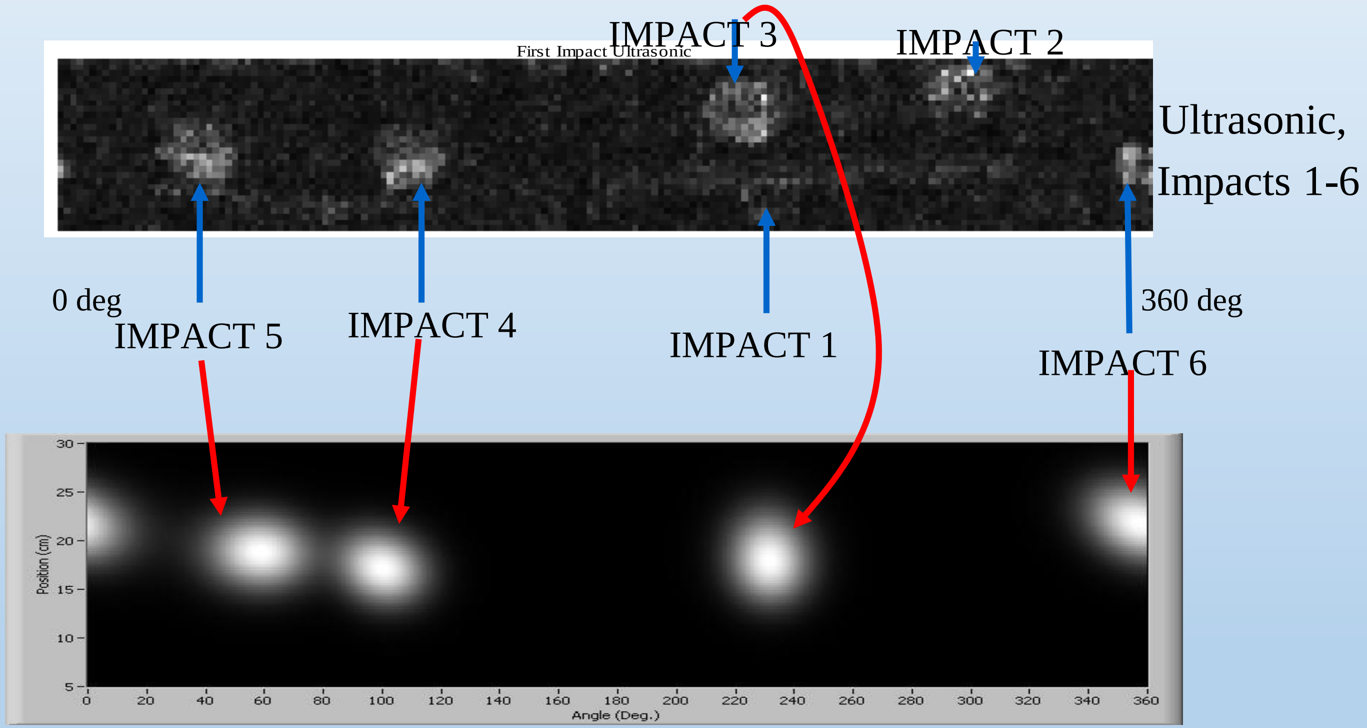
What is SHM?

In some cases, SHM my be defined as the inverse of Nondestructive Evaluation (NDE). NDE is the science of investigating the integrity of a structure that has undergone stress or an impact, such as an airplane wing or a pressure vessel.

The photograph to the right shows a pressure vessel with SHM sensors that was impacted to cause internal damage.

The top image is an (NDE) ultrasonic (UT) image while the bottom image was created from the embedded optical sensors.

The SHM is real-time; the UT requires that the structure be taken out of service for scanning which is time consuming.



Taken from Blue Roads Research, Eric Udd.

Structural Health Monitoring

Why add SHM?

- ❑SHM allows the optimal use of structures
- ❑SHM minimizes downtime
- ❑SHM minimizes catastrophic failures
- ❑SHM allows the improvement of structures and mathematical models
- ❑SHM reduces labor needed for NDE techniques
- ❑SHM improves safety and reliability

NASA and SHM

- NASA has identified SHM as an enabling technology for future space systems.
- SHM is being demonstrated for deep space habitat at Marshall Space Flight Center.
- SHM was identified as a technology to continuously monitoring composite cryogenic fuel tanks under the Advance Exploration System program for Automated Propellant Loading.
- SHM sensors will be flown on the NASA’ Low-Earth Orbit Flight of an Inflatable Decelerator (LOFTID).

NASA's Automated Propellant Loading

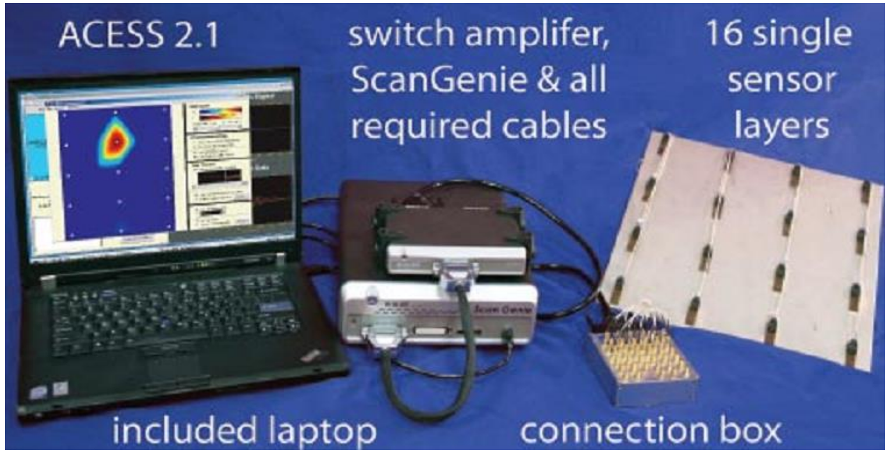
Objectives of Testing: The purpose the Structural Health Monitoring (SHM) sensors for Automated Propellant Loading is to develop a sensory system that can assess the fuel tank that is all composite. The system must be able to monitor the tank from post inspection to the point of operation. These systems will provide engineers with a quick assessment of the structural integrity without having to perform another lengthy NDE inspection. ***Sensors system must be able to withstand harsh cryogenic environment during fill cycles.***

Some test objectives to look for

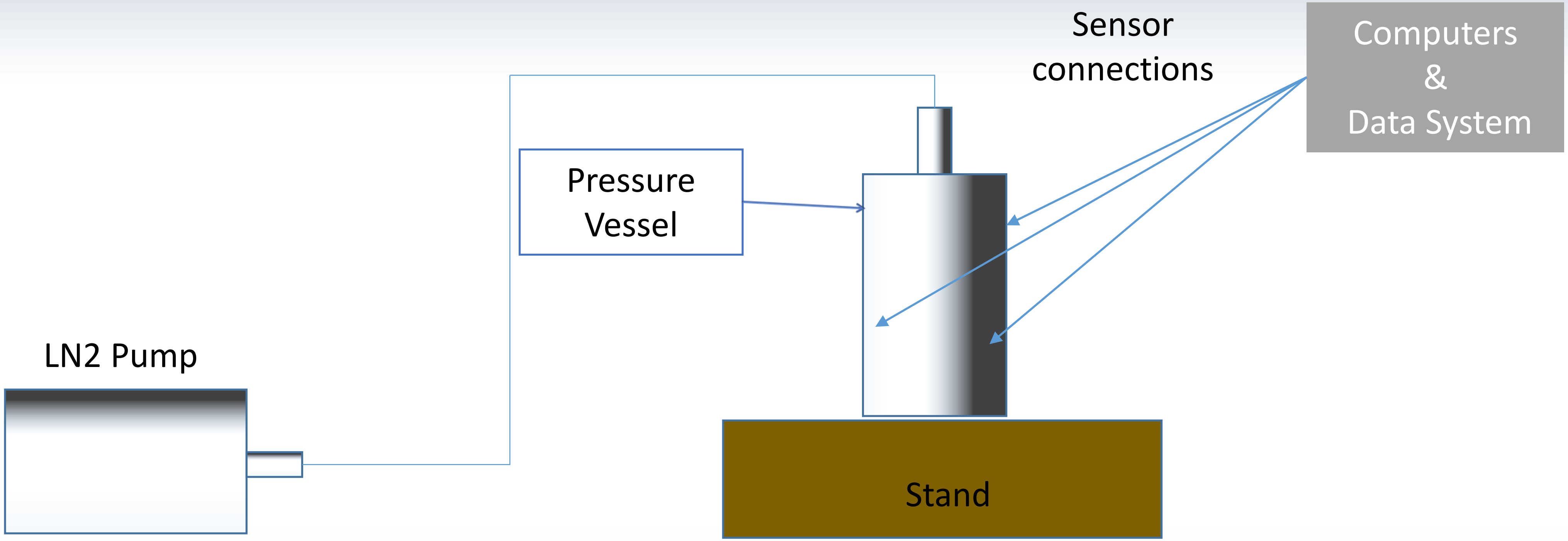
- Attachability: would the sensors remain attached at LN_2 temperature?
- Survivability: would the sensors survive at LN_2 Temperatures?
- Data integrity: is the data reliable?
- Damage assessment: can we locate, quantify, or detect the onset of damage?

MSFC SHM Assets

1. Fiber optic strain system
2. Acoustic emission system
3. Acellent SMART layer system



Experimental testing and setup



Stress rupture testing methodology

Amenable to Acoustic Emission (AE) data collection: Ramp-to Proof

1. Eliminates AE from formation of the characteristic damage state during each reloading
2. Enables evaluation of the Felicity ratio for each successive loading
3. Enables evaluation of the load-hold AE at successively higher stresses
4. Provides test manager with AE-based feedback on the state of the composite such that decisions to continue or stop loading can be made without generation of significant additional damage or catastrophic failure occurring.

Ramp-to-Proof Loading

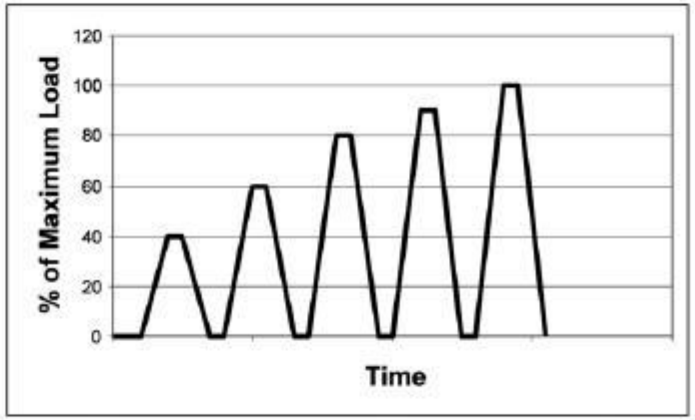


FIG. 3 Sequence of loading, hold and complete unloading. All ramps at equal rates and holds of equal duration.

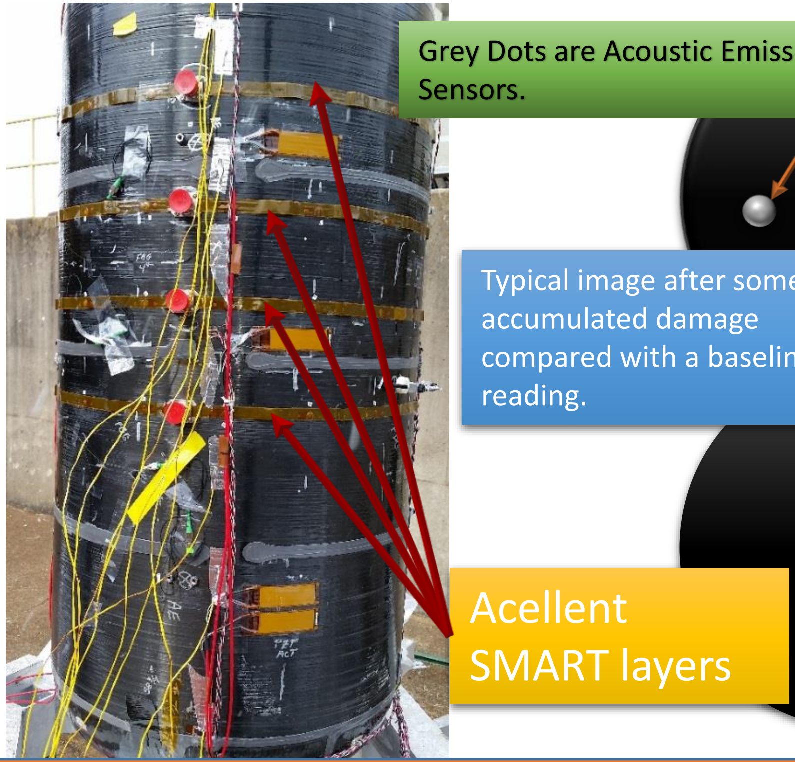
Results

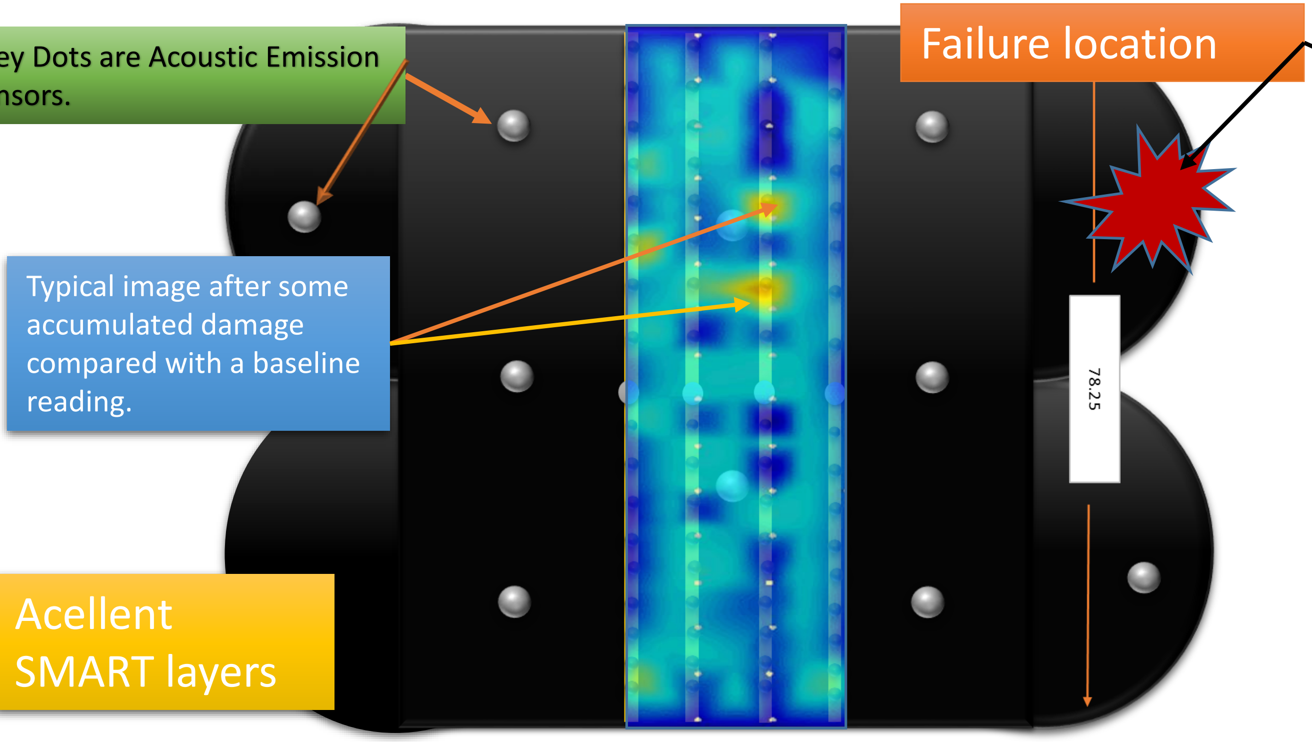
- ❑Fully carbon composite tank
- ❑Composite Overwrapped Pressure Vessel (COPV) tank 1
- ❑Composite Overwrapped Pressure Vessel (COPV) tank 2

Stress rupture of all-composite tank to determine SHM performance

Scorpius Tank: Direct Path Image using Acellent System

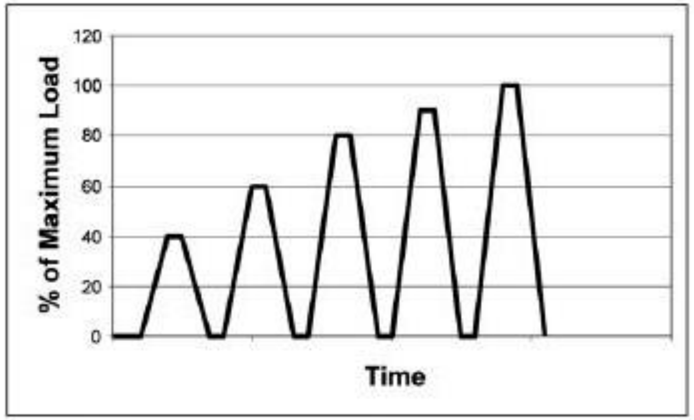
Frequency Range	step	Input voltage	Signal type
100kHz – 300kHz	50kHz	50	Burst Tone 5 Lamb wave
Damage accumulation is <u>*compared with a baseline reading*</u>			



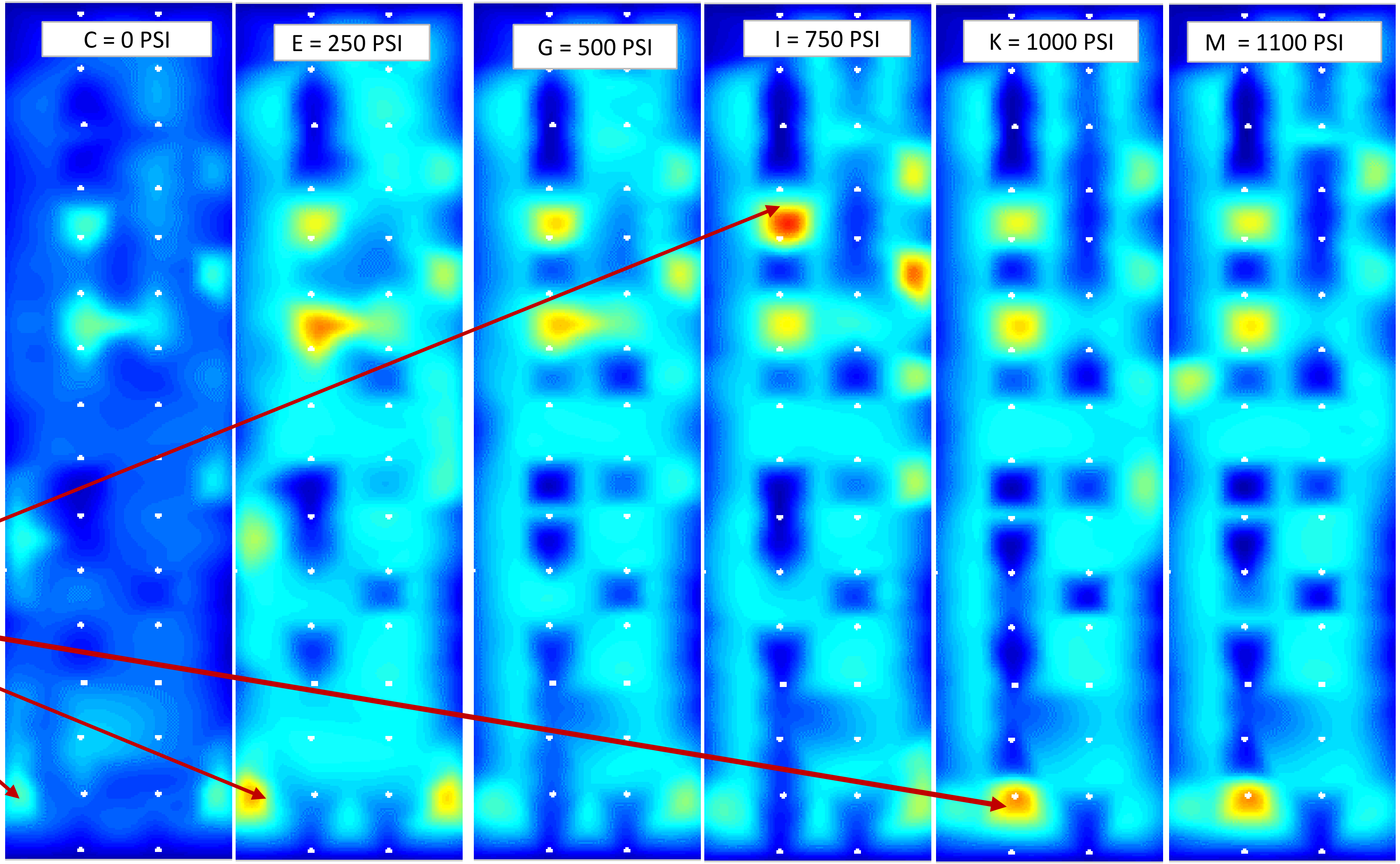


Scorpius Direct Path Image-Threshold 2.7677

Cycle pressure profile.



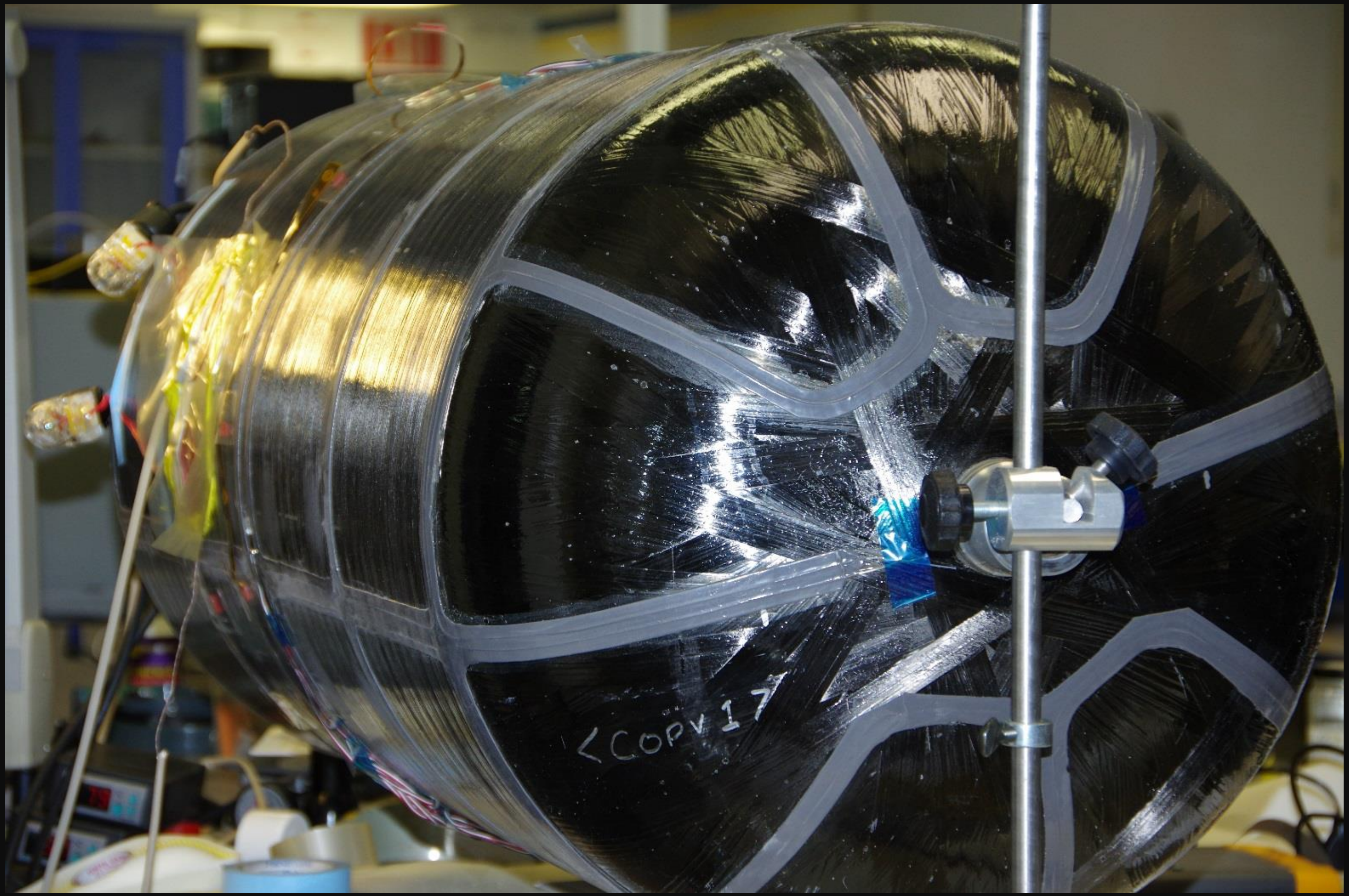
of loading, hold and complete unloading. All ramps at equal rates and holds of



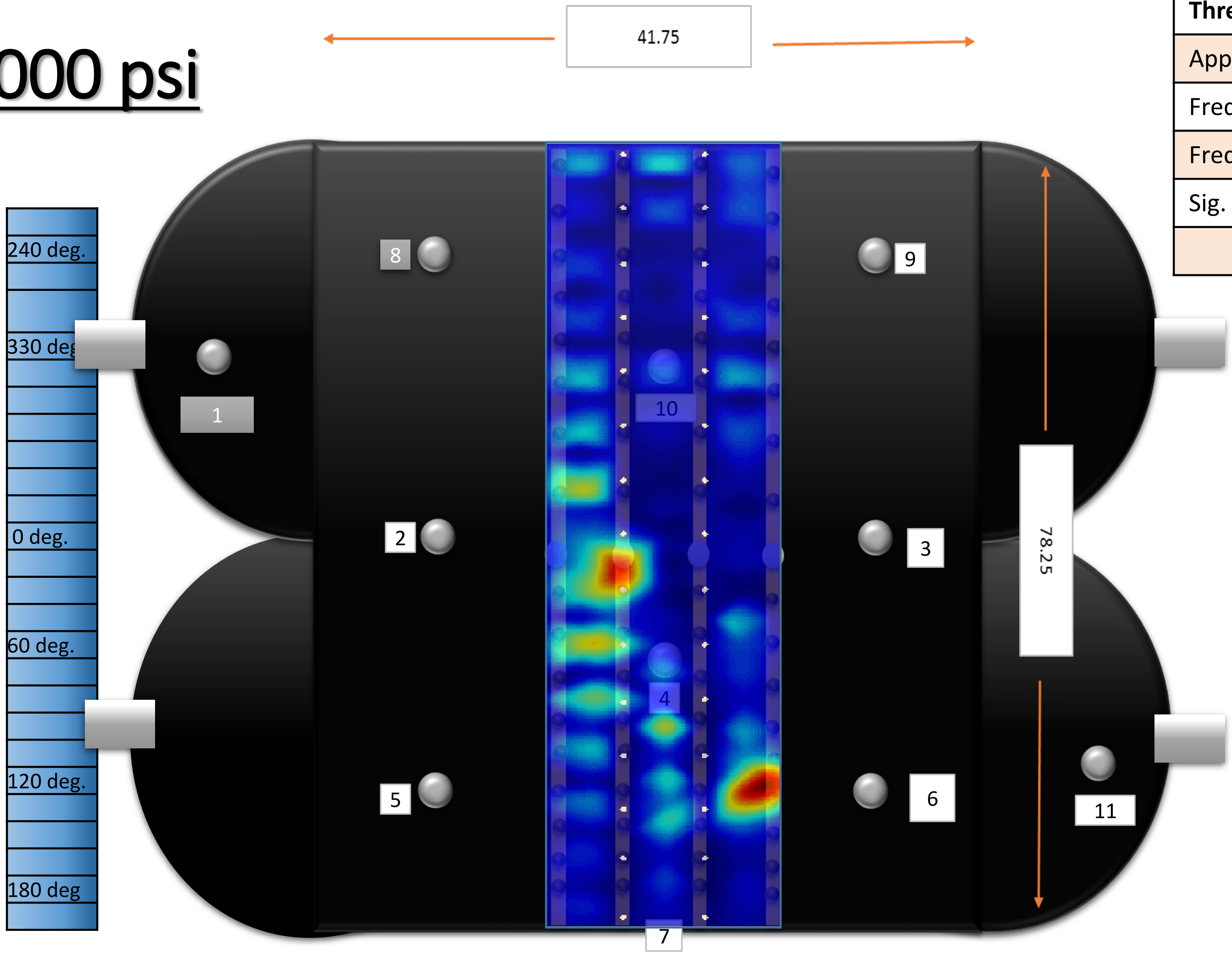
Composite Overwrapped Pressure Vessel

COPV 1

COPVs were tested to gage the performance of the sensors at LN_2 temperatures.



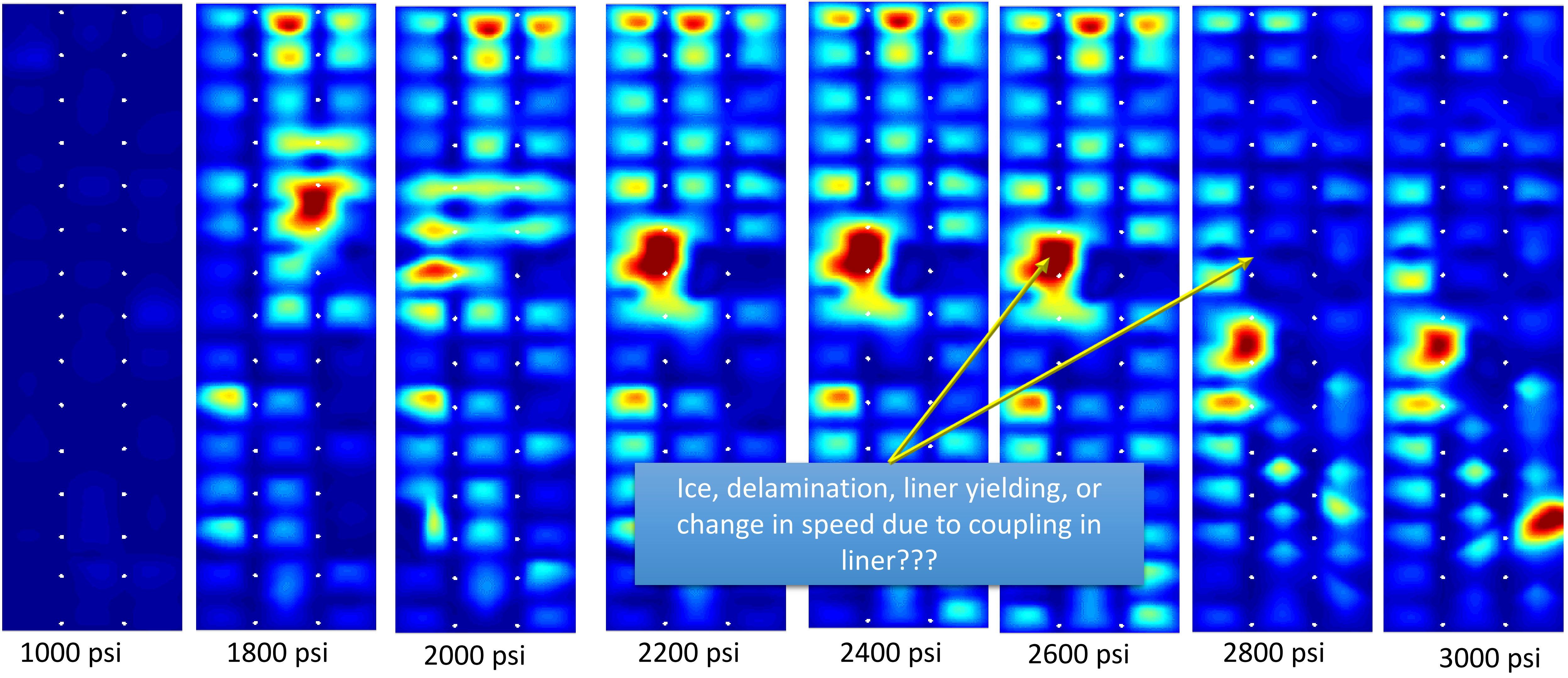
COPV 1 3000 psi



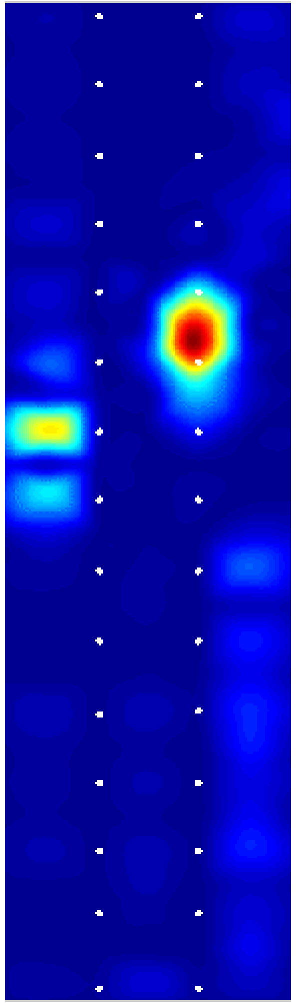
Threshold	0.5675
Applied Volt	30V
Frequency	100 -300 kHz
Freq. Step	50 kHz
Sig. Typ.	Burst5

Computer Channel ID	Radially	Axially	Degree
1	0	9	0
2	26.08	9	120
3	52.16	9	240
4	13.04	22	60
5	39.12	22	180
6	65.2	22	240
7	0	34.25	0
8	26.08	34.25	120
9	52.16	34.25	240
10		Top	
11		Bottom	

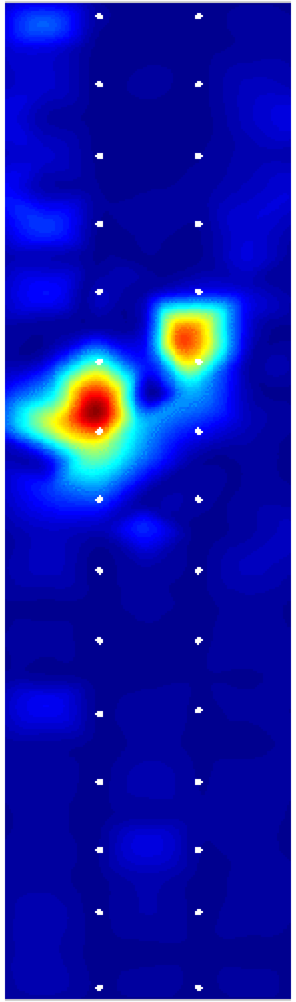
COPV 1 at 500 psi Baseline Threshold 0.5675



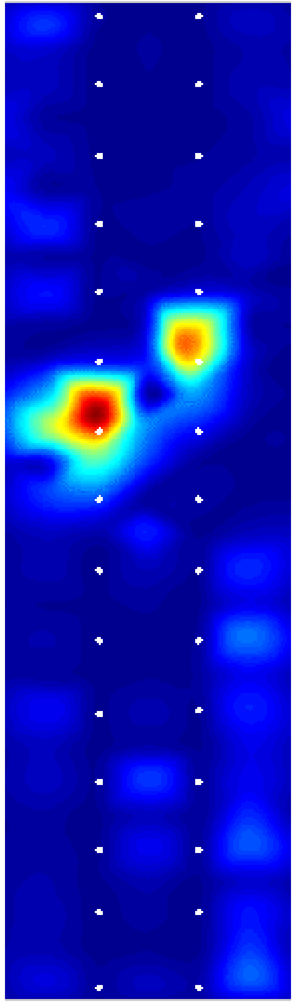
COPV 1 at 1800 psi Baseline



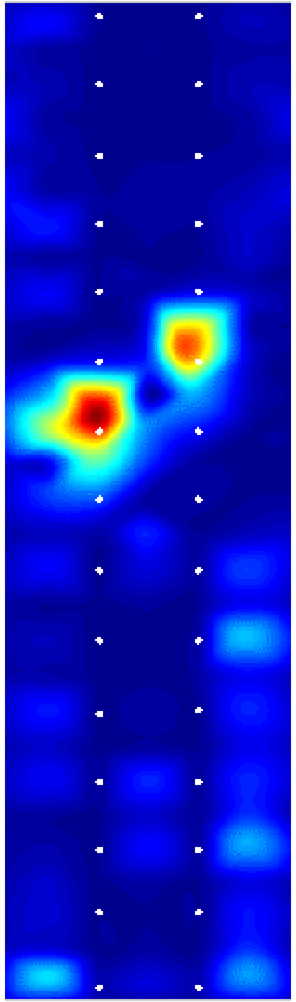
2000 psi – THD .5884



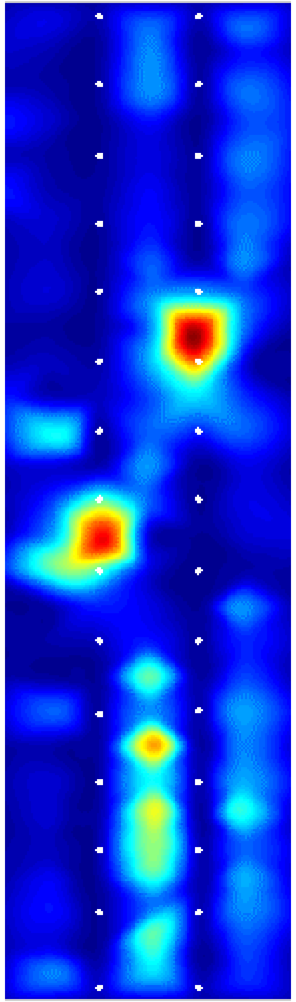
2200 psi – THD .5884



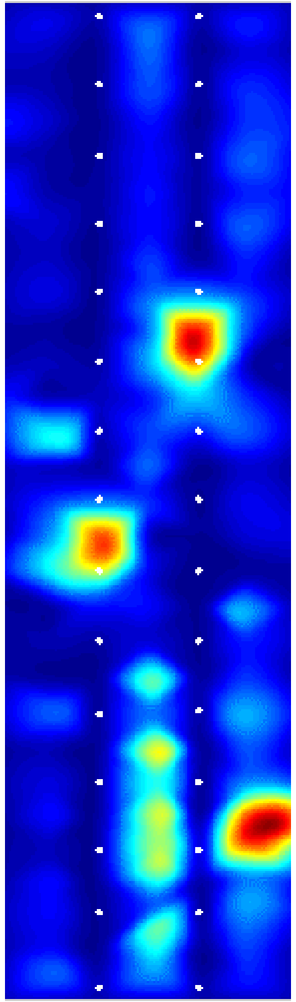
2400 psi – THD .5884



2600 psi – THD .5884



2800 psi – THD .5884



3000 psi – THD .6265

Difference Baseline 1800 psi and 500 psi

Damaged overwrap

Damaged overwrap

Damaged overwrap

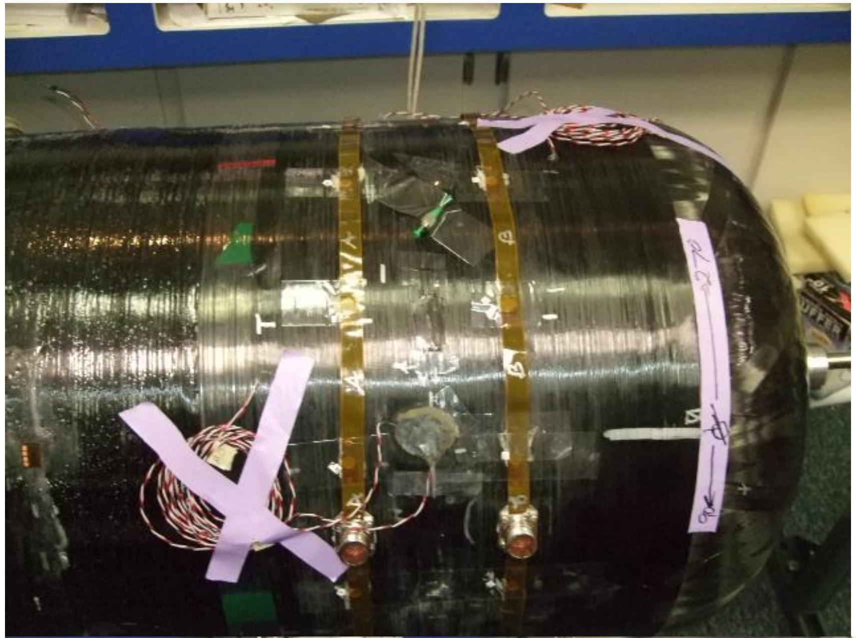
3000 psi with 500 psi baseline

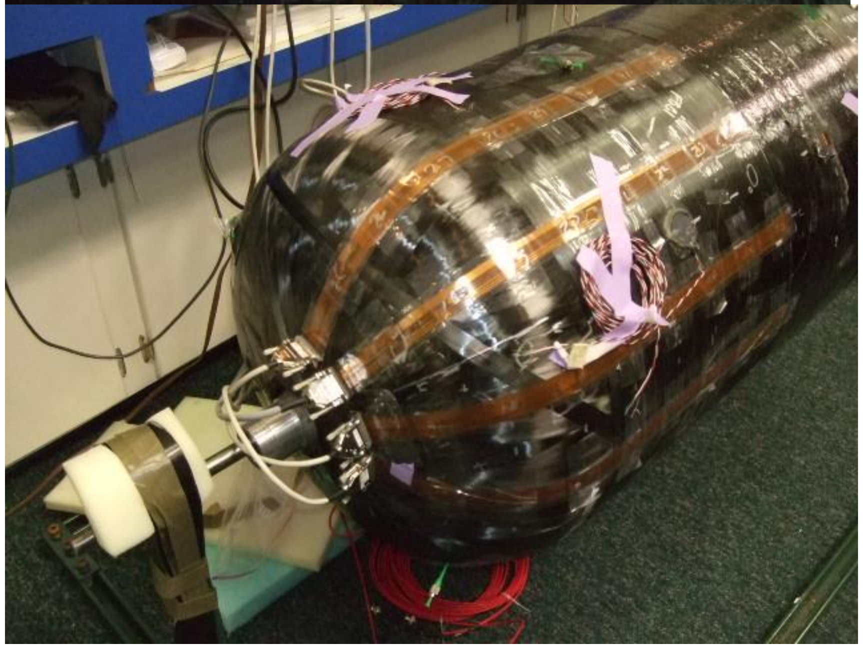
3000 psi with 1800 psi baseline

COPV 1 Burst at 3150 psi

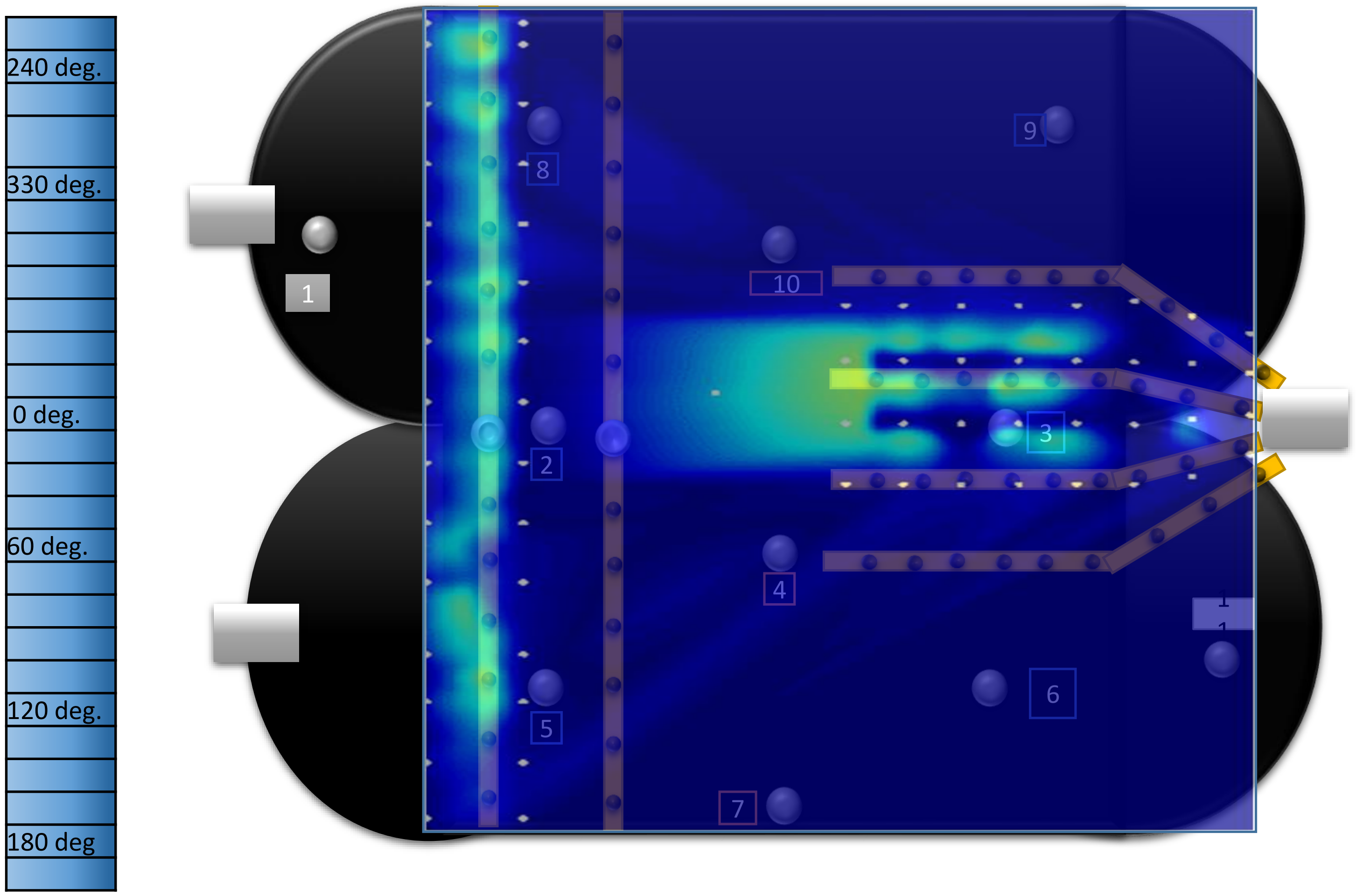
Acellent Lower Hoop Patch Layout

Cable A			Cable B		
Sensor	X (Radial)	Y (Axial)	Sensor	X (Radial)	Y (Axial)
33			49		
34	-28.5	-10	50	-28.5	-15
35	-23.625	-10	51	-23.625	-15
36	-18.75	-10	52	-18.75	-15
37	-13.825	-10	53	-13.825	-15
38	-9	-10	54	-9	-15
39	-4.25	-10	55	4.25	-15
40	0.75	-10	56	0.75	-15
41	5.75	-10	57	5.75	-15
42	10.625	-10	58	10.625	-15
43	15.5	-10	59	15.5	-15
44	21.375	-10	60	21.375	-15
45	25.25	-10	61	25.25	-15
46	30.25	-10	62	30.25	-15
47	34.825	-10	63	34.825	-15
48	-30.25	-10	64	-30.25	-15



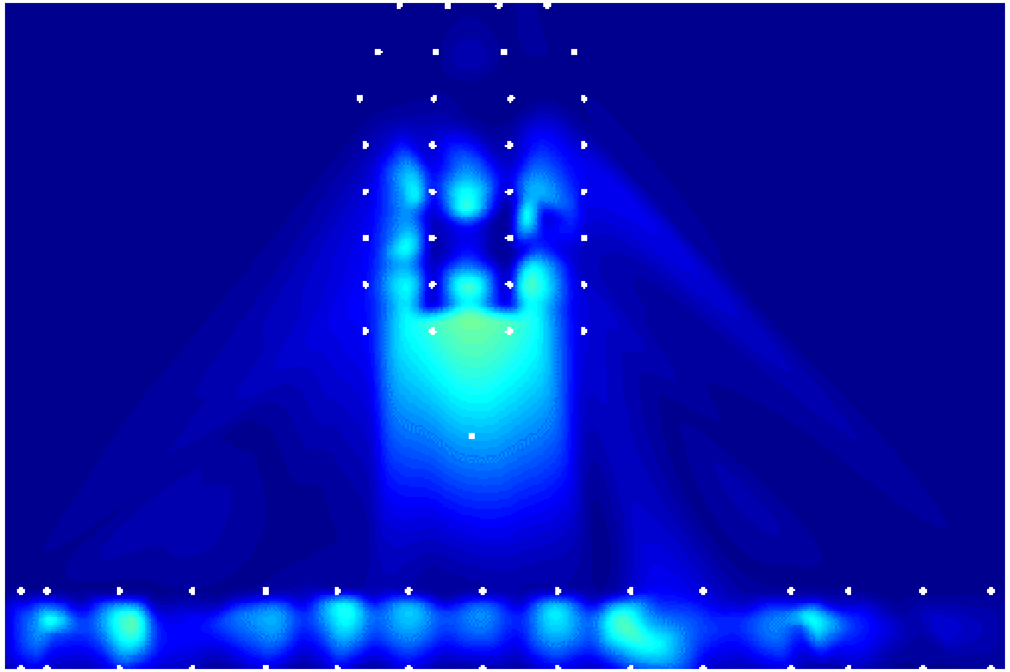


COPV 2 Acellent Sensor Patches and AE

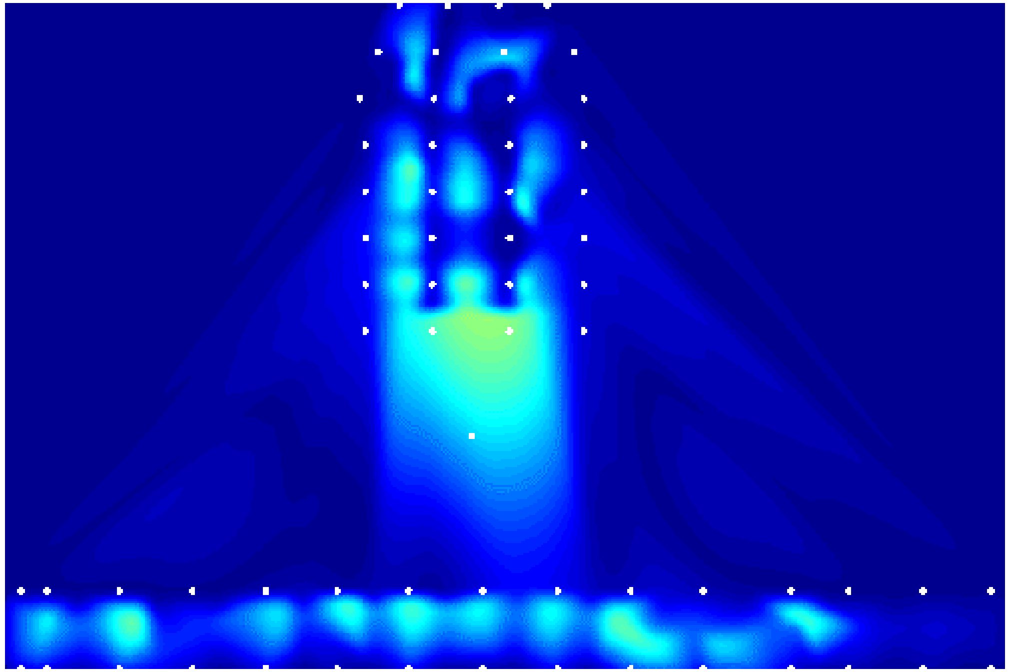


Computer Channel ID	Radially	Axially	Degree
3	0	9	0
6	26.08	9	120
9	52.16	9	240
4	13.04	22	60
7	39.12	22	180
10	65.2	22	240
2	0	34.25	0
5	26.08	34.25	120
8	52.16	34.25	240
11		Top	
1		Bottom	

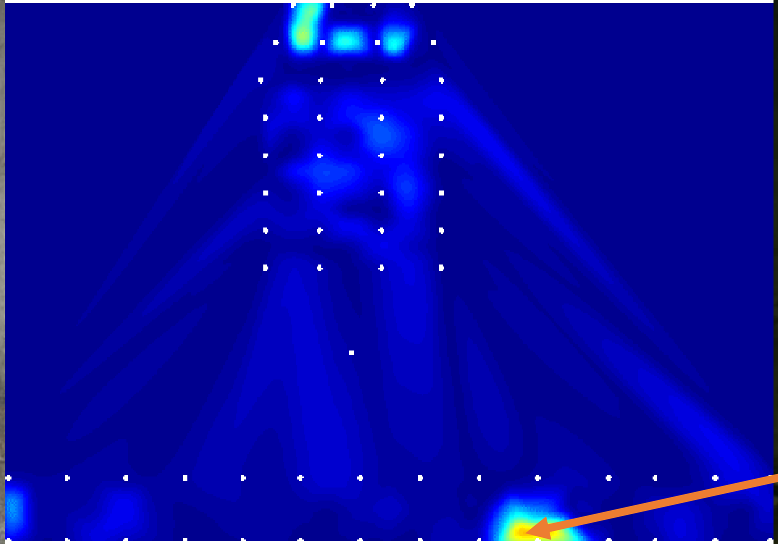
Baseline at 77 Degrees K-Threshold 1.6324



1500 Psi – Threshold 1.6324



1800 psi - Threshold 1.6324

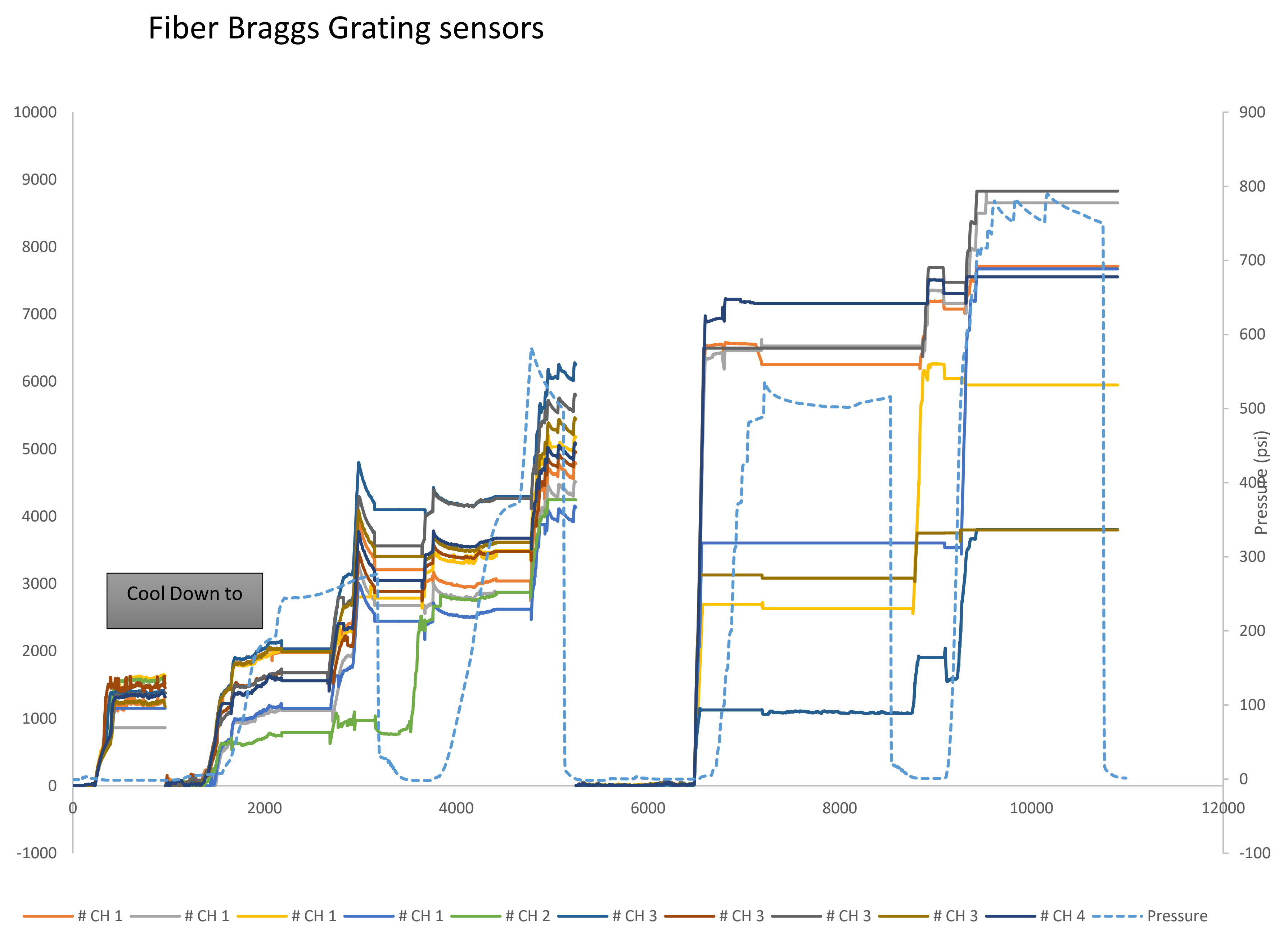


COPV 2 Burst at 3370 psi below the center. It was launched several feet in the air and landed about 350 ft. away.

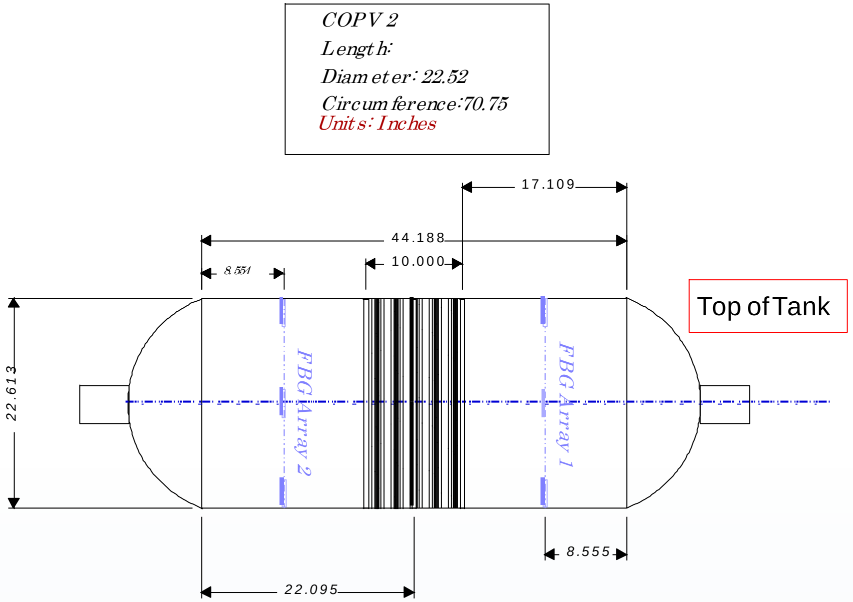
Empty Frame. The tank landed about 350 feet away.

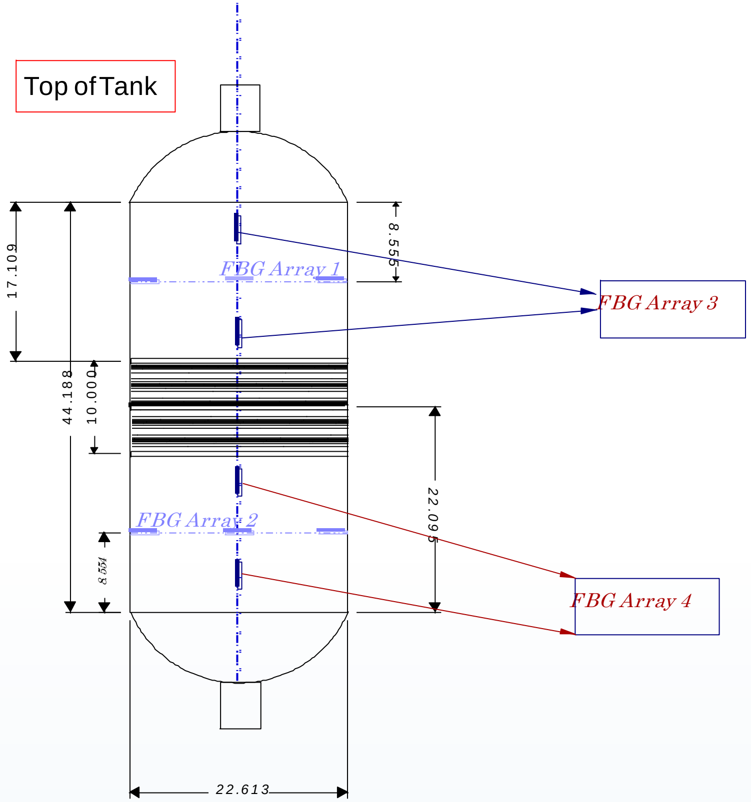
10 FBG Sensors

Micron Optics FBGs					
FBG Channel No.	FBG Number	wavelength (nm)	Radially	Axially	angle
Channel 1	FBG 1	1526			
	FBG 2	1536	16	16	90.00
	FBG 3	1546	35.875	16	180.00
	FBG 4	1556	55.75	16	270.00
	FBG 5	1566	75.75	16	358.00
Channel 2	FBG 6	1526			
	FBG 7	1536	16	27.75	90.00
	FBG 8	1546	35.875	27.75	180.00
	FBG 9	1556	55.75	27.75	270.00
	FBG 10	1566	75.75	27.75	358.00
Channel 3	FBG 11				
	FBG 12				
	FBG 13				
	FBG 14		Ch1	axial	
	FBG 15		Ch2	lower hoop	
Channel 4	FBG 16		Ch3	Upper hoop	
	FBG 17		Ch4	single hoop	
	FBG 18				
	FBG 19				
	FBG 20				


Fiber Braggs Grating sensors
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
900
800
700
600
500
400
300
200
100
0
-100
Pressure (psi)
0
2000
4000
6000
8000
10000
12000
Cool Down to
CH 1
CH 1
CH 1
CH 1
CH 2
CH 3
CH 3
CH 3
CH 3
CH 4
Pressure

COPV 2 FBGs





Distance	Wavelength
17.75 (at 90 degree)	1566
9.75 (at 90 degree)	1556
12 (at 90 degree)	1546
16.5 (at 90 degree)	1536
24.25 (at 90 degree)	1526
-16.5 (at 180 degree)	1566
-7.75 (at 180 degree)	1556
10 (at 180 degree)	1546
17.5 (at 180 degree)	1536
25.25 (at 180 degree)	1526
-12.5 (Bottom Hoop)	1556
-12.5 (Bottom Hoop)	1546
-12.5 (Bottom Hoop)	1536

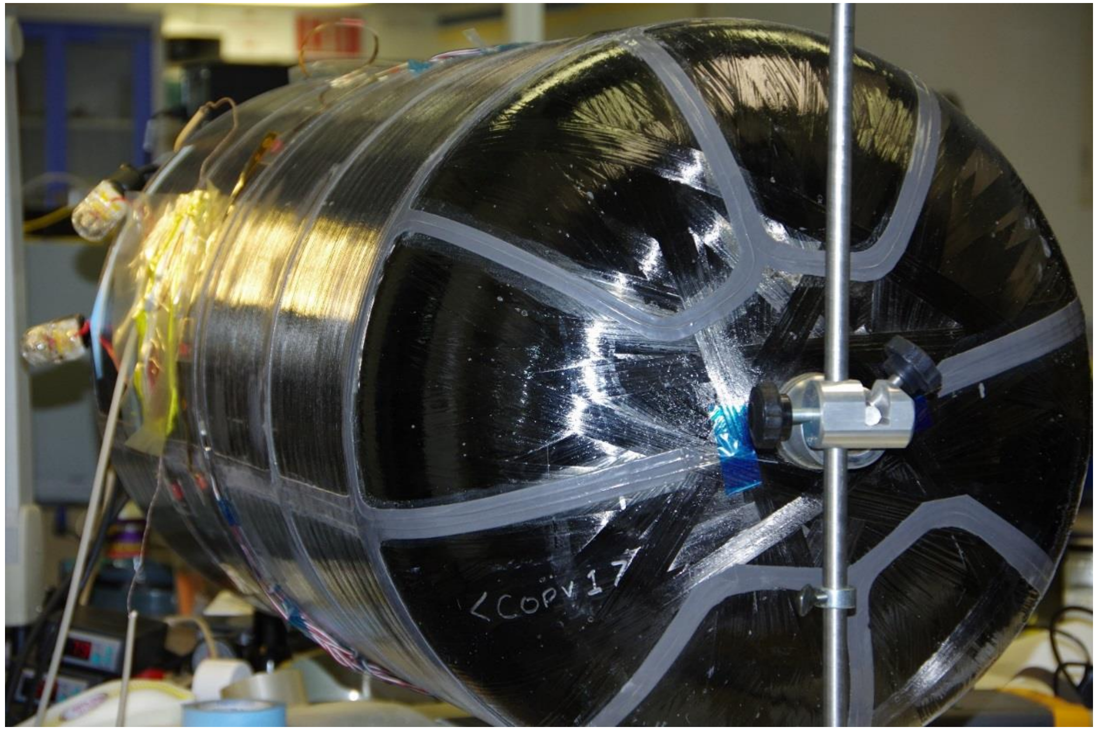
Conclusion

- Acellent stayed attached to the vessels during all testing. We used M-bond Epoxy for cryogenic application.
- The data in both cases, optical and electrical, was not corrected for temperature effects; the strips we used were not able to take advantage of temperature compensation that’s available from Acellent.
- The sensors held up at the LN_2 temperatures.
- The optical fibers suffered from peak splitting but the data could be averaged, reconstructed, and verified with traditional strain data. Some of the sensors fell out.
- The damage could be detected and reasonably located with the Acellent smart strip patch.
- Ice formation made it difficult to distinguish between structural damage and ice. the Ice damps the acoustic signals but it tends to fall from the structure during testing.
- The AE data is not shown but showed good results

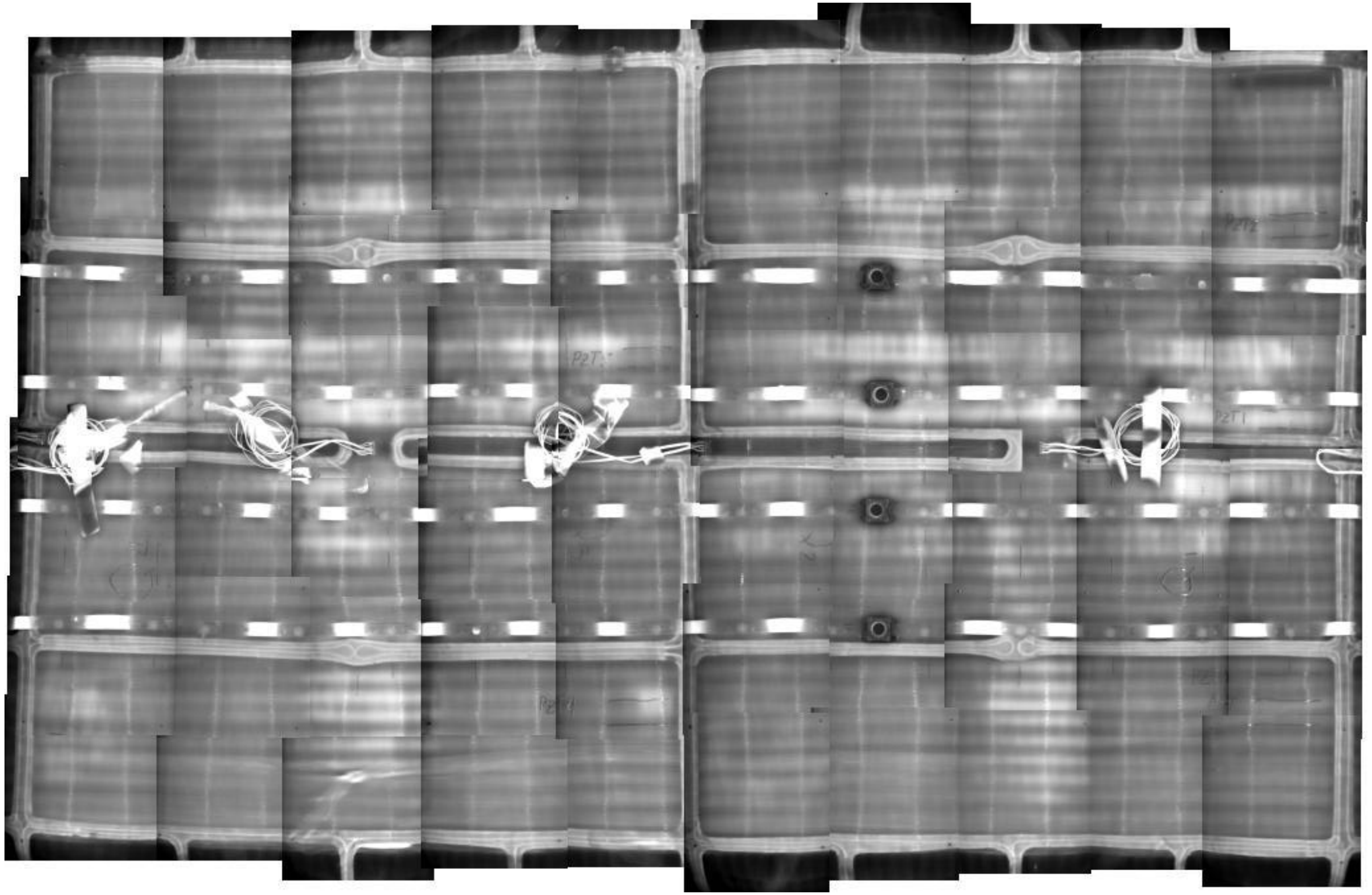
Extra Slides

COPV 1 Flash Thermography

- **Specimen Information**
- Project COPV 1
- **Inspection Equipment**
- Infrared Camera FLIR SC6000
- Lens 25 mm
- Heating Method Flash Lamps
- Hood Configuration Small FOV
- **Inspection Settings**
- Capture Software EchoTherm 8
- Image Size 640 x 512
- Capture Frequency 30 Hz
- Capture Duration 9.7 seconds
- Flash Duration N/A
- Flash Delay 0 milliseconds
- Flash Frame 10
- TSR Skip Frames 1

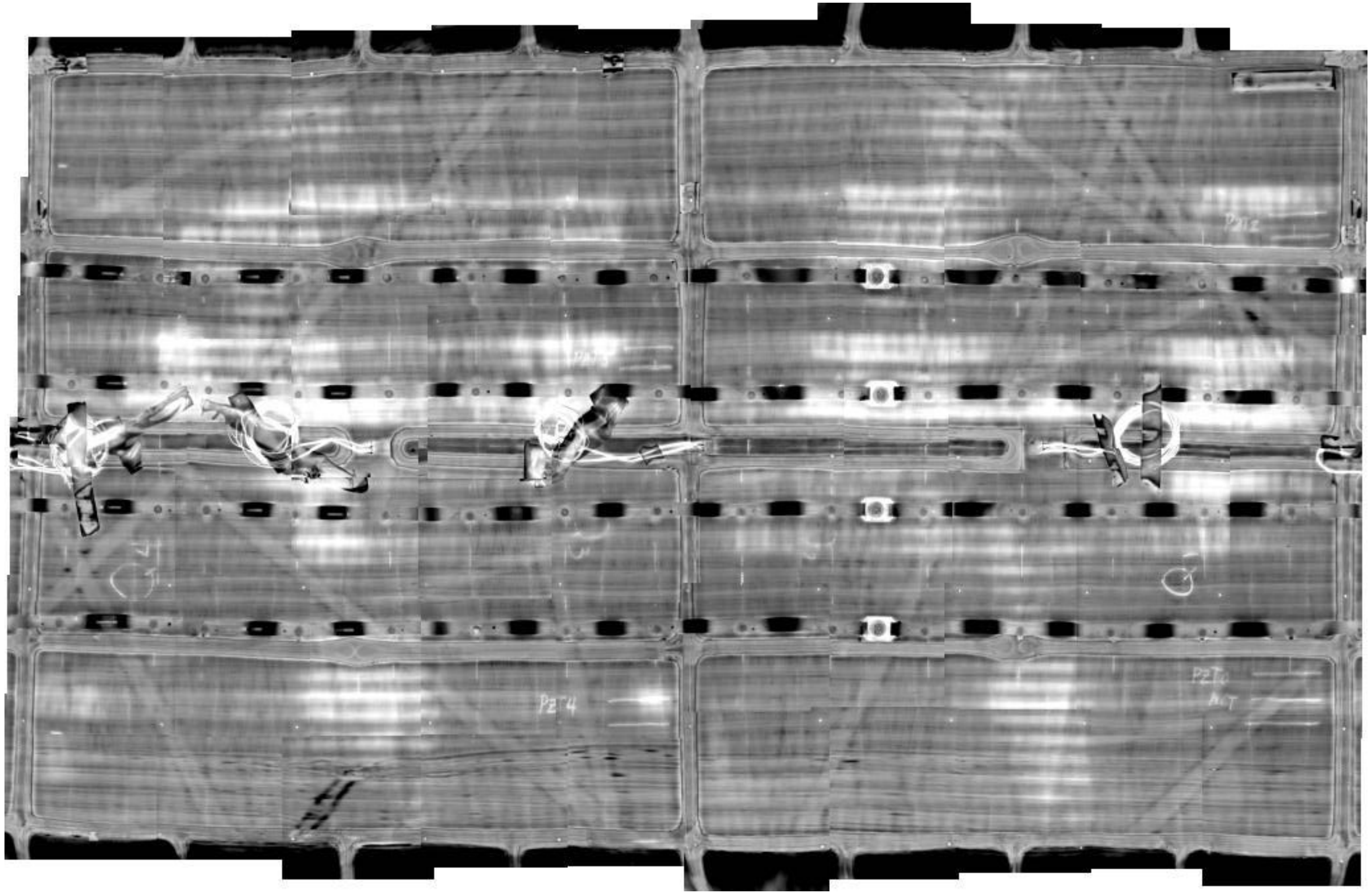


IRT Inspection



Significant portions of the surface of the COPV were obscured by sensors. A contrast-leveled image shows levels of variations in exposed areas of the acreage.

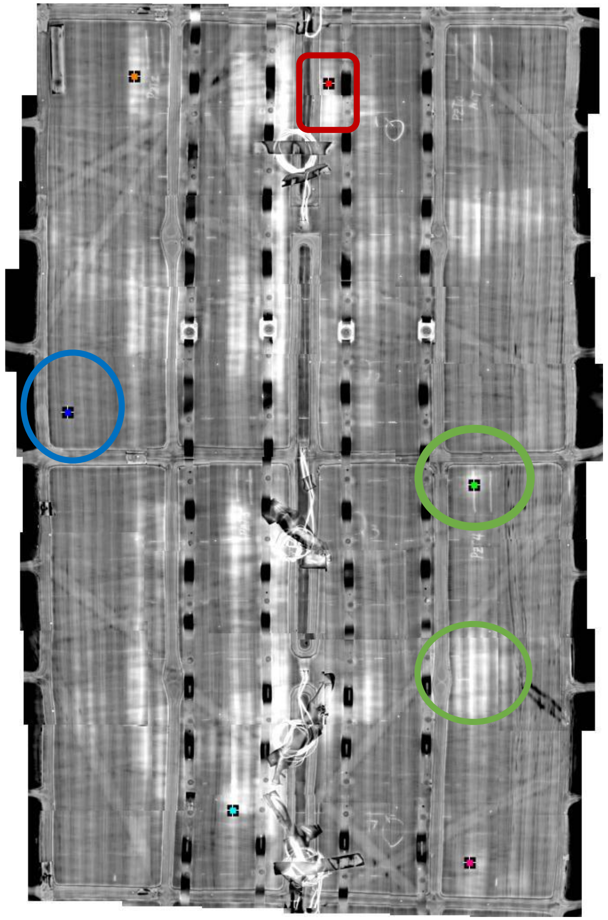
IRT First Derivative Plot



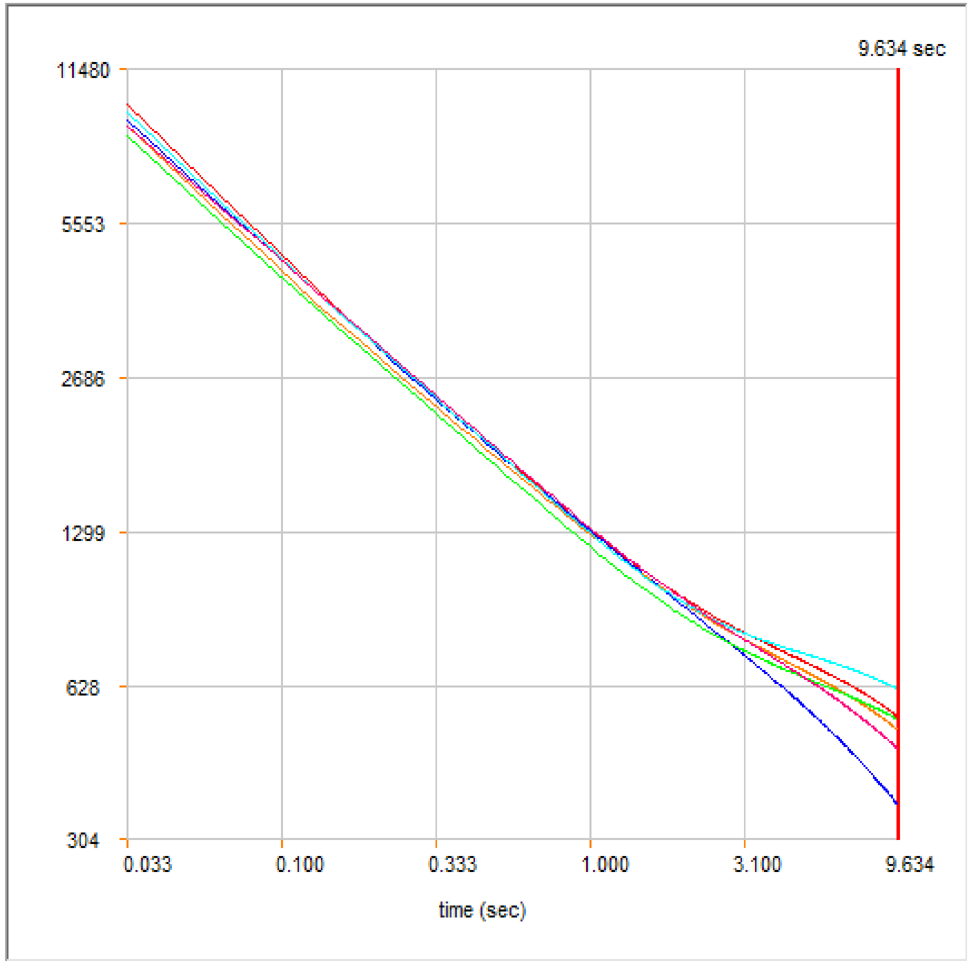
First derivative processing more clearly shows areas of interest, the majority of which, are concentrated in the middle of the vessel along the full circumference.

Logarithmic Time vs Temperature

The logarithmic time versus temperature plot shows the areas of interest (shown in white) deviate from the nominal acreage (blue cursor) late in the acquisition sequence which suggests a lower quality bond between the overwrap and the vessel itself.



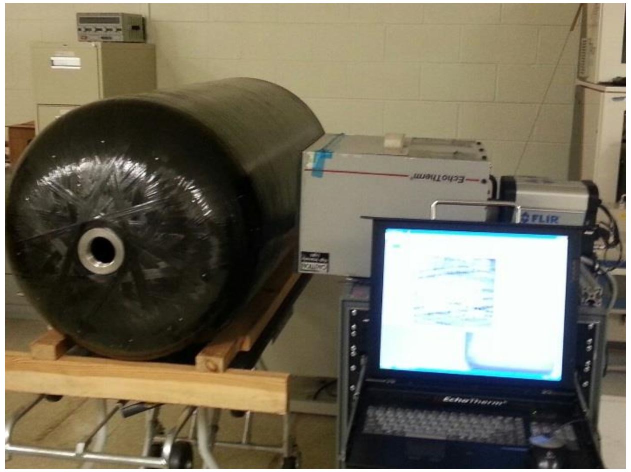
First Derivative, Frame 125
Time vs Temperature Cursors

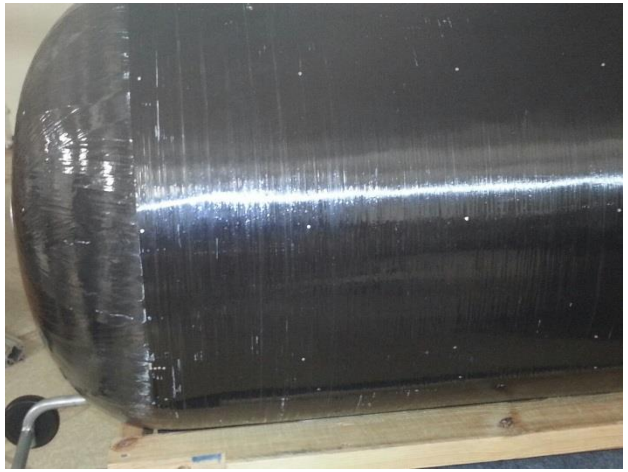


Logarithmic Time versus Temperature Plot

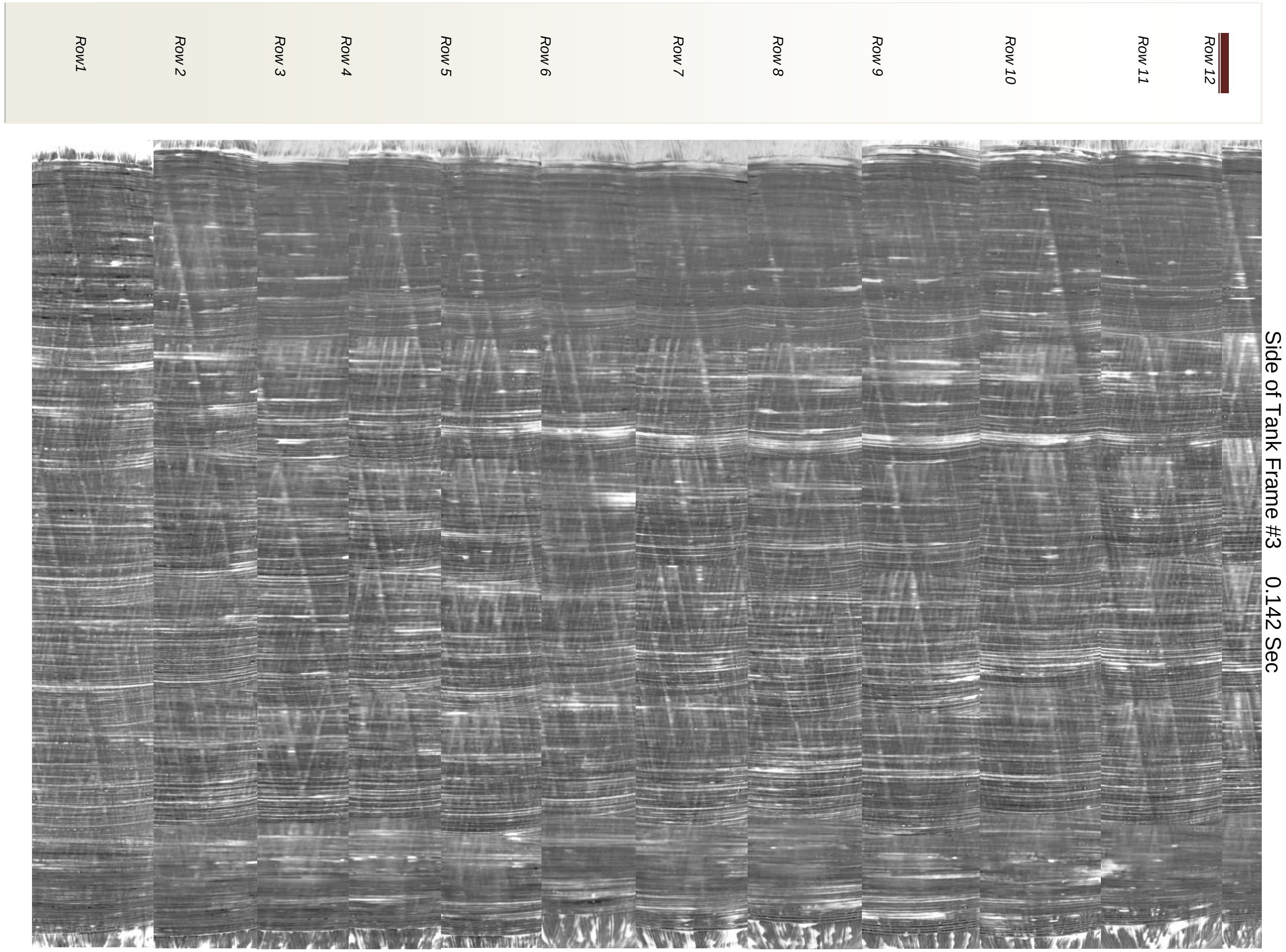
Flash Thermography of Scorpius Tank

Project	**OTC**
Serial Number	**100 gallon tank**
Surface Preparation	**None**
Special Handling	**None**
Inspection Equipment	
Infrared Camera	**FLIR SC6000**
Lens	**25 mm**
Heating method	**Flash Lamps**
Hood Configuration	**Small FOV**
Inspection Settings	
Capture Software	**EchoTherm 8**
Image Size	**640 x 512**
Capture Frequency	**21hz**
Capture Duration	**13.7 sec**
Flash Duration	**2 msec**
Flash delay	**N/A**
Flash Frame	**10**
TSR Skip Frames	**1**

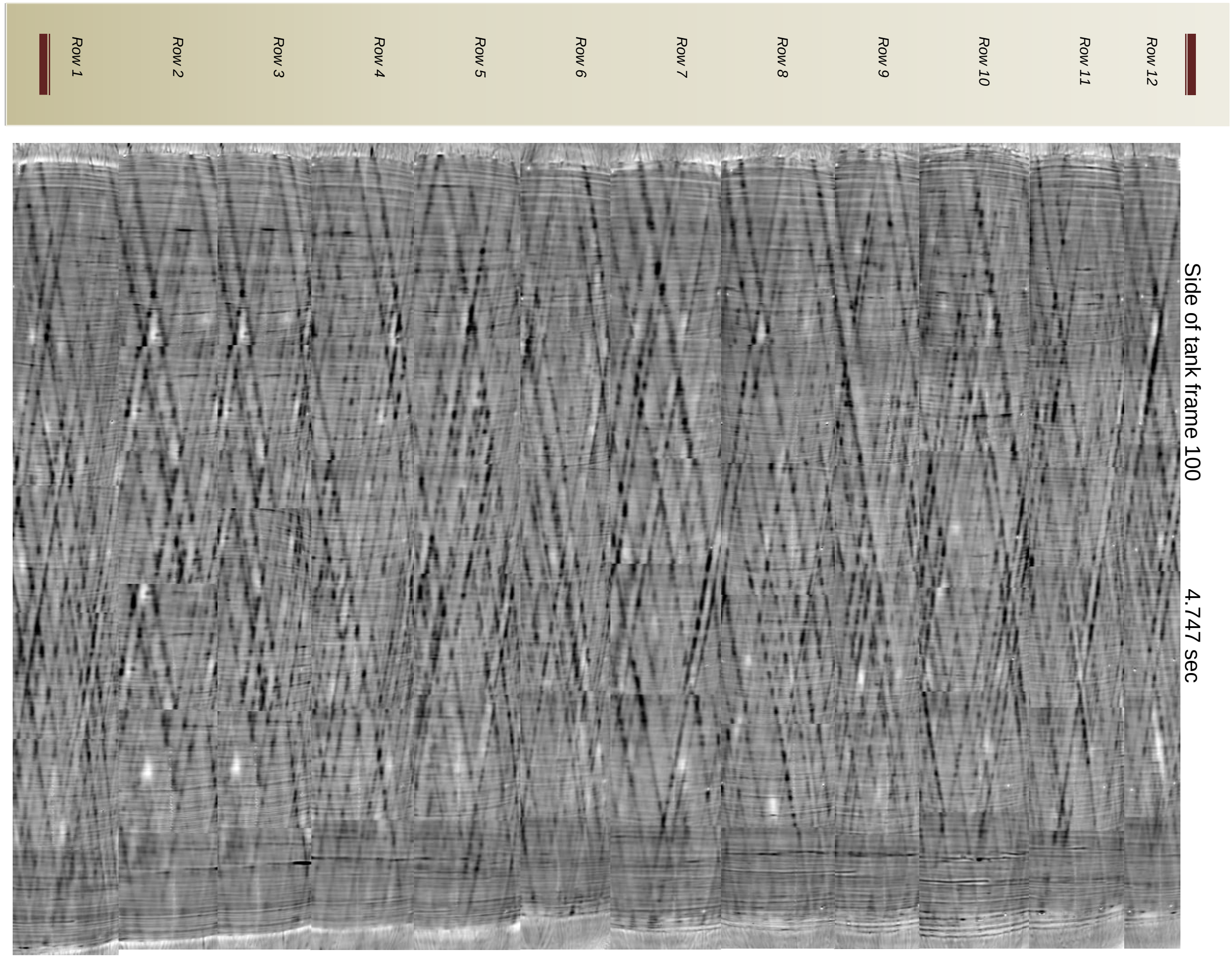




Flash Thermography of Scorpius Tank

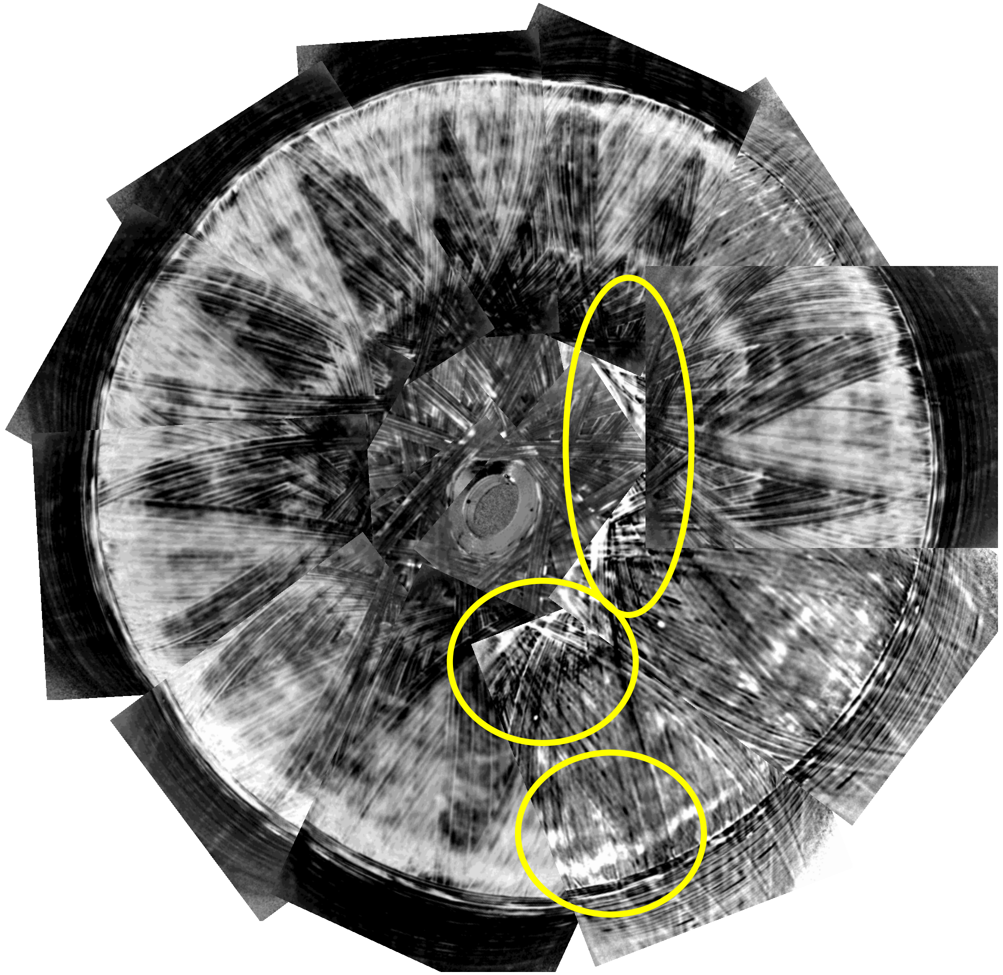


Flash Thermography of Scorpius Tank



Flash Thermography of Scorpius Tank

Left end dome Frame 3 0.142 sec



Left end dome Frame 30 1.42 sec