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Measurement of mechanical properties of three epoxy adhesives at cryogenic temperatures for CCD construction

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Abstract

Materials testing of an adhesive for bonding Silicon to a substrate is presented. Test results include Young's Modulus, Poisson's Ratio, and the coefficient of thermal expansion at temperatures ranging from room temperature to 100 K. Data for 3 epoxies (Tra-Con F113, Epotek 301-2, Hysol 9361) are presented.

1 Introduction

The SNAP CCD focal plane has to meet stringent performance requirements, especially on flatness. As the CCDs are manufactured at room temperature and will operate at 130 K in space, it is necessary to characterize their behavior as a function of temperature. In addition, it is expected that the CCD focal plane will undergo thermal cycles in space. As the construction materials (Si, AlN, SiC) have different coefficients of thermal expansion (CTE), there may be stress on all of the epoxy joints. NASA has criterion on the stress/strength relation for such joints [1]. This note details tensile strength tests and coefficient of thermal expansion measurements on proposed epoxies for use in the CCD assembly.

Tensile strength tests to measure Young's Modulus and Possion's Ratio [2] were performed at Precision Measurements and Instruments Corporation (PMIC) [3] at 5 temperatures (295K, 250K, 200K, 150K, 100K). An additional measurement was made at Fermilab at 295K. Measurements of the CTE from 77 K to 295 K were made at Fermilab.

Three epoxies were measured, Hysol 9361, Tra-Con F113, and Epotek 301-2. The Hysol is being considered for the AlN-SiC joint, the Tra-Con and Epotek for the CCD-AlN joint. In Table 1, we summarize the properties of the glue joints as reported by the manufacturer.

The Hysol sets in 24 hours, with a full cure in 7 days at room temperature. The epoxy samples used in the tensile strength tests had a 7 day cure. For the Hysol CTE measurements, we used a sample with am accelerated 2 day cure. For the Epotek and Tra-Con CTE measurements, measurements were made with samples with both a 2 day cure and a 7 day cure. The Epotek epoxy has an additional manufacturing specification on residuals ions (salts) in the resin which is important for silicon bonding applications.

Epoxy	Modulus	Viscosity	CTE @ 295 K
Hysol 9361	723 MPa	1000 Pa s	-
Tra-Con F113	-	180 cps @25 C	55 ppm/C
Epotek 301-2	-	225-425 cps	37 ppm/C

Table 1: Epoxy properties as provided by the manufacturers.

Ambient

Tra-Con F113	Elastic Modulus (psi)	356886± 12523	3.51%
	Poisson's Ratio	0.401±0.003	0.64%
	Maximum Stress (psi)	2539± 86	3.40%
Epotek 301-2	Elastic Modulus (psi)	531427± 6166	1.16%
	Poisson's Ratio	0.358±0.001	0.35%
	Maximum Stress (psi)	3751± 45	1.21%
Hysol 9361	Elastic Modulus (psi)	154678± 1526	0.99%
	Poisson's Ratio	0.433±0.007	1.67%
	Maximum Stress (psi)	1153± 9	0.77%

Table 2: Epoxy properties as measured at ambient temperatures.

2 Tensile Tests

Tensile tests were performed by PMIC and also the Fermilab Material Testing Group. Both tests used samples prepared at Fermilab. The samples were dogbone shaped and machined out of cast plates of epoxy. The samples were degassed to minimize the number and size of air bubbles. We note that the Hysol samples did have visible bubbles on the machined surfaces.

PMIC measurements were performed per ASTM method D-638. Five dogbones of each epoxy were measured at 5 temperatures (295K, 250K, 200K, 150K, 100K). The sample modulus was calculated using the Secant Method at a 0.68% strain (or the highest strain achieved if the sample failed before that level). The Hysol samples did fail before 0.68% strain was achieved for the lower temperature measurements. Tables 2, 3, 4, 5, and 6 summarize the measurements. The full report from PMIC is included as Appendix 1.

The Fermilab Material Testing group also performed a tensile measurement at ambient temperature on the three epoxies. The steepest slope over a series of ranges was used to calculated

250 K

Tra-Con F113	Elastic Modulus (psi)	519361± 16547	3.19%
	Poisson's Ratio	0.372 ± 0.005	1.25%
	Maximum Stress (psi)	3527± 120	3.41%
Epotek 301-2	Elastic Modulus (psi)	595903± 16547	3.19%
	Poisson's Ratio	0.365 ± 0.004	1.05%
	Maximum Stress (psi)	4115± 79	1.91%
Hysol 9361	Elastic Modulus (psi)	239242± 4375	1.83%
	Poisson's Ratio	0.435 ± 0.004	1.02%
	Maximum Stress (psi)	1736± 35	2.02%

Table 3: Epoxy properties as measured at 250 K.

200 K

Tra-Con F113	Elastic Modulus (psi)	615588± 26807	4.35%
	Poisson's Ratio	0.368 ± 0.003	0.69%
	Maximum Stress (psi)	4272± 198	4.64%
Epotek 301-2	Elastic Modulus (psi)	648860± 12482	1.92%
	Poisson's Ratio	0.349 ± 0.005	1.32%
	Maximum Stress (psi)	4471± 99	2.22%
Hysol 9361	Elastic Modulus (psi)	560786± 11976	2.14%
	Poisson's Ratio	0.357 ± 0.005	1.27%
	Maximum Stress (psi)	3912± 84	2.15%

Table 4: Epoxy properties as measured at 200 K.

150 K

Tra-Con F113	Elastic Modulus (psi)	886035± 40429	4.56%
	Poisson's Ratio	0.367 ± 0.008	2.28%
	Maximum Stress (psi)	5983± 264	4.42%
Epotek 301-2	Elastic Modulus (psi)	833220± 14089	1.69%
	Poisson's Ratio	0.334 ± 0.007	2.16%
	Maximum Stress (psi)	5681± 106	1.87%
Hysol 9361	Elastic Modulus (psi)	822654± 14072	1.71%
	Poisson's Ratio	0.357 ± 0.012	3.46%
	Maximum Stress (psi)	4641± 79	1.71%

Table 5: Epoxy properties as measured at 150 K.

100 K

Tra-Con F113	Elastic Modulus (psi)	1105895± 40675	3.69%
	Poisson's Ratio	0.348 ± 0.005	1.44%
	Maximum Stress (psi)	7092± 649	9.15%
Epotek 301-2	Elastic Modulus (psi)	1014310± 14384	1.42%
	Poisson's Ratio	0.350 ± 0.008	2.34%
	Maximum Stress (psi)	6783± 162	2.39%
Hysol 9361	Elastic Modulus (psi)	1132056± 13051	1.19%
	Poisson's Ratio	0.353 ± 0.016	4.55%
	Maximum Stress (psi)	4225± 201	4.76%

Table 6: Epoxy properties as measured at 100 K.

	Ambient		
Tra-Con F113	Elastic Modulus (ksi)	384.84 ±85.7	22.2%
	Ultimate Tensile Strength (psi)	4798.2±569.1	11.9%
Epotek 301-2	Elastic Modulus (ksi)	650.6± 176.2	% 27.1
	Ultimate Tensile Strength (psi)	9664.2±1769.6	18.3%
Hysol 9361	Elastic Modulus (ksi)	137.5± 17	12.3%
	Ultimate Tensile Strength (psi)	2400.4± 190.6	7.94%

Table 7: Epoxy properties as measured at ambient temperatures by the Fermilab Material Properties Testing group.

the modulus. The crosshead pull speed was greater than 0.05 inches per minute. The results are summarized in Table 2.

3 Coefficient of Thermal Expansion Measurements

CTE measurements were made at Fermilab. The measurements were performed in the spirit of ASTM-E831. Samples were approximately 8 mm × 8 mm × 20 mm, machined from samples cast in a mold. Each sample was vacuum degassed during the casting to minimize the size and number of trapped gas bubbles.

The CTE was measured by placing the sample in a holder inside of a cryostat. Liquid nitrogen is poured into the cryostat. Once the temperature stabilized at 77 K, a heater is used to ramp the temperature to ambient temperature with a rate of 1-2deg C/minute. An LVDT [4] at the top of the sample measured the change in sample length. The length and temperature were recorded during the cooldown and the warmup. In Figure 1, we show a picture of the sample in the holder. The LVDT is at the top of the picture, connected via quartz rods to the sample holder. The sample holder is installed inside the cryostat. We report the integral fractional change in length (dL/L) of the sample as a function of temperature in Table 8. In Figures 2, 3, and 4, we show the fractional change in length as a function of temperature for one sample of Tra-Con F113, Epotek 301-2, and Hysol 9361. In Figure 5, we show a representative time ramp for one of the measurements.

4 Stress/Strength Ratios

The NASA guideline for epoxy joints [1] is a safety margin of a factor of 2 on the stress. With the measured modulus and CTE, we can calculate the expected stress on the joint and compare to yield strength, using the following logic:

$$\begin{aligned} \mathrm{Modulus} &= \frac{\mathrm{Stress}}{\mathrm{Strain}} \\ \mathrm{Strain} &= \frac{\mathrm{dL}}{\mathrm{L}} \\ \frac{\mathrm{dL}}{\mathrm{L}}\ (\mathrm{epoxy}) &= \mathrm{CTE\ (epoxy)} \times \Delta\mathrm{T} \end{aligned} \tag{1}$$

With the assumption that the CTE of the substrate is small compared to the epoxy, the stress on the joint is simply:

$$\mathrm{Stress} = \mathrm{Modulus} \times \mathrm{CTE\ (epoxy)} \times \Delta\mathrm{T} \tag{2}$$

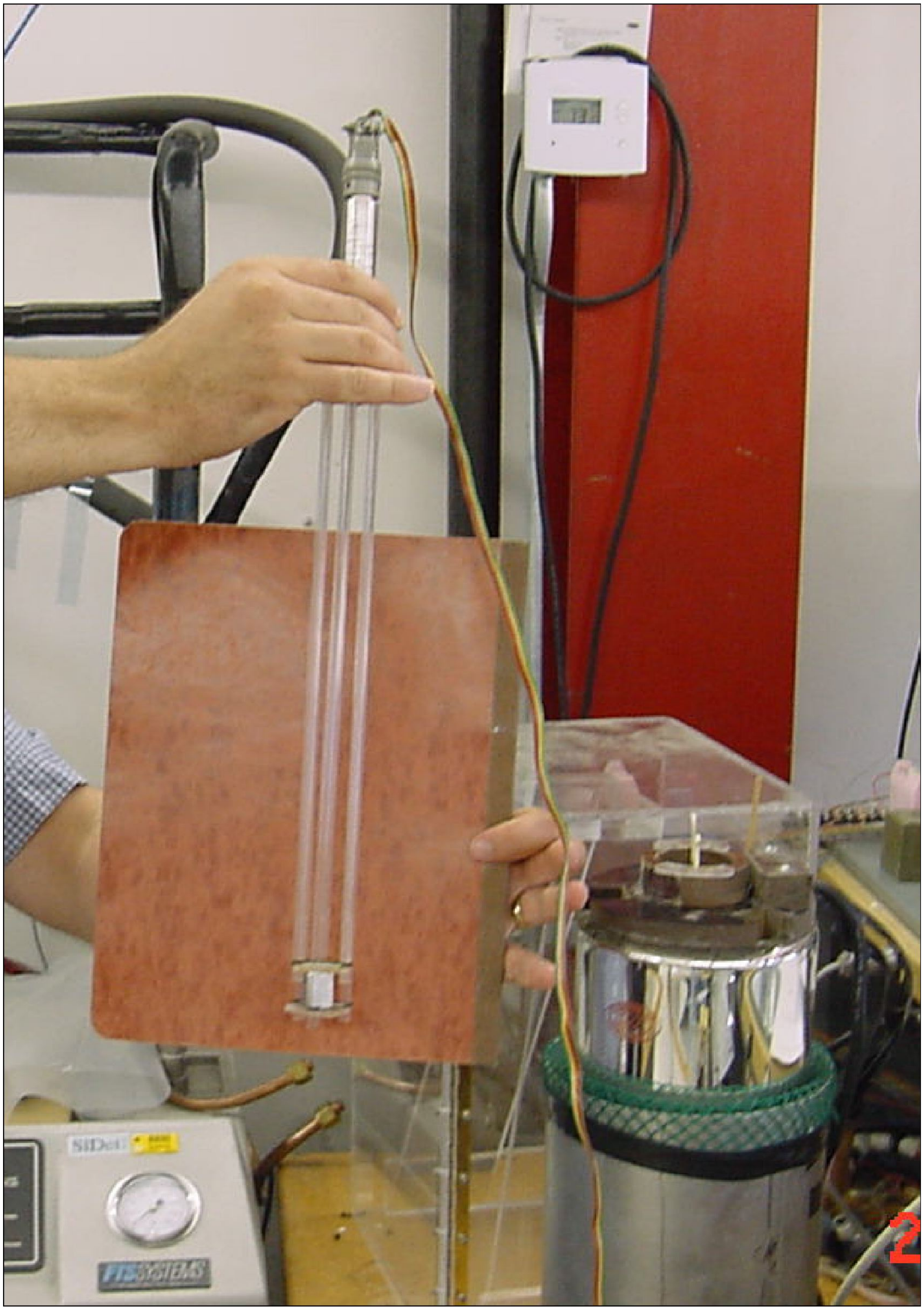

Figure 1: The sample holder for use in the dL/L measurements.

Ambient Temperature		
Tra-Con F113 dL/L ($\times 10^{-3}$)	–	–
Epotek 301-2 dL/L ($\times 10^{-3}$)	–	–
Hysol 9361 dL/L ($\times 10^{-3}$)	–	–
250 K		
Tra-Con F113 dL/L ($\times 10^{-3}$)	-3.27 $\pm$ 0.13	3.94%
Epotek 301-2 dL/L ($\times 10^{-3}$)	-2.83 $\pm$ 0.04	1.52%
Hysol 9361 dL/L ($\times 10^{-3}$)	-4.69 $\pm$ 0.04	0.8%
200 K		
Tra-Con F113 dL/L ($\times 10^{-3}$)	-6.20 $\pm$ 0.11	1.73%
Epotek 301-2 dL/L ($\times 10^{-3}$)	-5.45 $\pm$ 0.03	0.59%
Hysol 9361 dL/L ($\times 10^{-3}$)	-8.69 $\pm$ 0.02	0.3%
150 K		
Tra-Con F113 dL/L ($\times 10^{-3}$)	-8.71 $\pm$ 0.06	0.76%
Epotek 301-2 dL/L ($\times 10^{-3}$)	-7.70 $\pm$ 0.11	1.37%
Hysol 9361 dL/L ($\times 10^{-3}$)	-11.3 $\pm$ 0.003	0.2%
100 K		
Tra-Con F113 dL/L ($\times 10^{-3}$)	-10.7 $\pm$ 0.08	0.72%
Epotek 301-2 dL/L ($\times 10^{-3}$)	-9.66 $\pm$ 0.18	1.88%
Hysol 9361 dL/L ($\times 10^{-3}$)	-13.3 $\pm$ 0.03	0.2%

Table 8: Integral dL/L for the three epoxies as measured at the 5 temperatures.

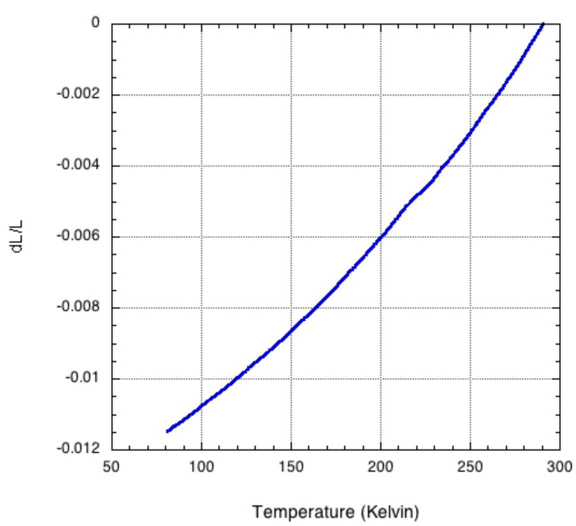

Figure 2: The integral dL/L vs temperature for a representative Tra-Con F113 sample.

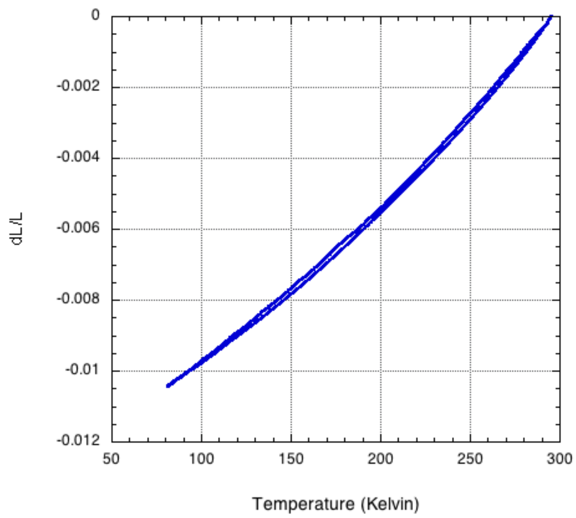

Figure 3: The integral dL/L vs temperature for a representative Epotek 301-2 sample.

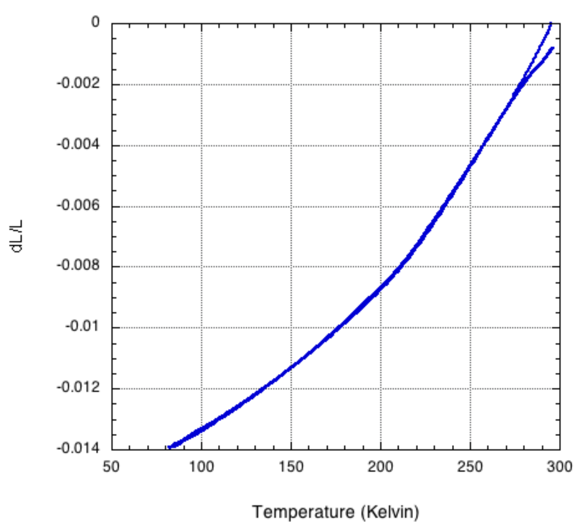

Figure 4: The integral dL/L vs temperature for a representative Hysol 9361 sample.

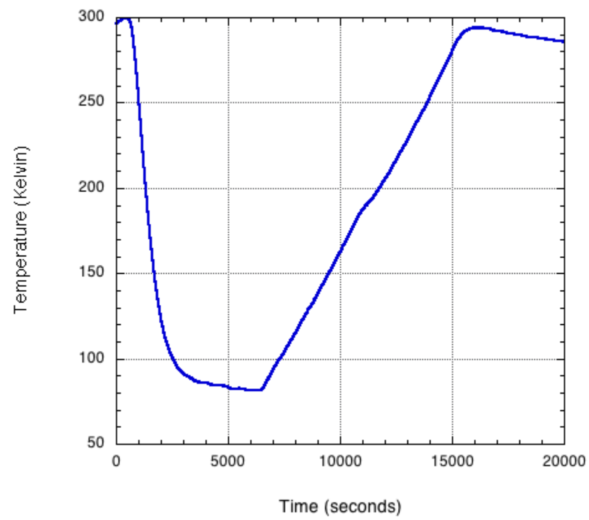

Figure 5: The temperature vs time for a representative CTE measurement.

	Ambient	250 K	200 K	150 K	100 K
Tra-Con F113	–	2.8	1.1	0.76	0.65
Epotek 301-2	–	5.9	2.7	1.5	1.0
Hysol 9361	–	2.1	0.83	0.5	0.29

Table 9: The ratio of strain to stress as defined in equation 3.

A criterion that the yield strength must be more than twice the stress leads to the requirement that

$$\frac{\text{yield strength (epoxy)}}{\text{Modulus} \times \text{CTE (epoxy)} \times \Delta\text{T}} > 2. \tag{3}$$

The stress reported in the data sets is not the epoxy yield strength, it is the strength at 0.68% strain. A conservative guideline can still be determined if the maximum stress achieved is used in the calculations as a proof stress. We will use either the room temperature ultimate strength or the maximum stress applied to the sample at temperature, whichever is larger. As the strength is known to increase with decreasing temperature, this selection is a conservative approach. In Table 9, we show the ratio of strength over stress as defined above.

The Epotek has the lowest bond strain and, at ambient temperature, the highest ratio of maximum strength to strength at 0.68%. Although none of the epoxies meet the criteria for temperatures below 200 K, it does not mean the joint will fail. We have chosen to take a conservative approach in the calculation of the maximum stress. In addition, the tensile strength data collected was taken at high pull rates (0.10 inch/minute for the PMIC tests). Epoxies, as with most plastics, are visco-elastic materials which respond differently based on how quickly the load is transferred to the material. The high rates of strain applied to the samples during testing will have a much higher modulus and stress than in the actual application. During flight, the CCD focal plane will have a cool down rate of 3 degrees per minute, taking at least 20 minutes to achieve operating temperature and allowing the epoxy to creep and relieve some

of the stresses.

5 Conclusions

We have presented measurements on epoxy properties for use in the SNAP CCD assembly, covering temperatures from ambient to 100 K. Test results on Young's Modulus, Poisson's Ratio, and integral dL/L have been presented. A criterion for the epoxy has been proposed.

References

[1] NASA-STD-5001 - Structural Design and Test Factors of Safety for Spaceflight Hardware

[2] Young's Modulus is the ratio of tensile stress to tensile strength and is a measure of how a material changes length under tension or compression. Poisson's Ratio is defined as the strain normal to an applied load divided by the strain in the direction of the applied load and is a measure of the material's tendency to get thinner as it is stretched or thicker as it is compressed.

[3] Precision Measurements and Instruments Corporation, 3665 SW Deschutes Street, Corvallis, OR 97333

[4] LVDT stands for Linear Variable Differential Transformer, outputting a voltage dependent upon physical displacement.

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PURCHASE ORDER NUMBER 565015

ELASTIC PROPERTY MEASUREMENTS OF EPOXY SPECIMENS

February 28, 2006

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ELASTIC PROPERTY MEASUREMENTS OF EPOXY SPECIMENS

WORK CONDUCTED FOR FERMILAB
PURCHASE ORDER NUMBER 565015

February 28, 2006

Precision Measurements and Instruments Corporation measured the elastic properties of 75 epoxy resin specimens. Coupons were prepared for Modulus testing and Poisson's Ratio testing. Testing was conducted at 100K, 150K, 200K, 250K and ambient temperatures. Testing was performed per ASTM method D-638. Results are presented in the attached tables. A brief description of the test procedure, data analysis and comments on the results follow.

Specimen Description

Fermilab provided the following specimens.

Quantity	Description	Length	Width	Thickness
35	Tranon F113	8.0"	1.0"	0.125"
30	Epo-Tek 301-2	8.0"	1.0"	0.125"
33	Hysol ES 8561	8.0"	1.0"	0.125"

Test Procedure

- Specimen Check-In

The specimens were received on December 19th, January 11th and January 12th, via Federal Express. The specimens were inspected for damage. No damage was observed. However, it was noted that the Hysol specimens had bubbles visible on the machined surfaces. The specimens were stored at room temperature prior to measurement. A complete list of the specimens is located at the end of the report.

- Specimen Preparation

The specimen preparation and strain gage attachment procedures suggested by the strain gage supplier were followed. Micro Measurements CEA-06-125UT-350 strain gages were used for both axial and lateral strain measurement on the specimens. Strain gages were bonded to each side of the specimen at corresponding positions, using Micro-Measurements M-Bond AE-10 adhesive. The specimens were clamped and cured for 6+ hours at ≈95°F. Each gage was then wired in series to the corresponding gage on the opposite surface to account for specimen bending. In a few cases the strain gages were shifted axially on the specimen to avoid placing them close to the bubbles.

- Test Procedure

The tensile test machine crosshead speed was set to 0.10 inch/minute. 2 VDC strain gage excitation was used. The specimens were first secured in the machine with the top wedge grip, centered and aligned with the direction of force. For the low temperature tests thermocouples

were placed at three points in the vicinity of the strain gages. The gauge portion of the specimen was enclosed in an insulated chamber. Liquid nitrogen was used to achieve cooling for the 100 K, 150 K, 200 K and 250 K tests. The cryogen was directed close to the proximity of the specimens on either side by dual spray bars. Approximately 20-60 minutes was allowed for the specimens to equilibrate at the desired temperatures. At this point the strain gage conditioning circuitry was balanced, the lower wedge grip tightened and the test started. The load was applied to the specimens by movement of the upper grip until the limits of the strain gage were reached, failure occurred, or the specimens began to yield outside of the gauge section. Load, strain and temperature data were recorded every half second.

- Analysis

The various elastic properties were calculated over certain strain ranges selected to coincide with a level obtained by all, or nearly all, specimens. The first data point used for all calculations was generally the first positive point after all slack was removed. The last data point was generally the limit of the axial strain gage/electronics, ~6800 µ-in/in. In some cases the last point was limited by breakage or yielding outside of the temperature controlled zone. In a few cases the endpoints were shifted somewhat due to unusual temperature fluctuations. The secant modulus was calculated by taking the change in axial stress divided by the change in axial strain between the chosen endpoints. Poisson's Ratio was calculated by using the change in transverse strain divided by the change in axial strain at the same endpoints. The nominal dimensions were used in all of the calculations.

Test Results

The results are presented in tabular format in **Table 1**. The stress and strain of the maximum endpoint at which each property is calculated are listed with the results. The properties may be determined for other strain ranges. The raw stress and strain data is being supplied to the requesting engineer.

Some of the specimens broke during the test. The location of the break was always in the area of the specimen held by the upper grip or right beneath it. All but two of the broken specimens were in the Hysol group. In this group, three out of five of the 100 K specimens broke, all of the 150 K specimens broke, and one of the ambient specimens broke. This could have been due to bubbles which were visible in these specimens. In every case of a break, a bubble could be seen in the fractured surfaces. In one of the Hysol specimens the strain gage was slightly offset vertically in order to avoid a bubble. This specimen did not break. In addition, one of the Epo-Tek specimens broke, at 200 K, and one of the Tracon specimens broke, at 100 K.

Possible sources of error include the presence of bubbles in the specimens, the impact of the strain gages on the material and temperature gradients. Digital control of the cryogen flow also induced some degree of temperature fluctuation, which is evident in some of the strain data.

Please contact our technical staff at (541) 753-0607 if you have any questions or require additional information regarding these measurements.

Submitted by:

Don Schneider
Project Engineer

Ann Gaidos-Morgan
Test Technician

Precision Measurements and Instruments Corporation [illegible] test results are obtained by techniques based on relevant ASTM standards, calibrations with NIST standard reference materials and/or published procedures. [illegible] test results beyond the [illegible] of the contract rendered.

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TABLE 1. ELASTIC MODULUS AND POISSON'S RATIO

Ambient (295 K)				
Specimen ID	Elastic Modulus psi	Poisson's Ratio	Maximum Strain %	Maximum Stress psi
TB_5_5	327,203	0.384	0.60	2,374
TB_8_5	368837	0.407	0.69	2,637
TB_8_5	360047	0.436	0.69	2,771
TB_9_5	369262	0.403	0.58	2,611
TB_11_5	323016	0.386	0.69	2,352
ave	356,886	0.401		[illegible]
st dev	28,002	0.008		
ET_1_5	541511	0.352	0.69	3,404
ET_2_5	537958	0.358	0.69	3,791
ET_7_5	542996	0.362	0.69	3,852
ET_19_5	516372	0.359	0.69	3,596
ET_20_5	524756	0.356	0.65	3,728
ave	531,427	0.358		[illegible]
st dev	13,787	0.003		[illegible]
HS_14_5	155524	0.452	0.59	1,196
HS_15_5	159329	0.434	0.59	[illegible]
HS_16_5	150287	0.406	0.59	1,122
HS_17_5	155575	0.433	0.68	1,162
HS_18_5	152574	0.428	0.59	1,149
ave	154,678	0.433		[illegible]
st dev	3,413	0.016		

250 K				
Specimen ID	Elastic Modulus psi	Poisson's Ratio	Maximum Strain %	Maximum Stress psi
TB_5_4	515,054	0.369	0.67	3,479
TB_8_4	522,770	0.358	0.68	3,501
TB_8_4	545,348	0.375	0.67	3,463
TB_9_4	555,162	0.383	0.69	3,927
TB_11_4	460,474	0.373	0.67	3,179
ave	519,361	0.372		3,527
st dev	37,000	0.010		
ET_1_4	637,210	[illegible]	0.67	4,355
ET_2_4	571,047	0.364	0.65	4,015
ET_7_4	604,871	0.359	0.63	4,238
ET_19_4	568,374	0.357	0.68	3,973
ET_20_4	597,729	0.379	0.63	4,249
ave	595,905	0.365		[illegible]
st dev	28,022	0.009		
HS_14_4	233,015	0.442	[illegible]	1,590
HS_15_4	225,658	0.425	0.69	1,644
HS_17_4	240,048	0.445	0.69	1,812
HS_18_4	245,875	0.438	0.72	1,813
HS_19_4	241,677	0.454	0.66	1,744
ave	239,240	0.425		[illegible]
st dev	9,752	0.010		

TABLE 1. ELASTIC MODULUS AND POISSON'S RATIO

200 K				
Specimen ID	Elastic Modulus psi	Poisson's Ratio	Maximum Strain %	Maximum Stress psi
TB_[illegible]_3	607,45[illegible]	0.367	0.60	4658
TB_6_3	615,755	0.37[illegible]	0.66	4295
TB_8_3	65[illegible],935	0.371	0.66	4659
TB_11_3	522,538	0.358	0.68	3650
TB_5_6	581,559	0.374	0.67	2638
ave	615,689	0.368		[illegible]
st dev	59,843	0.006		
ET_1_3	634,489	0.344	0.68	4427
ET_7_3	678,932	0.358	0.69	4788
ET_19_3	658,731	0.339	0.56	4181
ET_22_3	654,135	0.33[illegible]	0.58	4372
ET_2_3	657,585	0.357	0.58	4042
ave	648,880	0.349		[illegible]
st dev	27,816	0.010		
HS_14_3	603,489	0.347	0.66	4220
HS_15_3	538,850	0.351	0.62	3734
HS_13_3	581,845	0.365	0.69	3601
HS_17_3	561,774	0.388	0.79	3570
HS_18_3	539,892	0.361	0.69	3825
ave	566,786	0.357		[illegible]
st dev	26,780	0.010		

160 K				
Specimen ID	Elastic Modulus psi	Poisson's Ratio	Maximum Strain %	Maximum Stress psi
TB_5_2	873,858	0.355	0.60	5802
TB_6_2	911,689	0.35[illegible]	0.63	[illegible]
TB_8_2	909,767	0.358	0.63	6364
TB_9_2	966,010	0.369	0.63	6353
TB_11_2	730,776	0.360	0.63	4954
ave	886,035	0.367		[illegible]
st dev	90,402	0.019		
ET_1_2	825,968	0.327	0.66	6104
ET_2_2	866,247	0.351	0.58	5756
ET_7_2	852,680	0.375	0.60	5902
ET_19_2	756,872	0.322	0.69	5507
ET_20_2	852,372	0.352	0.66	5614
ave	833,220	0.334		[illegible]
st dev	31,086	0.016		
HS_14_2	731,235	0.322	0.58	4612
HS_15_2	838,534	0.355	0.54	4893
HS_13_2	817,872	0.394	0.56	4869
HS_18_2	849,042	0.395	0.54	4739
HS_17_2	908,835	0.338	0.55	4398
ave	822,854	0.357		[illegible]
st dev	91,467	0.028		

TABLE 1. ELASTIC MODULUS AND POISSON'S RATIO

100 K				
Specimen ID	Elastic Modulus psi	Poisson's Ratio	Maximum Strain %	Maximum Stress psi
TB_5_1	[illegible]	[illegible]	0.69	7515
TB_6_1	[illegible]	[illegible]	0.69	[illegible]
TB_8_1	[illegible]	[illegible]	0.65	[illegible]
TB_3_1	[illegible]	0.352	0.69	[illegible]
[illegible]	952,414	0.341	0.45	4514
ave	1,105,896	0.348		[illegible]
st dev	91,153	0.011		
ET_1_1	1,032,227	0.350	0.59	6360
ET_2_1	1,022,622	0.326	0.60	6870
ET_7_1	1,062,459	0.375	0.20	7327
ET_20_1	1,009,726	0.347	0.69	6686
ET_19_1	974,344	0.345	0.69	6794
ave	1,014,310	0.350		[illegible]
st dev	32,164	0.016		
HS_14_1	[illegible]	0.367	0.35	4226
HS_13_1	[illegible]	0.314	0.39	[illegible]
HS_19_1	1,177,258	[illegible]	0.41	[illegible]
HS_17_1	1,141,779	[illegible]	0.51	3602
HS_18_1	1,123,786	0.374	0.40	4033
ave	1,132,056	0.363		[illegible]
st dev	30,190	0.036		

The following table is a listing of the Tracon test specimens

1) Tracon F113 TB_5_1 (100K) 8" X 1" X 0.13"	18) Tracon F113 TB_8_4 (250K) 8" X 1" X 0.13"
2) Tracon F113 TB_5_2 (150K) 8" X 1" X 0.13"	19) Tracon F113 TB_8_5 (300K) 8" X 1" X 0.13"
3) Tracon F113 TB_5_3 (200K) 8" X 1" X 0.13"	20) Tracon F113 TB_9_1 (100K) 8" X 1" X 0.13"
4) Tracon F113 TB_5_4 (250K) 8" X 1" X 0.13"	21) Tracon F113 TB_9_2 (150K) 8" X 1" X 0.13"
5) Tracon F113 TB_5_5 (300K) 8" X 1" X 0.13"	22) Tracon F113 TB_9_3 (200K) 8" X 1" X 0.13"
6) Tracon F113 TB_5_6 (Spare) 8" X 1" X 0.13"	23) Tracon F113 TB_9_4 (250K) 8" X 1" X 0.13"
7) Tracon F113 TB_5_7 (Spare) 8" X 1" X 0.13"	24) Tracon F113 TB_9_5 (300K) 8" X 1" X 0.13"
8) Tracon F113 TB_6_1 (100K) 8" X 1" X 0.13"	25) Tracon F113 TB_9_6 (Spare) 8" X 1" X 0.13"
9) Tracon F113 TB_6_2 (150K) 8" X 1" X 0.13"	26) Tracon F113 TB_11_1 (100K) 8" X 1" X 0.13"
10) Tracon F113 TB_6_3 (200K) 8" X 1" X 0.13"	27) Tracon F113 TB_11_2 (150K) 8" X 1" X 0.13"
11) Tracon F113 TB_6_4 (250K) 8" X 1" X 0.13"	28) Tracon F113 TB_11_3 (200K) 8" X 1" X 0.13"
12) Tracon F113 TB_6_5 (300K) 8" X 1" X 0.13"	29) Tracon F113 TB_11_4 (250K) 8" X 1" X 0.13"
13) Tracon F113 TB_6_6 (Spare) 8" X 1" X 0.13"	30) Tracon F113 TB_11_5 (300K) 8" X 1" X 0.13"
14) Tracon F113 TB_6_7 (Spare) 8" X 1" X 0.13"	31) Tracon F113 TB_11_6 (Spare) 8" X 1" X 0.13"
15) Tracon F113 TB_8_1 (100K) 8" X 1" X 0.13"	32) Tracon F113 TB_12_1 (Spare) 8" X 1" X 0.13"
16) Tracon F113 TB_8_2 (150K) 8" X 1" X 0.13"	33) Tracon F113 TB_12_2 (Spare) 8" X 1" X 0.13"
17) Tracon F113 TB_8_3 (200K) 8" X 1" X 0.13"	34) Tracon F113 TB_12_3 (Spare) 8" X 1" X 0.13"
	35) Tracon F113 TB_12_4 (Spare) 8" X 1" X 0.13"

[illegible]
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The following table is a listing of the Epo-Tek 301-2 specimens.

36) Epo-Tek 301-2 ET_1_1 (100K) 8" X 1" X 0.13"	53) Epo-Tek 301-2 ET_4_2 (Spare) 8" X 1" X 0.13"
37) Epo-Tek 301-2 ET_1_2 (150K) 8" X 1" X 0.13"	54) Epo-Tek 301-2 ET_7_1 (100K) 8" X 1" X 0.13"
38) Epo-Tek 301-2 ET_1_3 (200K) 8" X 1" X 0.13"	55) Epo-Tek 301-2 ET_7_2 (150K) 8" X 1" X 0.13"
39) Epo-Tek 301-2 ET_1_4 (250K) 8" X 1" X 0.13"	56) Epo-Tek 301-2 ET_7_3 (200K) 8" X 1" X 0.13"
40) Epo-Tek 301-2 ET_1_5 (300K) 8" X 1" X 0.13"	57) Epo-Tek 301-2 ET_7_4 (250K) 8" X 1" X 0.13"
41) Epo-Tek 301-2 ET_2_1 (100K) 8" X 1" X 0.13"	58) Epo-Tek 301-2 ET_7_5 (300K) 8" X 1" X 0.13"
42) Epo-Tek 301-2 ET_2_2 (150K) 8" X 1" X 0.13"	59) Epo-Tek 301-2 ET_19_1 (100K) 8" X 1" X 0.13"
43) Epo-Tek 301-2 ET_2_3 (200K) 8" X 1" X 0.13"	60) Epo-Tek 301-2 ET_19_2 (150K) 8" X 1" X 0.13"
44) Epo-Tek 301-2 ET_2_4 (250K) 8" X 1" X 0.13"	61) Epo-Tek 301-2 ET_19_3 (200K) 8" X 1" X 0.13"
45) Epo-Tek 301-2 ET_2_5 (300K) 8" X 1" X 0.13"	62) Epo-Tek 301-2 ET_19_4 (250K) 8" X 1" X 0.13"
46) Epo-Tek 301-2 ET_2_6 (Spare) 8" X 1" X 0.13"	63) Epo-Tek 301-2 ET_19_5 (300K) 8" X 1" X 0.13"
47) Epo-Tek 301-2 ET_3_1 (Spare) 8" X 1" X 0.13"	64) Epo-Tek 301-2 ET_19_6 (Spare) 8" X 1" X 0.13"
48) Epo-Tek 301-2 ET_3_2 (Spare) 8" X 1" X 0.13"	65) Epo-Tek 301-2 ET_20_1 (100K) 8" X 1" X 0.13"
49) Epo-Tek 301-2 ET_3_3 (Spare) 8" X 1" X 0.13"	66) Epo-Tek 301-2 ET_20_2 (150K) 8" X 1" X 0.13"
50) Epo-Tek 301-2 ET_3_4 (Spare) 8" X 1" X 0.13"	67) Epo-Tek 301-2 ET_20_3 (200K) 8" X 1" X 0.13"
51) Epo-Tek 301-2 ET_3_5 (Spare) 8" X 1" X 0.13"	68) Epo-Tek 301-2 ET_20_4 (250K) 8" X 1" X 0.13"
52) Epo-Tek 301-2 ET_4_1 (Spare) 8" X 1" X 0.13"	69) Epo-Tek 301-2 ET_20_5 (300K) 8" X 1" X 0.13"
	70) Epo-Tek 301-2 ET_20_6 (Spare) 8" X 1" X 0.13"

[illegible]

The following table is a listing of the HYSOL 9361 HS Specimens.

71) HYSOL 9361 HS_14_1 (100K)
8" X 1" X 0.13"

72) HYSOL 9361 HS_14_2 (150K)
8" X 1" X 0.13"

73) HYSOL 9361 HS_14_3 (200K)
8" X 1" X 0.13"

74) HYSOL 9361 HS_14_4 (250K)
8" X 1" X 0.13"

75) HYSOL 9361 HS_14_5 (300K)
8" X 1" X 0.13"

76) HYSOL 9361 HS_14_6 (Spare)
8" X 1" X 0.13"

77) HYSOL 9361 HS_15_1 (100K)
8" X 1" X 0.13"

78) HYSOL 9361 HS_15_2 (150K)
8" X 1" X 0.13"

79) HYSOL 9361 HS_15_3 (200K)
8" X 1" X 0.13"

80) HYSOL 9361 HS_15_4 (250K)
8" X 1" X 0.13"

81) HYSOL 9361 HS_15_5 (300K)
8" X 1" X 0.13"

82) HYSOL 9361 HS_15_6 (Spare)
8" X 1" X 0.13"

83) HYSOL 9361 HS_15_7 (Spare)
8" X 1" X 0.13"

84) HYSOL 9361 HS_16_1 (100K)
8" X 1" X 0.13"

85) HYSOL 9361 HS_16_2 (150K)
8" X 1" X 0.13"

86) HYSOL 9361 HS_16_3 (200K)
8" X 1" X 0.13"

87) HYSOL 9361 HS_16_4 (250K)
8" X 1" X 0.13"

88) HYSOL 9361 HS_16_5 (300K)
8" X 1" X 0.13"

89) HYSOL 9361 HS_16_6 (Spare)
8" X 1" X 0.13"

90) HYSOL 9361 HS_16_7 (Spare)
8" X 1" X 0.13"

91) HYSOL 9361 HS_17_1 (100K)
8" X 1" X 0.13"

92) HYSOL 9361 HS_17_2 (150K)
8" X 1" X 0.13"

93) HYSOL 9361 HS_17_3 (200K)
8" X 1" X 0.13"

94) HYSOL 9361 HS_17_4 (250K)
8" X 1" X 0.13"

95) HYSOL 9361 HS_17_5 (300K)
8" X 1" X 0.13"

96) HYSOL 9361 HS_17_6 (Spare)
8" X 1" X 0.13"

97) HYSOL 9361 HS_18_1 (100K)
8" X 1" X 0.13"

98) HYSOL 9361 HS_18_2 (150K)
8" X 1" X 0.13"

99) HYSOL 9361 HS_18_3 (200K)
8" X 1" X 0.13"

100) HYSOL 9361 HS_18_4 (250K)
8" X 1" X 0.13"

101) HYSOL 9361 HS_18_5 (300K)
8" X 1" X 0.13"

102) HYSOL 9361 HS_18_6 (Spare)
8" X 1" X 0.13"

103) HYSOL 9361 HS_18_7 (Spare)
8" X 1" X 0.13"

[illegible]