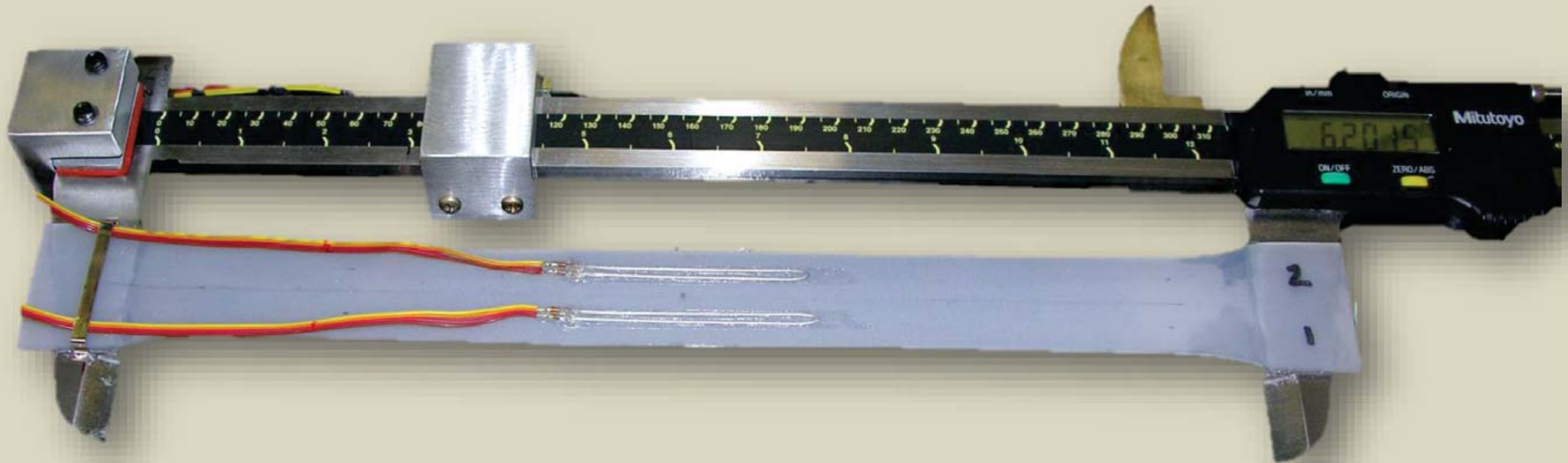
Highly Elastic Strain Gage for Low Modulus Materials



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NASA Armstrong Flight Research Center, Edwards CA

Spring WRSGC in San Antonio, TX
March 30th - April 1st, 2015

Outline

Background

Need

- Large magnitude strain measurements on highly elastic materials possessing low Young's modulus and high yield strain (i.e. fabrics, rubbers, elastomers, etc.)

Problem

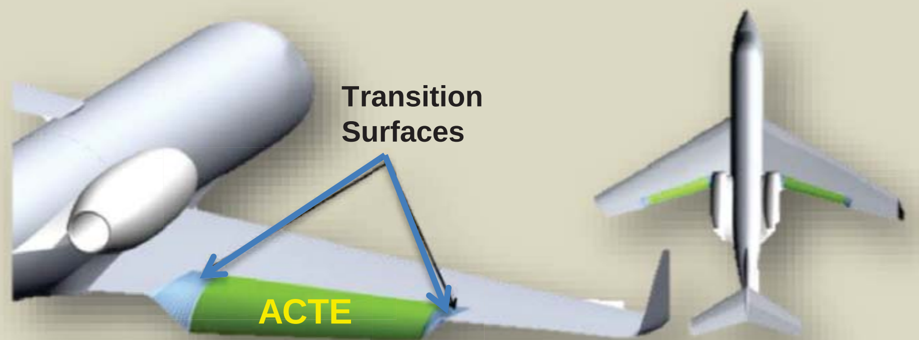
- Current resistive foil and fiber optic strain gages have limitations
  - Strain range < 20%
  - Localized stiffening due to relatively high modulus of sensor and adhesive

Proposed Solution

- Adapt current Plethysmography liquid metal strain gage technology for aerostructures (current use: testing endothelial dysfunction and reactive hyperemia)
  - Modify system for large strains > 100%
  - Modify sensor physically
  - Calibrate / evaluate to large strains required on aerostructure applications

Potential NASA Projects

- Inflatable reentry TPS concepts
- Gulfstream III ACTE



Current Application of Technology

Plethysmography: testing endothelial dysfunction and reactive hyperemia

Manufacturer (contacted)

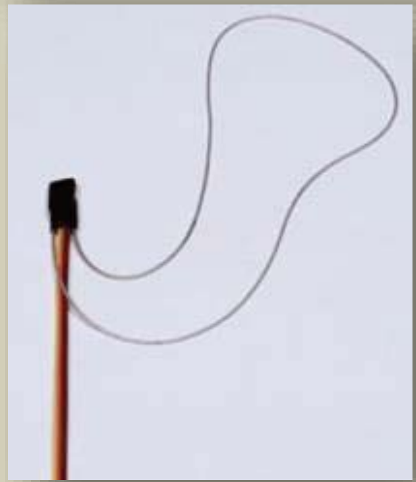
D. E. Hokanson, Inc.
12840 NE 21st Place
Bellevue, WA 98005 USA

System

EC6 features include AC and DC coupling, seven range settings, adjustable analog output for use with an external chart recorder, and a built-in RS232 data output.

Liquid Metal Strain Gage

Strain Gauge Sets	Sizes
Limb	Eight gauges from 22 to 36 cm in 2 cm increments
Forearm	Eight gauges from 16 to 30 cm in 2 cm increments
Digit	Seven gauges from 4.5 to 7.5 cm in 0.5 cm increments



LMSG Sensing Methodology

The resistance of the mercury in the tube can be measured with a pair of metal electrodes, one at each end. Since mercury is essentially incompressible, forces applied along the length of the tube stretch it, and also cause the diameter of the tube to be reduced, with the net effect of having the volume remain constant. The resistance of the strain gauge is given by

$$R = \frac{\rho L}{A} = \frac{\rho L^2}{V}$$

where ρ is resistivity of the mercury, L is length of the conductive fluid, A is the cross-sectional area, and V is the volume. Taking the derivative gives

$$\frac{dR}{dL} = \frac{2\rho L}{V} = \frac{2R}{L}$$

We define a quantity called the gage factor K as:

$$K = \frac{dR/R}{dL/L}$$

Since

$$\frac{dR}{dL} = \frac{2R}{L}$$

we have K = 2 for a liquid strain gage.

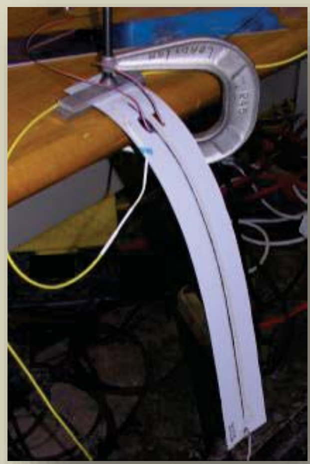
This means that the fractional change in resistance is twice the fractional change in length. In other words, if a liquid strain gauge is stretched by 1%, its resistance increases by 2%. This is true for all liquid strain gauges, since all that is needed is that the medium be incompressible.

Liquid strain gauges were used in hospitals for measurements of fluctuations in blood pressure. A rubber hose filled with mercury was stretched around a human limb, and the fluctuations in pressure were recorded on strip-chart recorders, and the shape of the pressure pulses could be used to diagnose the condition of the arteries. Such devices have been replaced by solid state strain gauge instruments in modern hospitals, but this example is still interesting to use as an introductory example.

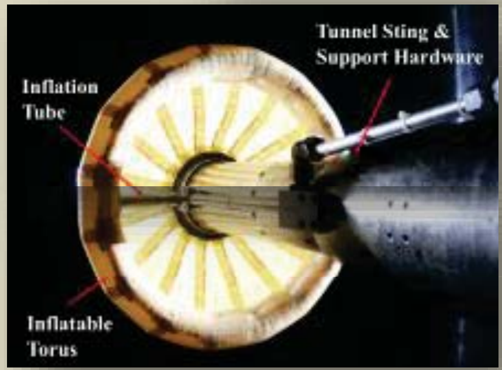
Source: http://www.stanford.edu/class/me220/data/lectures/lect03/lect_3.html

Evaluation / Characterization Plan

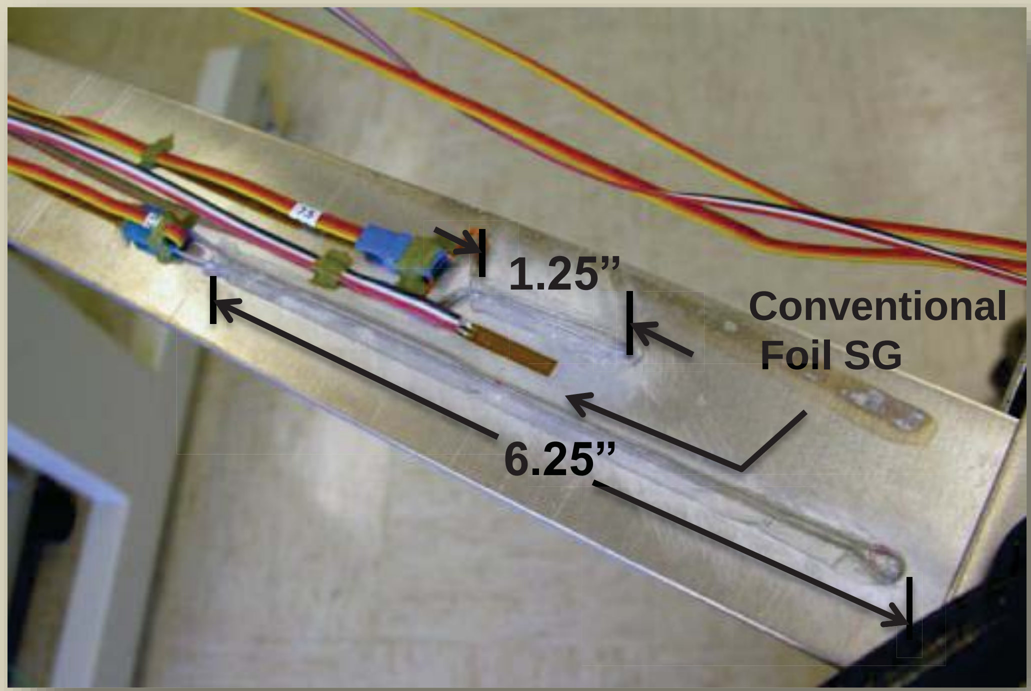
Sensor evaluation testing will be performed on liquid metal strain gage (LMSG) for high elastic strain measurement feasibility. Depending on results, further testing will include NASA project related substrates and structures

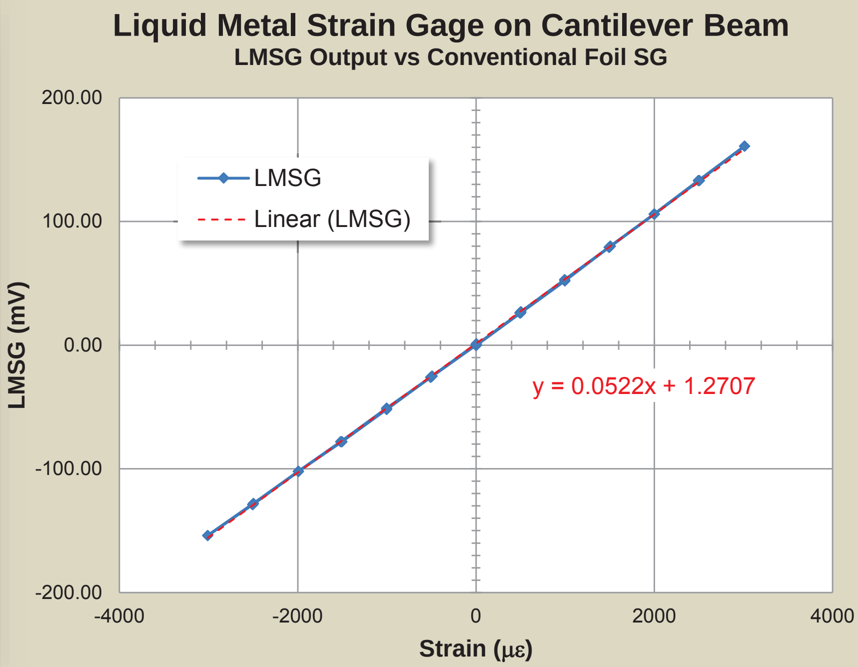


- Initial tests to be done on moderately elastic materials to enable comparison with foil strain gages and evaluate gage factor (GF), repeatability, scatter, and drift
  - — Extensometer hard attach with tensile load (2 pnt. w/epoxy)
  - — Full sensor bond under with applied bending loads on fiberglass or Plexiglas® (silicone adhesive)
  - — Study opening hoop versus folding back on self sensor configurations
  - — Characterize resistivity in varying thermal conditions
- If further testing warranted, test materials applicable to HIAD's and G-III against optical measurements
  - — Attach and test on appropriate materials
    - ballute straps provided by LaRC
    - elastomer skin provided by FlexSys Inc. (Ann Arbor, MI) and ATK



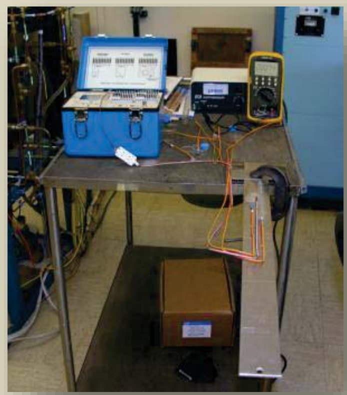
Initial Evaluation



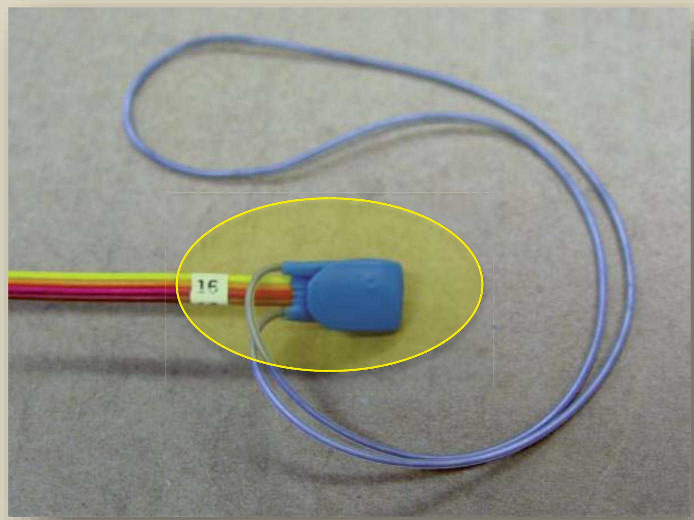


Attachment Procedure

- Sanded, cleaned/prepped substrate using standard SG procedures
- Encapsulated sensor with minimal taunt using silicone RTV (including end-loop)
- Connected phone jack connected input to EC6 system, adjusted range (0.5%) and balanced
- Recorded millivolt out with laboratory DAS



Initial Evaluation



Current Sensor/System Configuration

- Circumferal type measurement
- Plastic hook at electrical wire and LM silicon tubing interface for arterial Plethysmography measurements (in yellow)
- Liquid metal conductor: Indium-Gallium w/silicon tubing
- Stereo phone jack sensor input to EC6 system, adjustable range and balance (zero)
- Single channel system, millivolt output for recording to DAS
- Max-op strain range of 2% (D.E. Hokanson system limit)

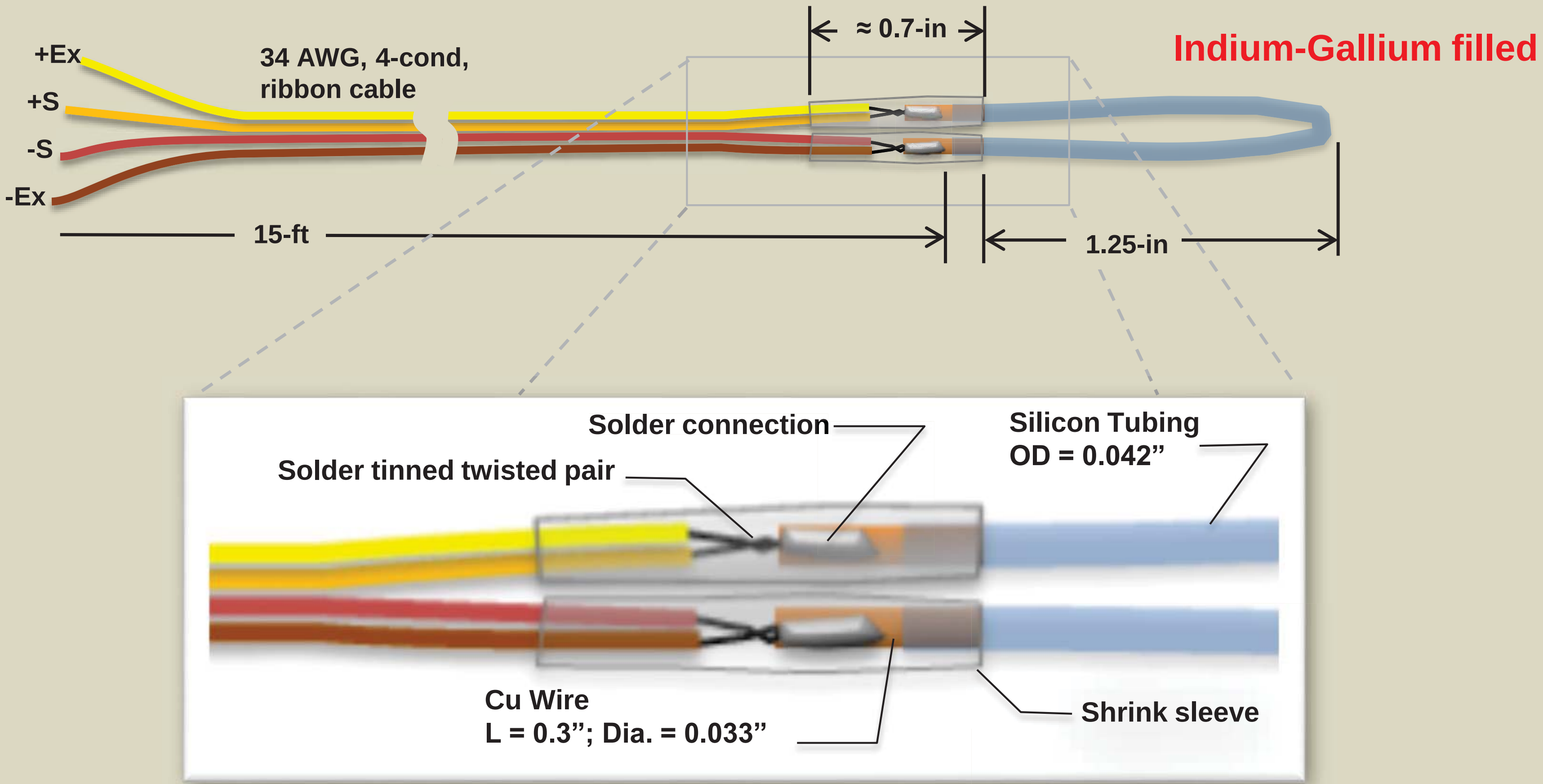
Future Configuration

- Transform to flat axial measurement: smooth/reduce transition from electrical wires to LMSG tubing (hook/plastic interface removed)
- Open strain range to >20% (D.E. Hokanson system mods)
- Attempt to adapt to traditional DAS by Wheatstone bridge or constant current if necessary
- If constant current, replace leadwires with smaller gauge wire since a Kelvin measurement
- Investigate mercury as LM conductor for flight applications (lower melting point temperature)

Modified Sensors Construction

Single Active Liquid Metal Strain Gage - GL - LWL

P# SALMSG-1.25-15



Modified Sensors Construction

Sensor Configuration for Proposed Temperature-Compensated LMSG for Flight Applications

Active Gage (ε_1) = applied mechanical strain (ε_{M1}) + strain due to temperature change (ε_{T1})

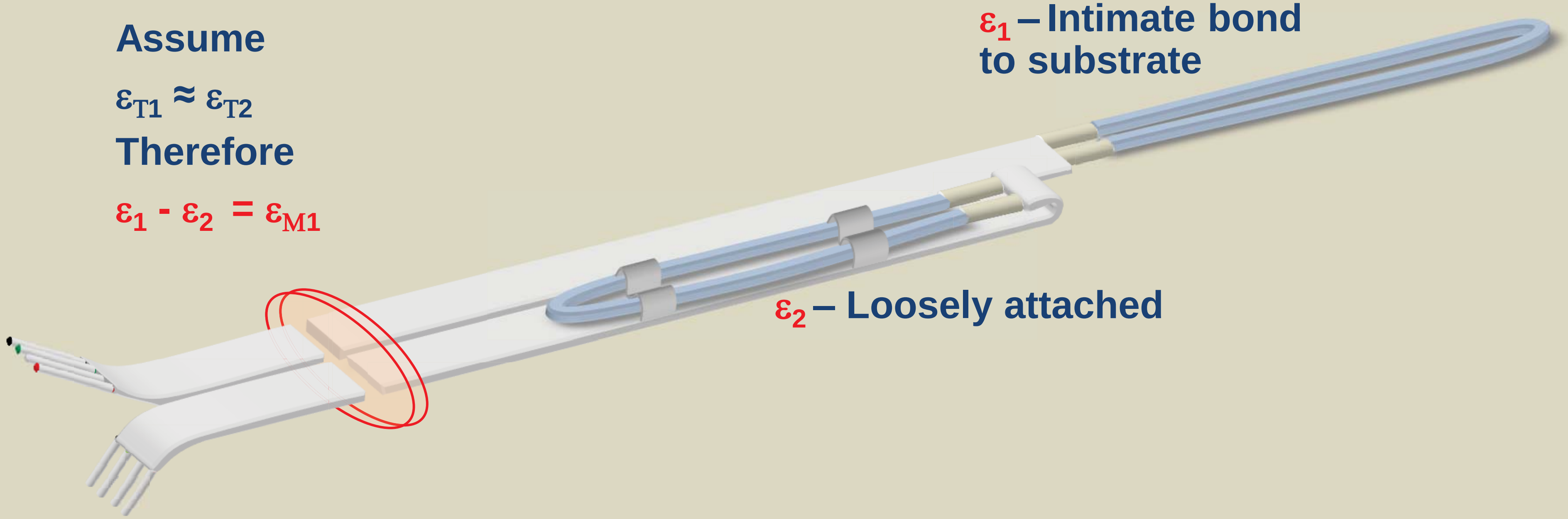
Dummy (ε_2) = strain due to temperature change (ε_{T2})

Assume

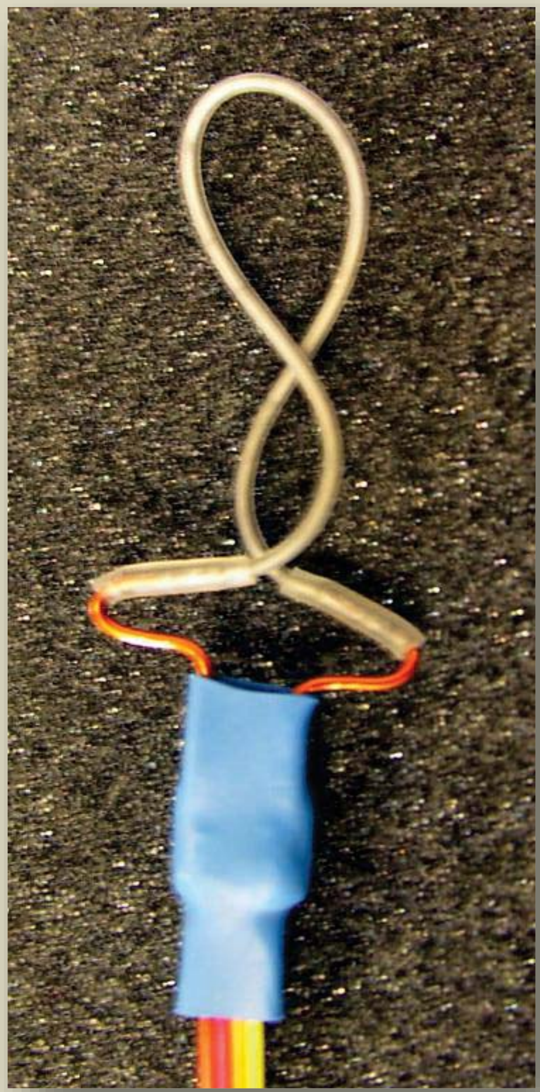
$\varepsilon_{T1} \approx \varepsilon_{T2}$

Therefore

$\varepsilon_1 - \varepsilon_2 = \varepsilon_{M1}$

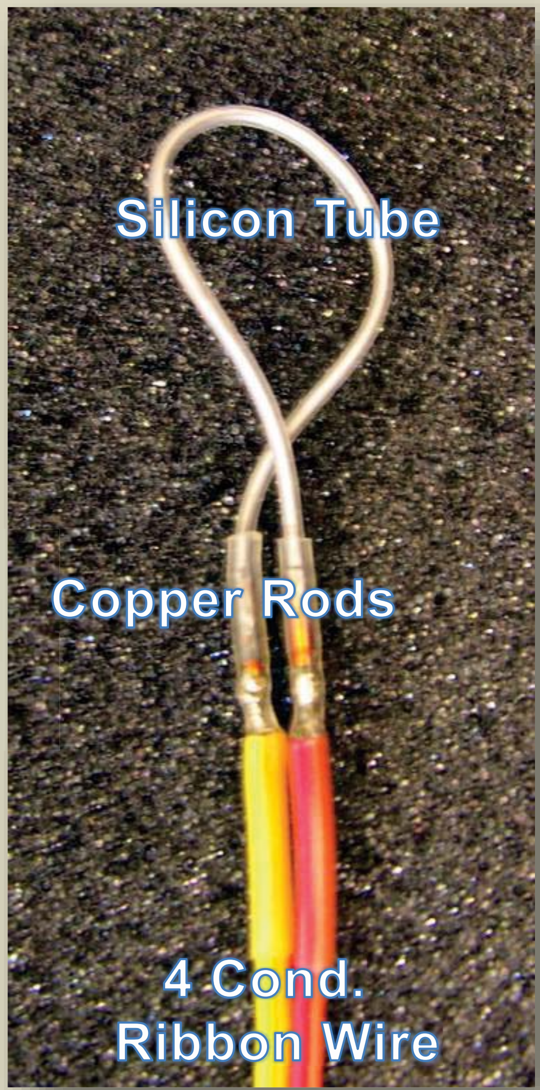


Modified Sensors Construction



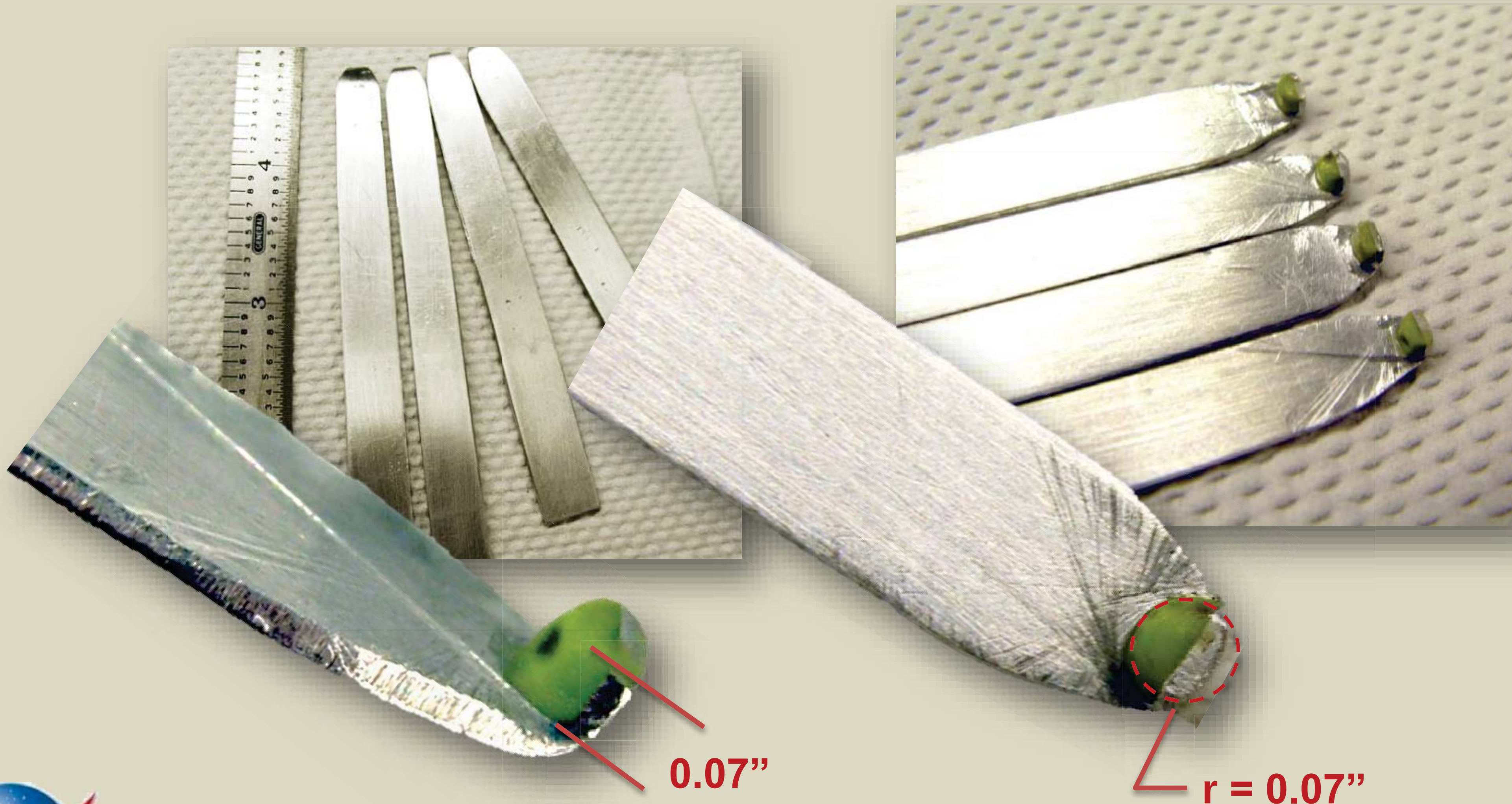
WAS

IS

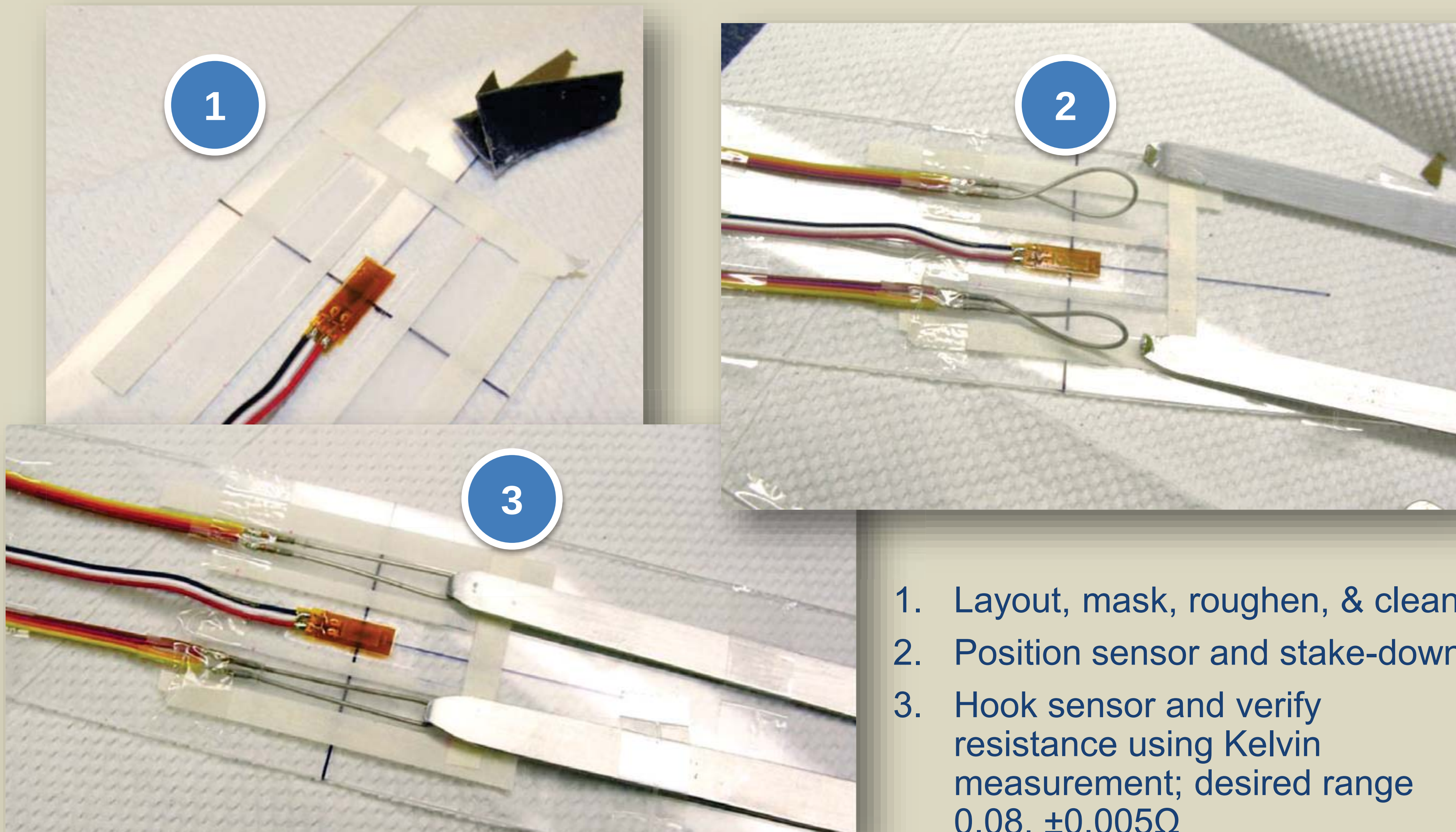


Installation Procedures

Stake-Down tools used to position sensor in adhesive and keep transverse sensitivity consistent between install



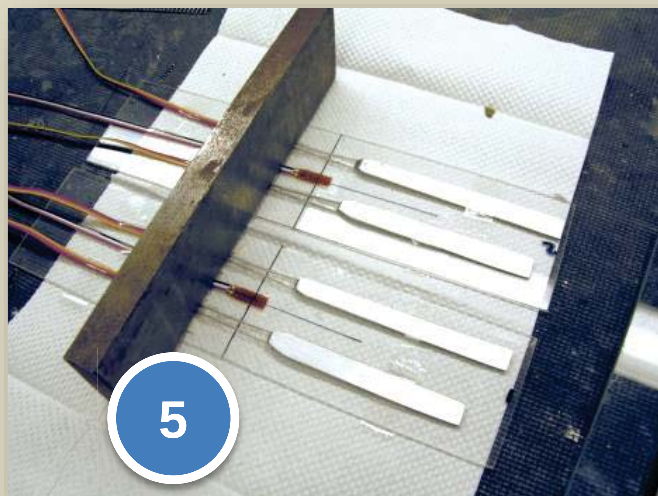
Installation Procedures

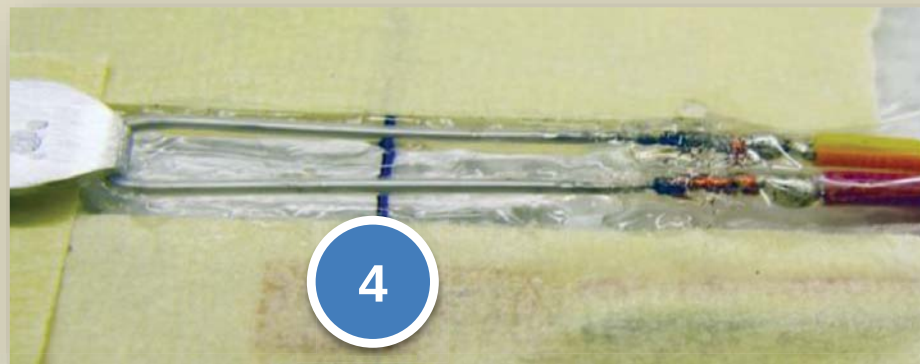


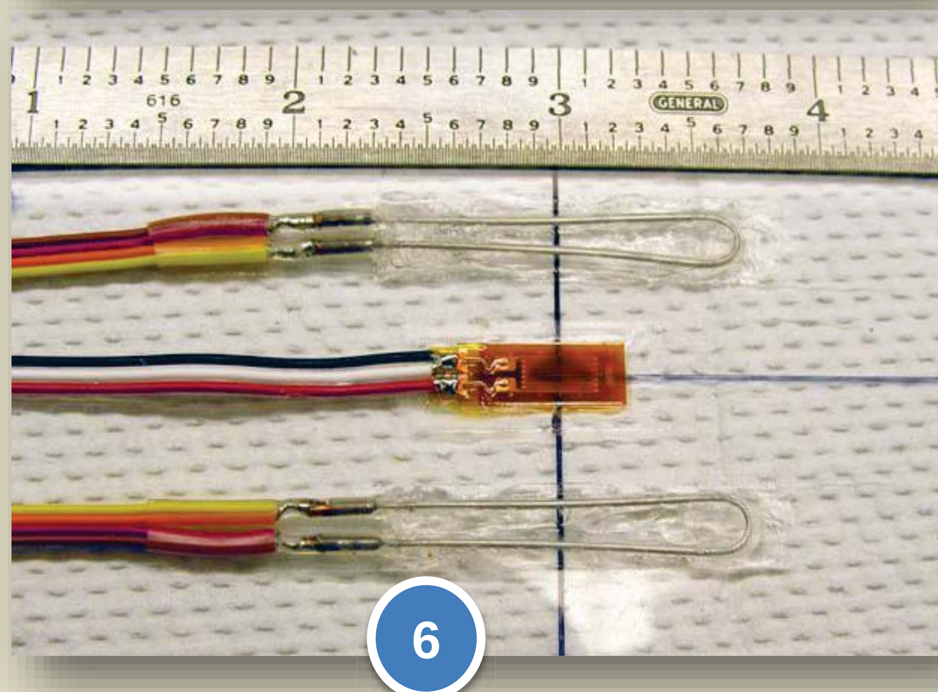
1. Layout, mask, roughen, & clean
2. Position sensor and stake-down
3. Hook sensor and verify resistance using Kelvin measurement; desired range 0.08, ±0.005Ω

Installation Procedures

4. Apply silicon adhesive to substrate; use heavier application on Cu elements
5. Weigh down Cu elements if possible
6. Remove masking check resistance

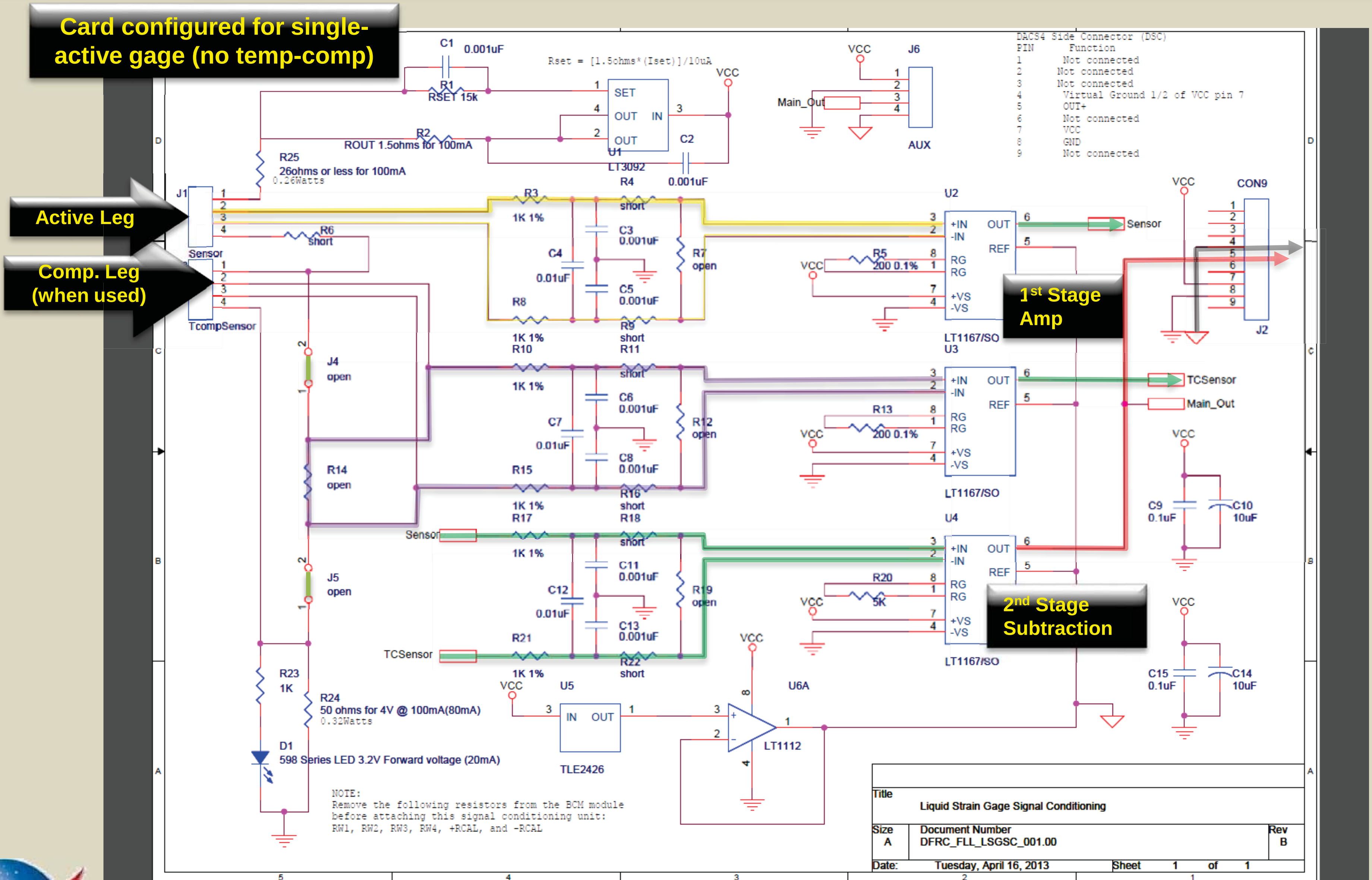






7. Procedure later modified to not encapsulate silicon tube and install in thin silicon bed (reduce stiffing)
8. Encapsulate only ½ of Cu elements

LMSG Signal Conditioning



Coefficient and Gage Factor (GF)

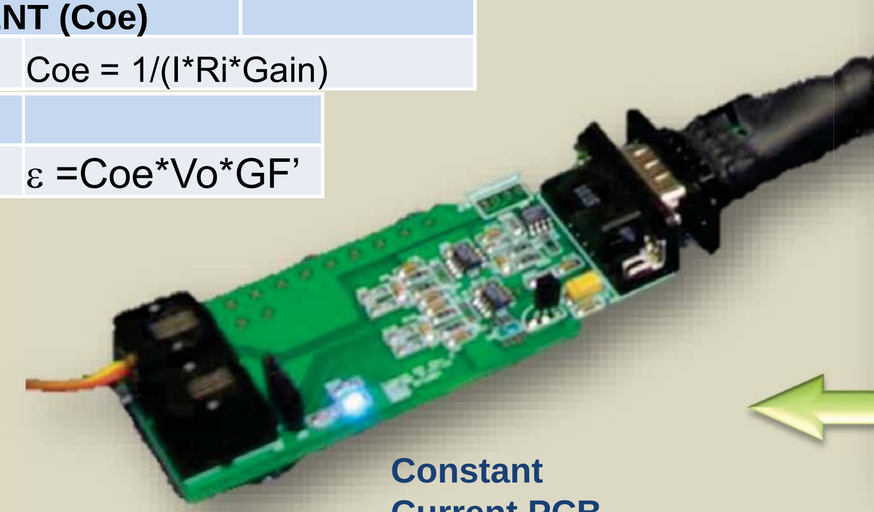
Signal Conditioning Gain (Av)							
	Amp Gain = 50K/RG						Av
		1st Stage	IN	0.00747	OUT	1.8475	247.32
		2nd Stage	IN	0.0324	OUT	0.349	10.77
				Total AV	Stage 1*Stage 2		2664.06

Ri	Initial sensor resistance (Ω)
ΔR	change in sensor resistance (Ω)
Vo	voltage out (V)
I	current (mA)

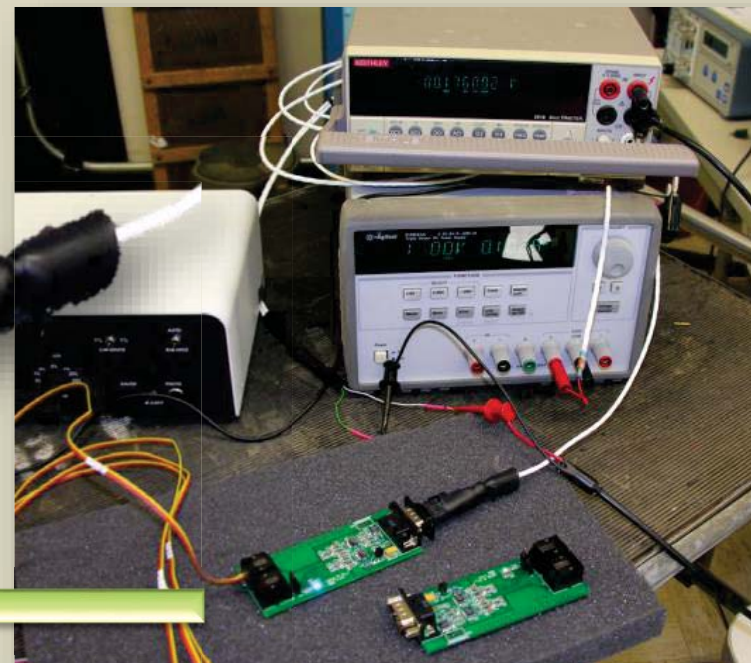
GAGE FACTOR (GF)	
	GF = (ΔR/Ri)/ε

COEFFICIENT (Coe)	
	Coe = 1/(I*Ri*Gain)

STRAIN (ε)	
	ε =Coe*Vo*GF’



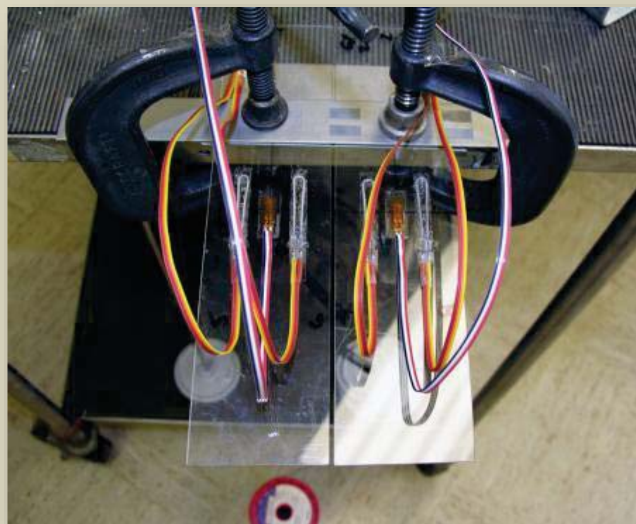
Constant Current PCB



Laboratory Cantilever Testing

Plexiglass Bending Beam

	Weight (lbs)	Strain (ue)
Leveled from ground (zeroed)	0	0
Clamps / Bracket (0.6lb)	0.6	1520
C&B (0.6ibs) / holder (1lb)	1.6	3460
C&B (0.6ibs) / holder (1lb) / weights (1.5lb)	3.1	5140
Leveled from ground	0	0

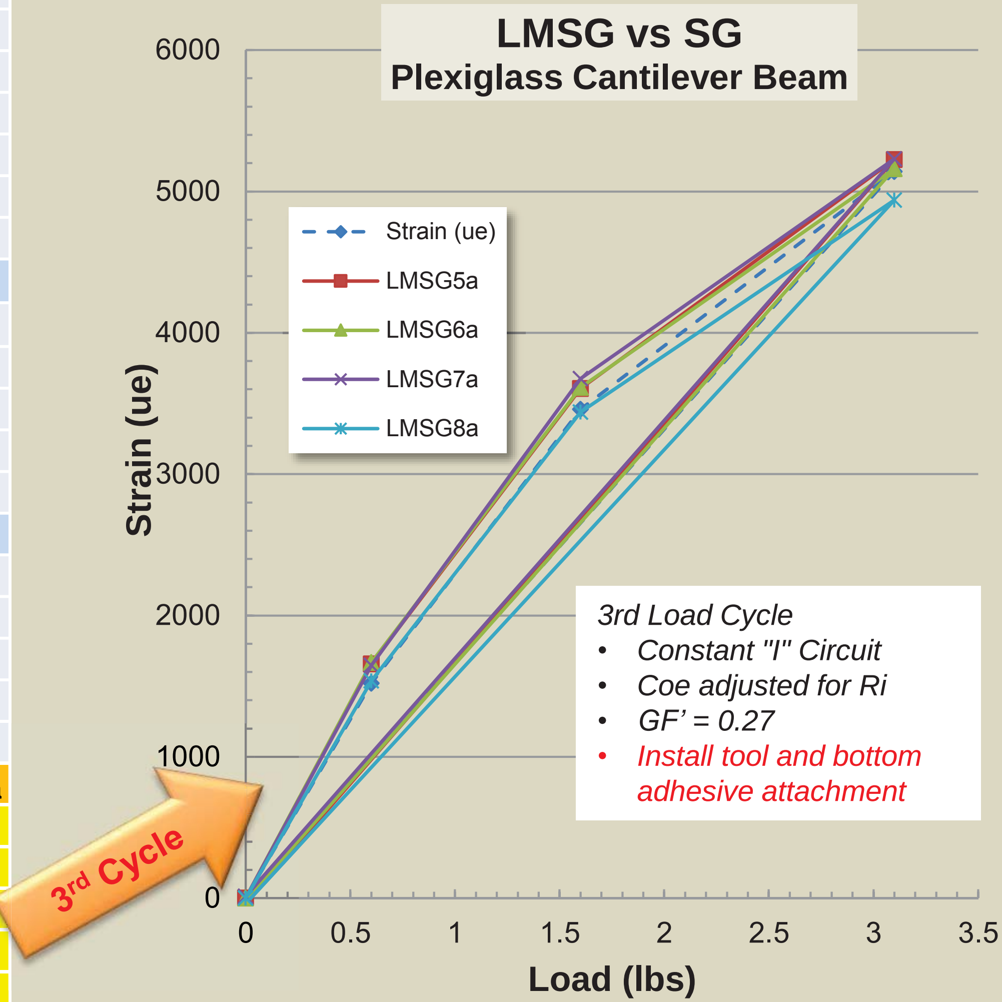


Plexiglass Substrate

Laboratory Cantilever Testing

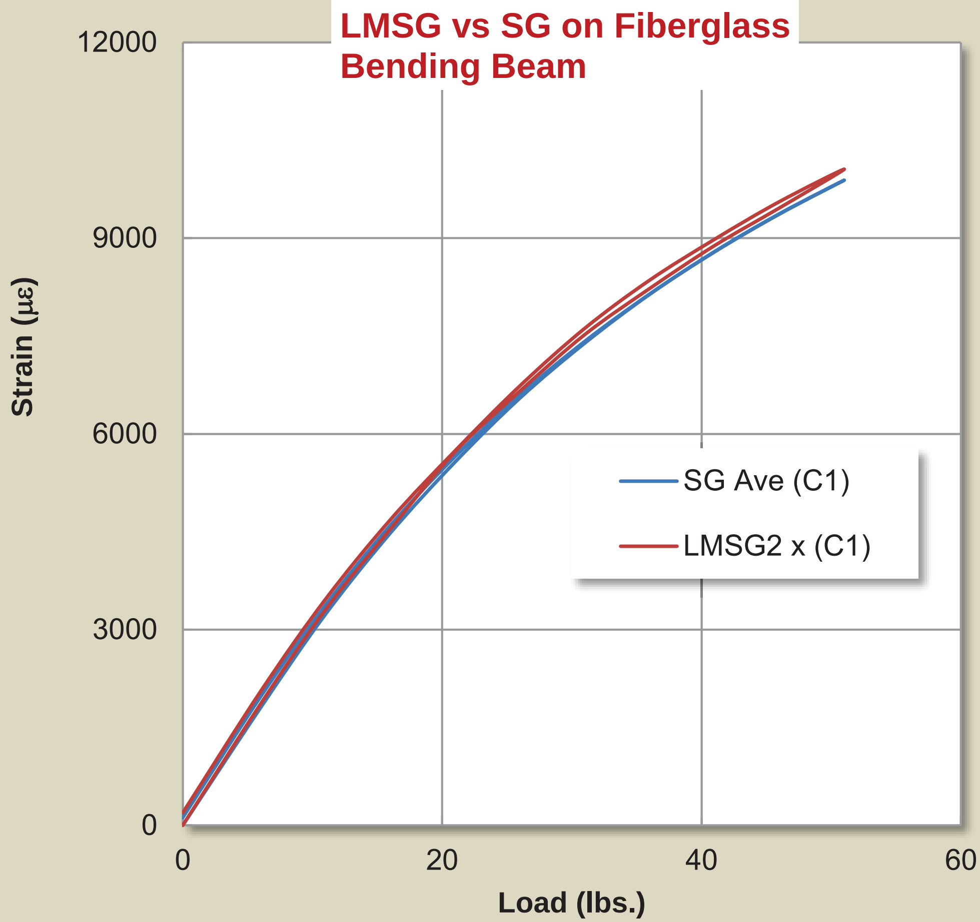
Plexiglass Bending Beam

	ε =Coe*Vout*GF'				
	Coe = 1/(I*Rinital*Gain)				
	I =	0.1			
Kelvin	Ri =	0.077	0.076	0.075	0.079
	Gain	2664.062			
	GF' =	0.27			
Strain (ue)	Strain (ue)	LMSG5	LMSG6	LMSG7	LMSG8
0	0	0	0	0	0
1550	1630	1672	1627	1635	1527
3450	3630	3699	3601	3649	3400
5000	5250	5265	5214	5257	4926
0	0	39	27	68	26
Strain (ue)	Strain (ue)	LMSG5	LMSG6	LMSG7	LMSG8
0	0	0	0	0	0
1520	1520	1658	1614	1581	1552
3460	3460	3685	3601	3581	3451
5140	5140	5225	5134	5216	4939
0	0	-13	-40	-41	0
Weight (lbs)	**Strain (ue)**	**LMSG5a**	**LMSG6a**	**LMSG7a**	**LMSG8a**
0	0	0	0	0	0
0.6	1520	1658	1667	1649	1539
1.6	3460	3606	3614	3676	3438
3.1	5140	5225	5161	5230	4939
0	0	-39	-13	14	-38



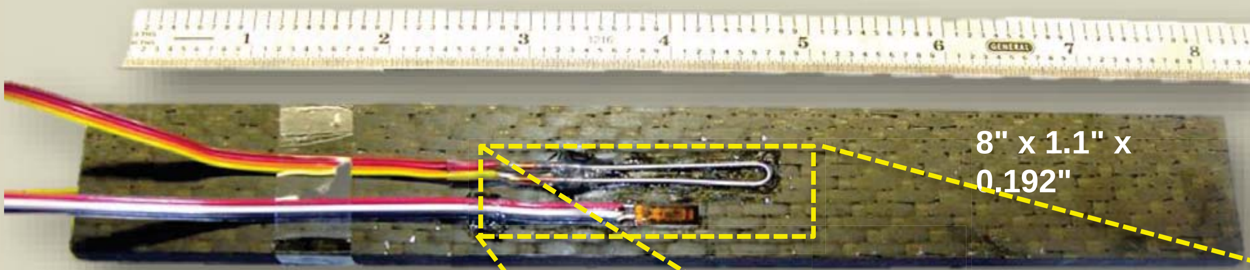
Laboratory Cantilever Testing

Fiber Glass Bending Beam



Laboratory Tensile Testing

Graphite Epoxy Tensile Bar

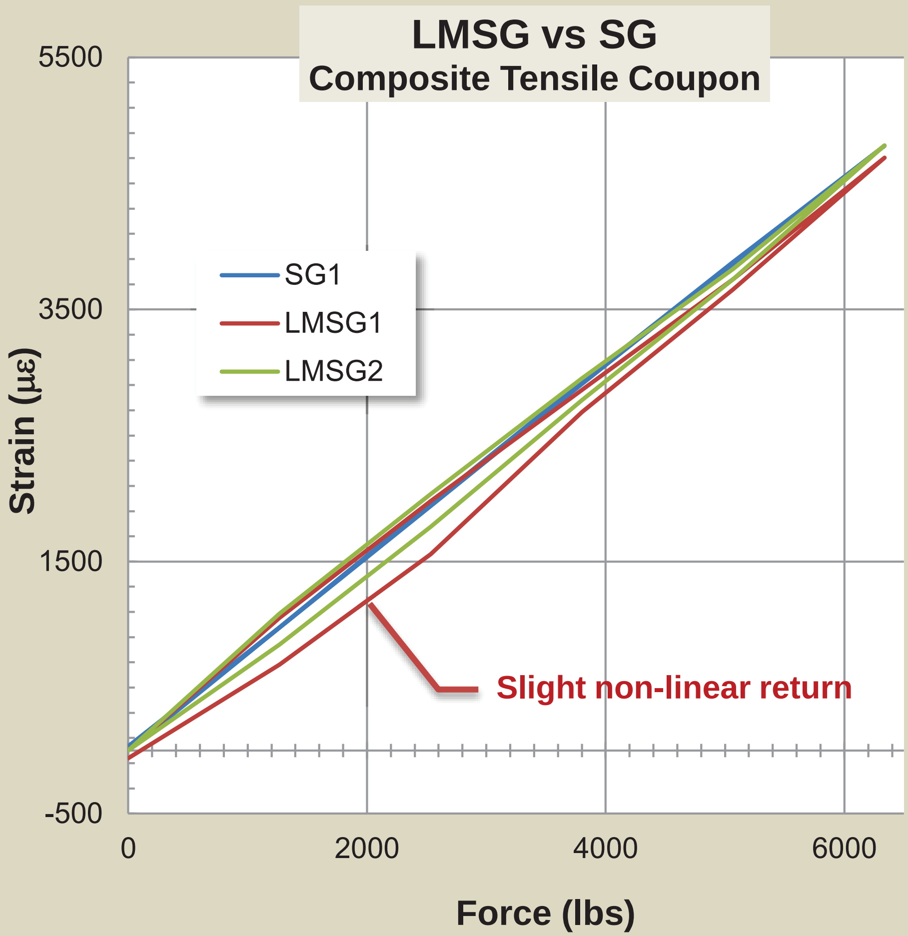


HOOK				
$\sigma=\varepsilon E$	and	$\sigma=F/A$		
$F/A=\varepsilon E$	»»	$F=\varepsilon AE$		
where				
σ	stress			
e	strain		Increment	0.001
F	force (lbs)			X
E	modulus (psi)			6000000
A	area (W"*H")	1.1	0.192	0.2112
		Ri =	0.869	0.0814
$F/1000\varepsilon\mu$ =	1267.2 lbs			

Laboratory Tensile Testing

Graphite Epoxy

STRAIN			
	ε = Coe*Vout*GF’		
	Coe = 1/(I*Rinital*Gain)		
	I =	0.1	
	Gain	2664.061596	
	GF’ =	0.51	
	Ri =	0.0869	0.0814
Load (lbs)	**SG1**	**LMSG1**	**LMSG2**
0	0	0	0
1267	975	1053	1087
2534	1940	1978	2037
3802	2909	2862	2954
5069	3864	3741	3822
6336	4798	4703	4802
5069	3877	3659	3742
3802	2928	2685	2780
2534	1961	1557	1776
1267	977	681	840
0	35	-59	0

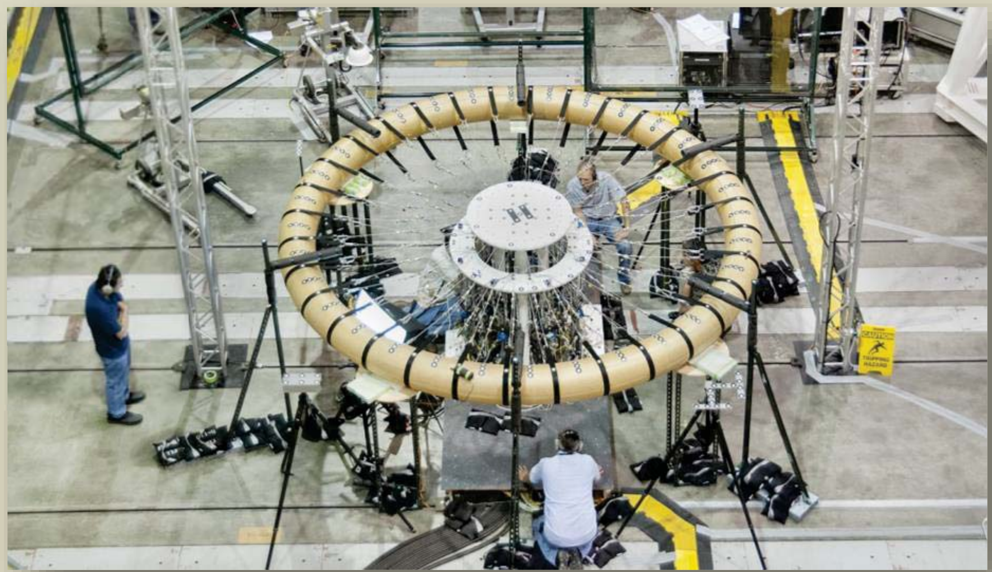


HIAD Torus Testing

Hypersonic Inflatable Aerodynamic Decelerator

Test Overview

- Six Tori were tested (from LaRC / UMaine)
- Kevlar reinforced rubber
- Tori diameters ranged from 11 to 14.5-ft
- Compression and torsion loads applied to cause in-plane and out-of-plane buckling
- Data used to improve *failure* models (takes no more load w/runaway displacements)

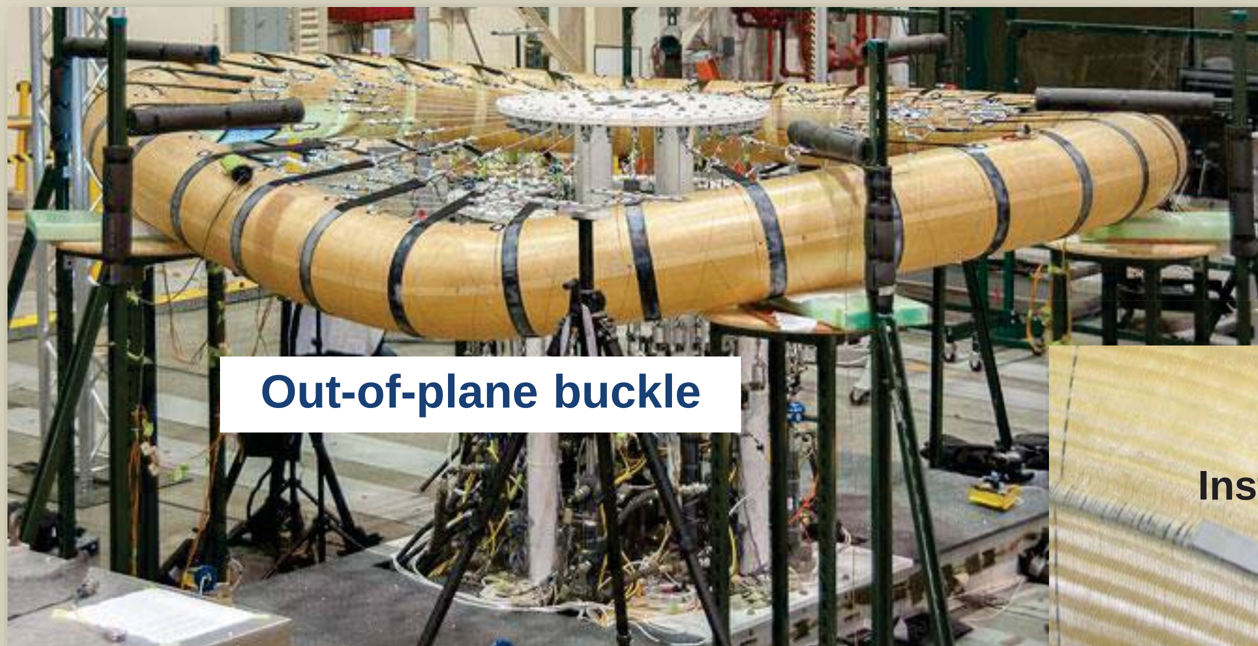


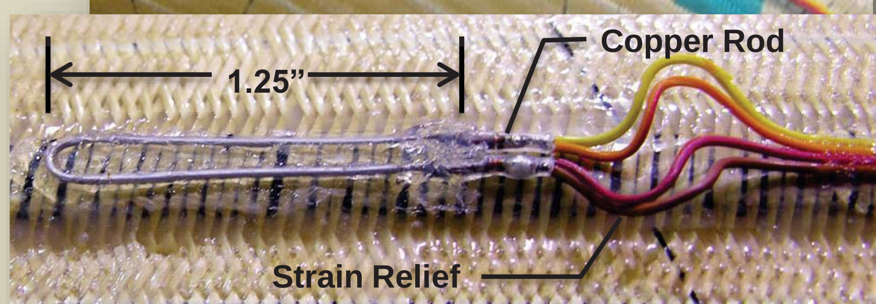
Instrumentation

- Eight string pots and 16 LRTs
- 64 load cells (16 controllers)
- Two photogrammetry systems:
  - — ARIMIS (strain)
  - — PONTOS (target displacement)
- 16 LMSGs per torus

http://www.nasa.gov/centers/armstrong/Features/HIAD_decelerator_system.html

HIAD Torus Installationε





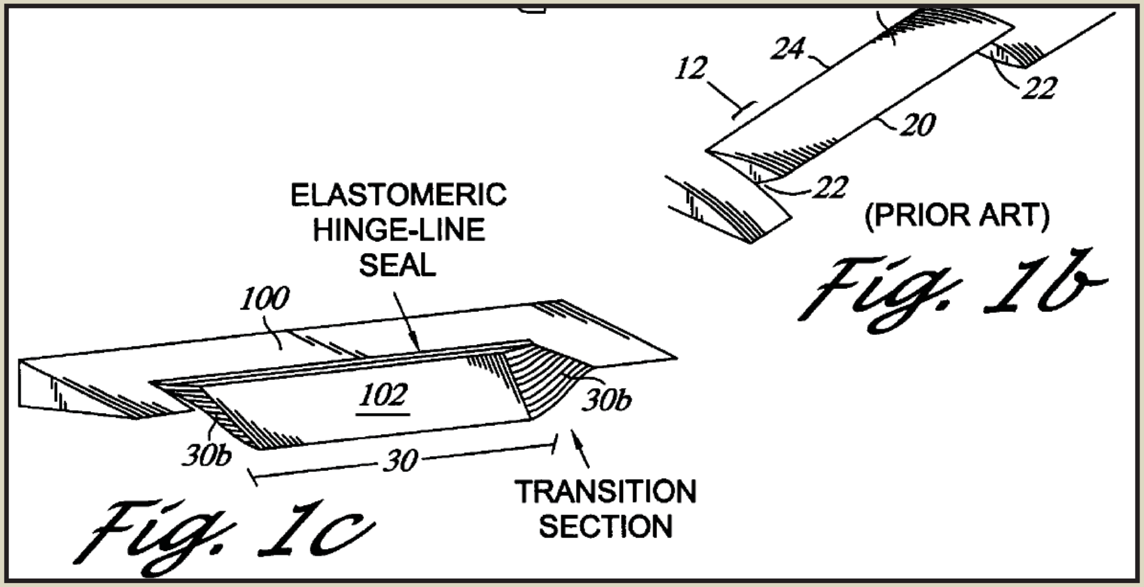
LMSGs

- High strains were not required (10,000 με), but structure possessed low elastic modulus
- Eight sensors on each upper and lower cord
- Measured strain to buckle (failure)
- Strains matched well with PONTOS Photogrammetry system

Elastomer Testing

Current AFRC Elastomer Projects

- NASA / AFRL Adaptive Compliant Trailing Edge
- AFRC CIF “Fundamental Research into Hyperelastic Materials for Flight Applications” – PI Eric Miller



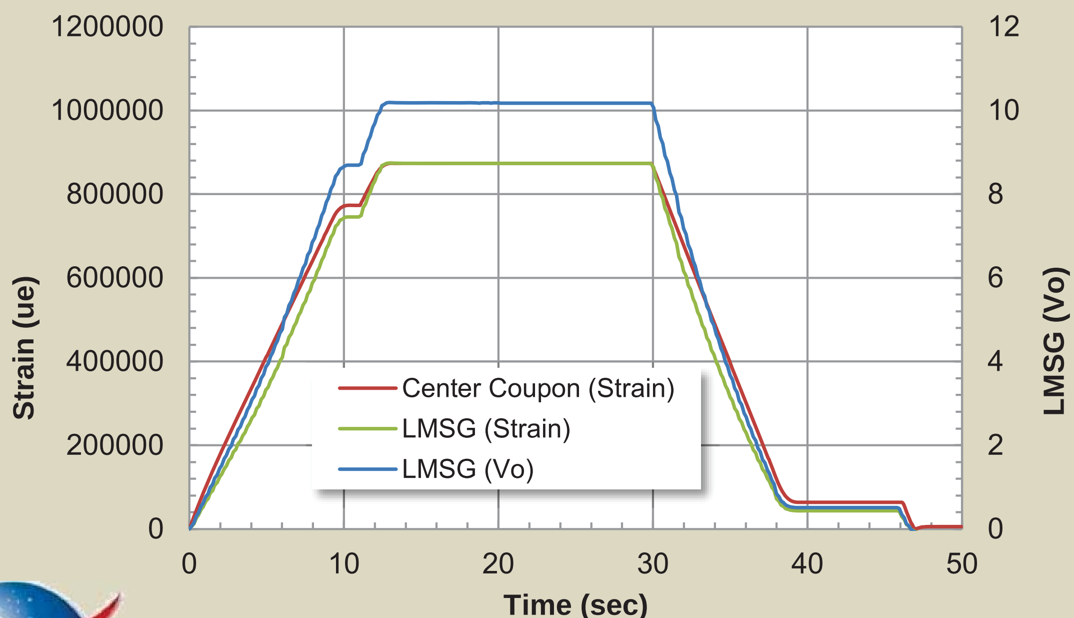
Diller, Joseph B. Miller, Nicholas F. 1998. Elastomeric Transition for Aircraft Control Surface. U.S. Patent 6,145,791, filed January 9, 1998, and issued November 14, 2000.

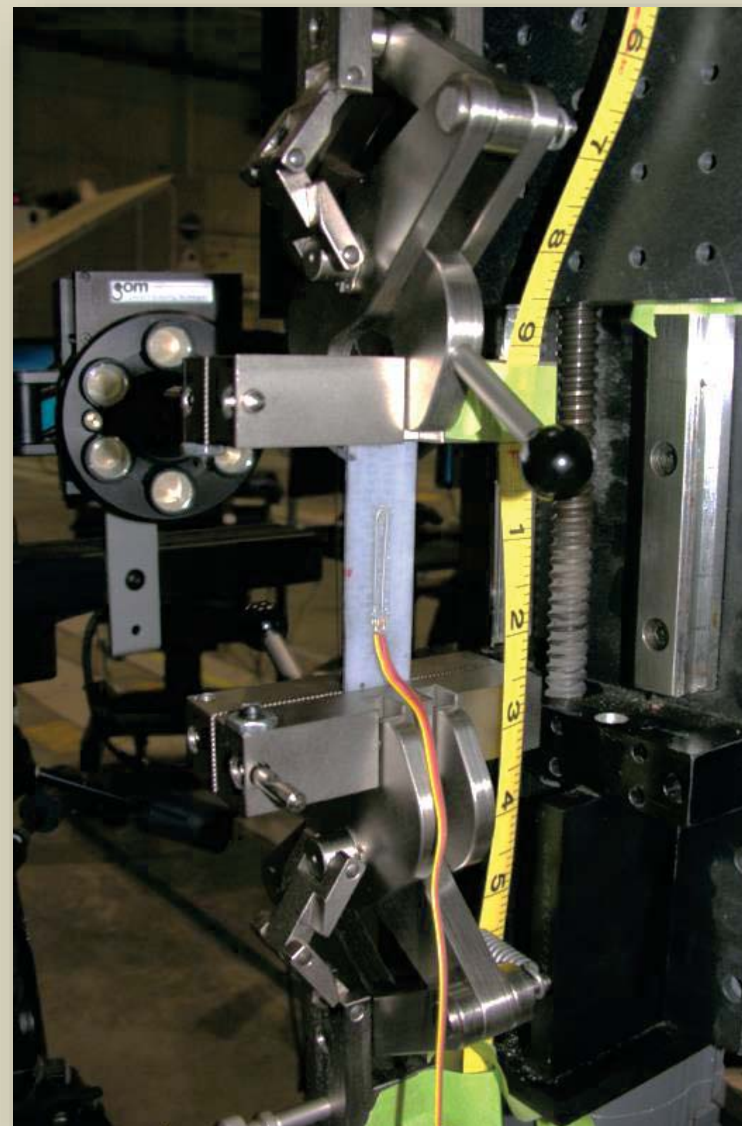
Elastomer Tensile Testing

Photogrammetry

GL determined using Aramis for coefficient

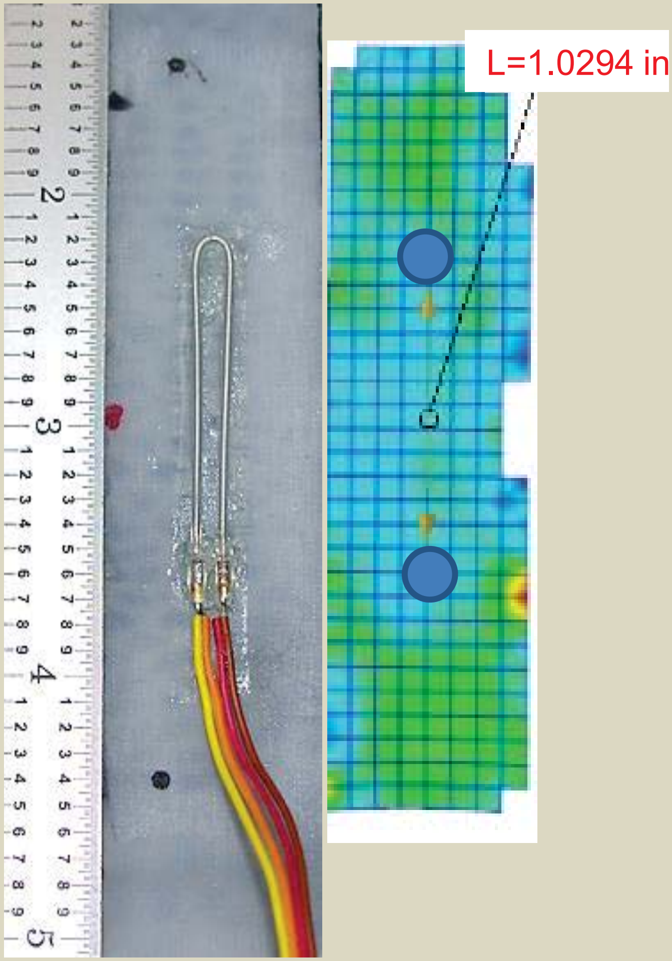
- Load was stopped approximate at doubling of GL using scale real-time
- Post test photogrammetry data was used to precisely determine strain at center of coupon
- Determined prelim strain coefficient: y=85804x
- LMSG slightly non-linear, second order poly will be determined and applied after first coupon

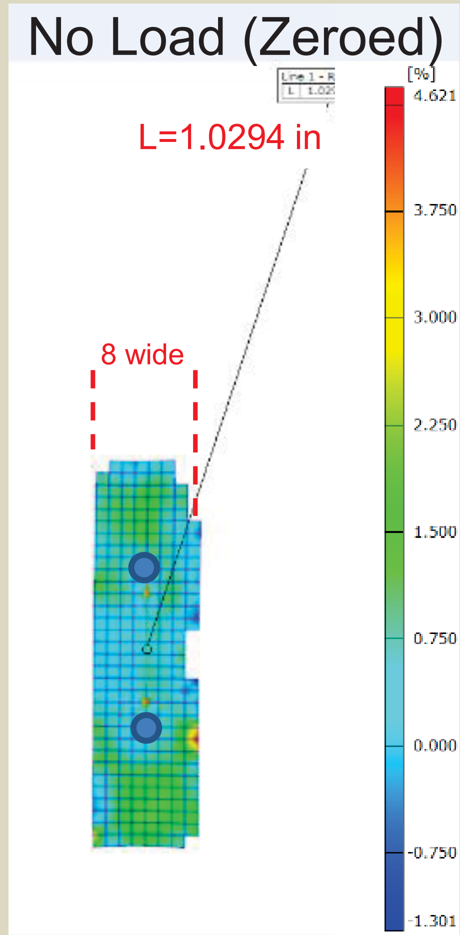


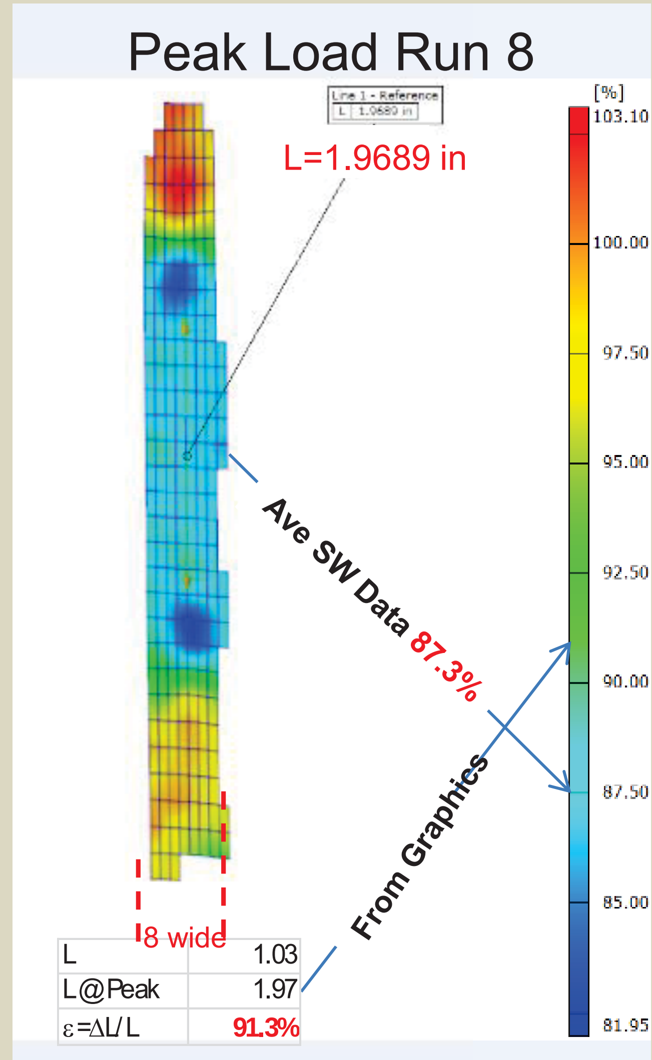


Elastomer Tensile Testing

Photogrammetry



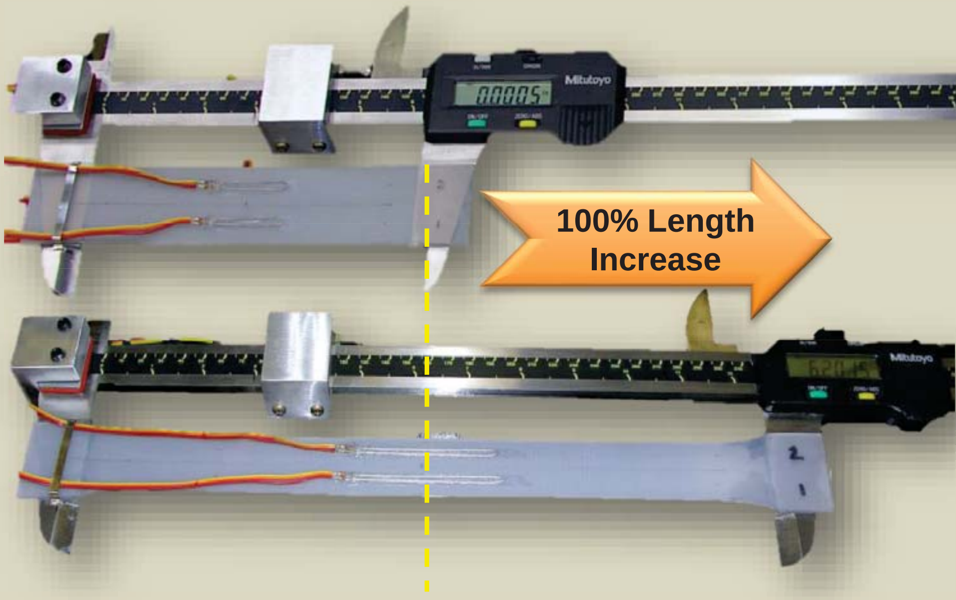




- Slightly different strain value when using the graphics vs. displacement output
- During these tests stiffening was minimized to be negligible

Elastomer Tensile Testing

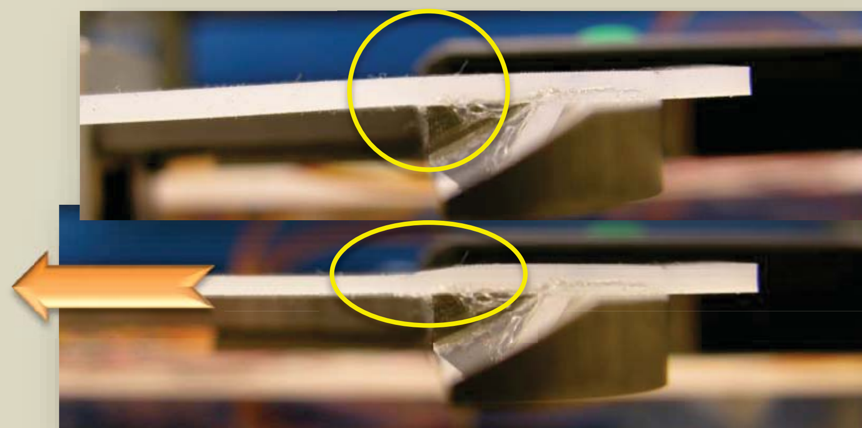
Length Based with Caliper



Nominal Strain	Nominal Strain	LMSG 1 (ΔL)	LMSG 2 (ΔL)	LMSG 1 GF	LMSG 2GF
	0	0	0		
0.5	3.1250	0.0919	0.0862	2.10	2.00
1	6.2500	0.2288	0.2170	2.61	2.52
	Initial R	0.0875	0.0862		

Observations from elastomer testing

- Cycle-to-cycle repeatability was excellent though gage-to-gage scatter was 5-6%
- Coefficient changed slightly over time, believed to be changes in bond at fixation
- Though direct bond fixation better than grips, true strain with photogrammetry more actuate than measured ΔL when determining GF

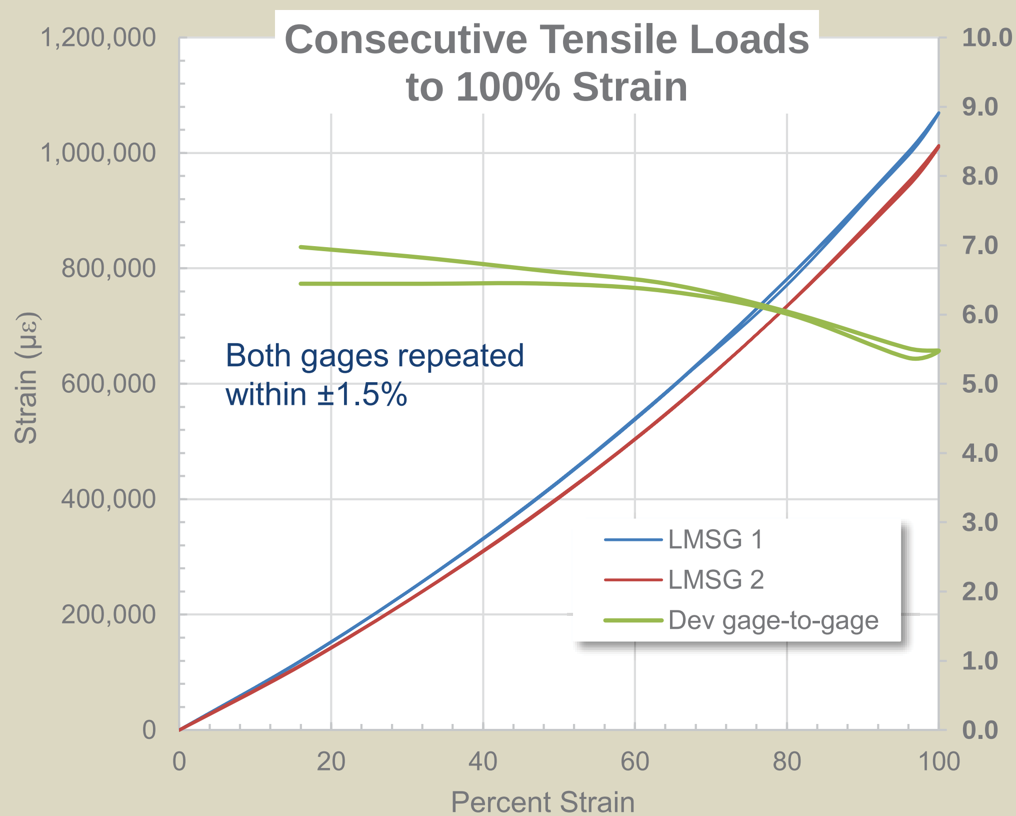


Elastomer Tensile Testing

Length Based with Caliper

	Start L = 6.250 in					
% Strain	Delta (in) Nominal	Delta (in) Actual	LMSG 1	LMSG 2	Dev Gage-to-Gage	
0	0 (Zeroed)	0.000	0	0		
16	1	1.001	119,876	112,150	6.44%	
32	2	2.003	256,520	239,990	6.44%	
48	3	3.000	409,390	383,000	6.45%	
64	4	4.000	583,150	546,180	6.34%	
80	5	5.005	781,290	734,320	6.01%	
96	6	5.998	995,940	942,420	5.37%	
100	6.25	6.251	1,069,280	1,010,720	5.48%	
96	6	5.999	998,900	943,850	5.51%	
80	5	5.005	781,370	734,150	6.04%	
64	4	3.999	584,700	547,000	6.45%	
48	3	2.996	409,820	382,640	6.63%	
32	2	2.006	256,990	239,460	6.82%	
16	1	0.999	119,160	110,850	6.97%	
0	0	0.000	-550	-700		
					Dev Repeatability	
0	0 (Zeroed)	0.000	0	0	LMSG 1	LMSG 2
16	1	1.000	120,130	112,240	-0.21%	-0.08%
32	2	2.003	257,270	240,570	-0.29%	-0.24%
48	3	3.003	411,250	385,050	-0.45%	-0.54%
64	4	4.002	582,920	546,060	0.04%	0.02%
80	5	5.002	781,250	735,000	0.01%	-0.09%
96	6	6.003	1,002,700	950,310	-0.68%	-0.84%
100	6.25	6.250	1,069,840	1,013,010	-0.05%	-0.23%
96	6	6.002	1,001,200	947,960	-0.23%	-0.44%
80	5	4.999	770,870	734,580	1.34%	-0.06%
64	4	4.000	584,750	547,750	-0.01%	-0.14%
48	3	3.000	411,010	384,270	-0.29%	-0.43%
32	2	2.002	256,920	240,230	0.03%	-0.32%
16	1	1.001	120,020	112,480	-0.72%	-1.47%
0	0	0.000	-80	270		

LMSG RT Elastomer Tensile Test
24-in Caliper
Dow Corning 3145 bond to caliper
Power supply to constant current PCB: 15VDC @ 0.208A
Coe: 105000



Summary

- Successfully adapted current Plethysmography liquid metal strain gage technology for Aerostructures
  - Highly elastic strain sensor (>100%), negligible stiffening
  - In-house designed signal conditioning
  - Excellent repeatability
  - Good scatter
  - If photogrammetry tests confirm nonlinearity, 2^{nd} order poly will be used
- Sensor and leadwire attachments developed
  - Initial resistance critical, devised stake-down tool
  - Minimal base adhesive used to minimize local stiffening (do not encapsulate)
  - Leadwire handling critical in avoiding unwanted induced strains
- LMSGs successfully used during HIADs testing on Kevlar enforce rubber substrate (seven tori instrumented with 16 LMSGs each)
- Completion of photogrammetry evaluation and maximum strain testing to be accomplished in near-future