477-kcmil, 3M^{TM} Composite Conductor Core Properties Mapping

3M Company
Purchase Order 0000592334

NEETRAC Project Number: 02-224

October, 2002

A Center of
The Georgia Institute of Technology

Requested by: Mr. Colin McCullough
3M

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Summary:

3M contracted with NEETRAC for a series of tests to experimentally measure the core strand strain as a function of stress and temperature. The experiment was modeled on the Aluminum Association's 1999 guide for stress-strain testing. Temperature was varied from room temperature, 21°C, to 225°C degrees, while load was held constant. Load was then varied from nominal 400 lbs to 30% of the core strand breaking strength. Recorded data permits extraction of actual thermal and elastic coefficients at different temperatures and different mechanical loads.

Samples:

1) Eight (8) meters (26 ft) of 477 kcmil, 3M™ Composite Conductor, from reel received 8/16/02.

References:

1) "Proprietary Information Agreement …." Dated 3/27/01
2) "A Method for Stress-strain testing of Aluminum and ACSR Conductors", Aluminum Association, 1999.
3) 3M Purchase Order 0000592334.
4) PRJ 02-224, NEETRAC Project Plan

Equipment Used:

1) MTS Servo-hydraulic tensile machine, Control # CQ 0195
2) Yokogawa Model DC100 data acquisition system, Control # CN 3022
3) High current AC test set, Control # CN 3007
4) Dynamics Research Corp./NEETRAC digital cable extensometer, Control # CQ3002

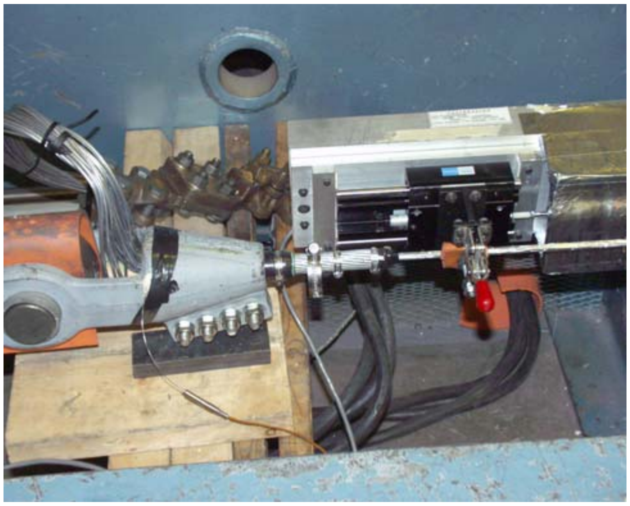
Procedure:

Testing was conducted in accordance with a NEETRAC procedure entitled "PRJ02224, CONFIDENTIAL – MMC Conductor Evaluation, 477 kcmil ACCR Core Properties Thermo-mechanical Properties Map". The procedure controls all technical and quality management details for the project.

An 8-meter (26 ft) sample was cut from the reel. All aluminum strands were removed, leaving a naked core. Two complete sets of aluminum strands each approximately 3 feet long, were wrapped over the sample ends to provide connections for electrical terminations. Cast-resin terminations were then fitted to each end of the sample. The aluminum strands were connected to tubular-to flat NEMA four-bolt connectors. This arrangement allows for application of mechanical tension (resin termination), and loading current (NEMA connector).

The sample was installed in the MTS tensile machine, which has a computer interface for load control and automatic logging of test data. Nominal tension of 400 lbs was applied. A center support was used to minimize sag. The DRC cable extensometer is an aluminum box beam, which hangs from counter balances. The counterbalance system permits the instrument to be attached to a sample without applying significant loads. One end of the instrument is clamped to the sample using a rigid knife-edge and clamp arrangement. The opposite end of the instrument has a knife-edge and clamp mounted on a low-friction precision carriage. Change in sample length causes the carriage to slide on its linear bearings. A digital high-resolution linear encoder tracks the movement of the carriage relative to the aluminum beam. The instrument is thermally insulated to operate near high temperature samples. The digital electronics are immune to fields generated by AC conductor current. The gage beam and the sample are instrumented for temperature. Photographs 1, 2, and 3 show the test in progress.

Photograph 1, long view of core properties test



Photograph 2, detail showing current lead, strain instrument, and resin termination

Photograph 3, detail showing center support

All tests were run on the same sample over a two day period. Overnight, the sample remained at 30% RBS, and was allowed to cool while data were recorded. The electrical and mechanical zero reference for the extensometer remained unchanged for the duration of the test. All strain data reported here are referenced to instrument zero at 400 lbs tension. Gage length is 18.000 feet (5.4864 meters).

The test started on October 3, 2002, at 1:27 PM. Data were recorded automatically for the next 22 hours, while the following loads and temperatures were applied to the sample:

Elapsed time Hours:	Test phase
0.000	Room temperature, nominal 400 lb tension
0.000 to 0.101	Increase load to 30% RBS (3,490 lbs), room temperature
0.101 to 0.185	5-minute load hold at 30% RBS, room temperature
0.185 to 0.296	Decreasing load to 400 lbs, room temperature
0.296 – 0.514	Repeat load cycle to 30% RBS, no load hold
0.548 – 1.112	Heat-up and stabilize at 75 C, 400 lbs tension
1.120 – 1.630	Two (2) load cycles at 75 C, one (1) 5-minute hold at 30% RBS
1.648 to 1.991	Heat-up and stabilize at 125 C, 400 lbs tension
1.991 to 2.394	Two (2) load cycles at 125 C, one (1) 5-minute hold at 30% RBS
2.411 to 17.604	Cool-down at 30% RBS, and load hold at 30% RBS overnight (automatic data logging, but unattended)
17.604 to 18.106	Heat-up and stabilize at 175 C, 30% RBS
18.106	Inadvertent trip of AC power supply
18.106 to 18.192	Natural cooling from 160 C to 88 C
18.192 to 18.648	Heat up and stabilize at 175 C, load changed from 30% RBS to 400 lbs (no usable data because both load and temperature were changing)
18.648 to 19.154	Two (2) load cycles at 175 C, one (1) 5-minute hold at 30% RBS
19.154 to 19.598	Heat up and stabilize at 225 C, 400 lbs
19.610 to 20.126	Two (2) load cycles at 225 C, one (1) 5-minute hold at 30% RBS
20.136 to 20.179	Increase load to 1,700 lbs, hold temperature at 225 C
20.179 to 21.619	Cool to room temperature at 1,700 lbs tension
21.619 to 21.708	Lower tension from 1,700 lbs to 400 lbs, at room temperature.

Figures 1 and 2 show the time history for temperatures, tension, and AC loading current for day 1 and day 2 of the test, respectively. Steady-state overnight data are not shown, but are recorded.

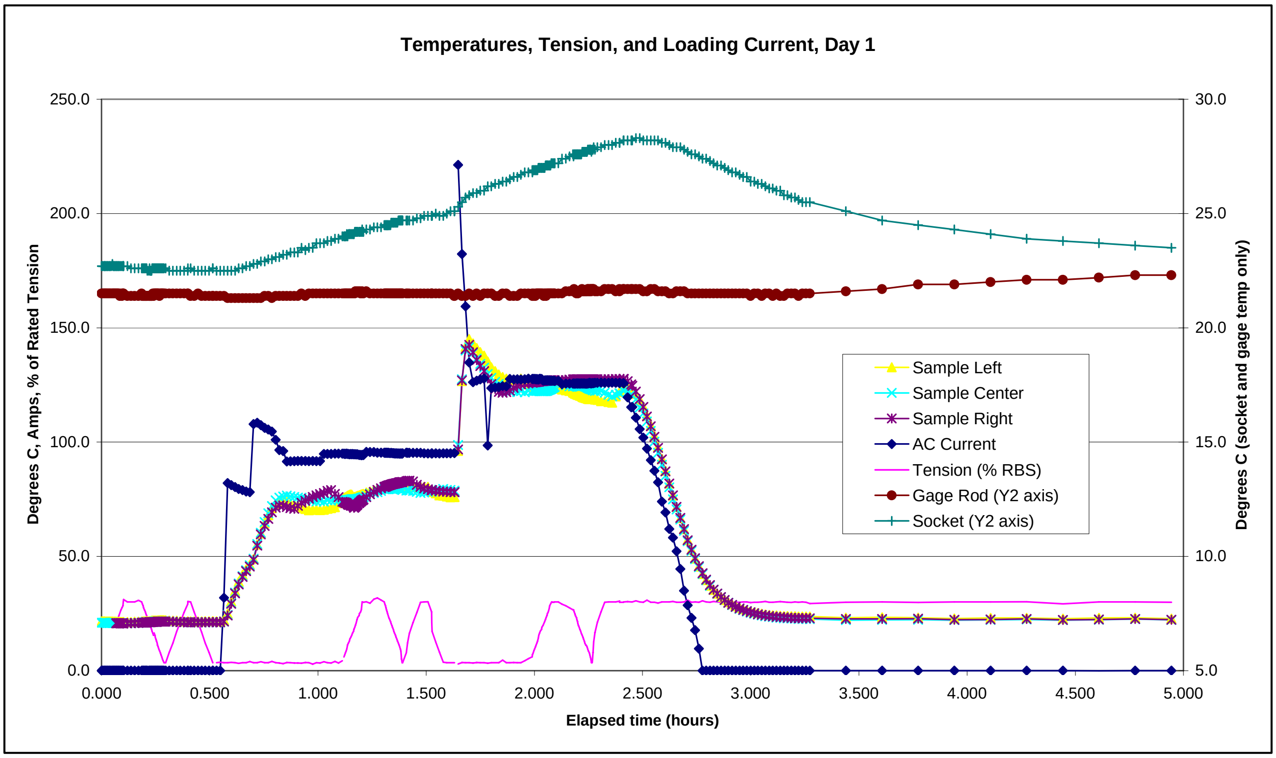


Figure 1, Temperatures, tension, and current during room temperature, 75 C and 125 C tests

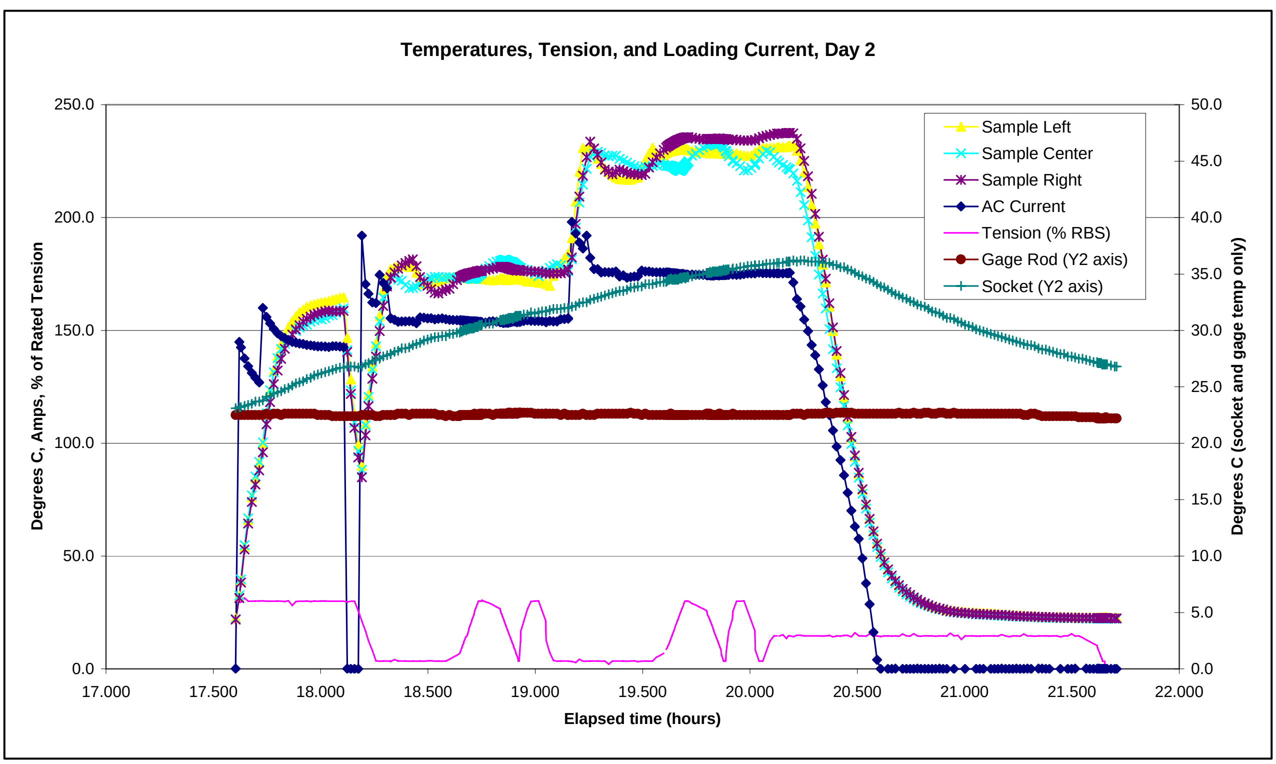


Figure 2, Temperatures, tension, and current during 175 C and 225 C tests

Appendix 1 shows graphical presentation of the stress-strain properties at room temperature (22 C), 75 C, 125 C, 175 C, and 225 C. Appendix 2 shows thermal expansion versus temperature at three different loads, 400 lbs, 1,700 lbs, and 3,490 lbs.

Accuracy of the strain data was estimated. The instrument uses an all-digital sensing technique, and has a digital resolution of 0.000046% (0.46 ppm). Load measurement is certified within +/- 0.5% of reading, and that is the largest error source. Heating of the sample raises the ambient temperature, which affects the length of the gage reference rod. The gage reference is therefore instrumented for temperature, and the strain data are corrected for temperature effects on the instrument. Overall accuracy is better than +/- 1% of reading. Repeatability is within 0.1% of reading. Test data show hysteresis of approximately 0.004% strain. The instrument hysteresis is less than 0.0002% strain, so the hysteresis is mostly due to conductor properties. This is reasonable, because, for a stranded sample, friction plays a role in strain behavior as the strands rub during elongation and contraction cycles.

Tests were run with fixed current setting once a stable temperature is achieved. Unavoidably, sample temperature increases with increasing load. There is no practical method to control current to compensate for temperature change. Spurious temperature effects were compensated for in post-processing of the data.

Load control during the thermal elongation tests was good, but not perfect. Therefore, load effects appear in the raw test data. Spurious effects of load variation were compensated by post processing the data. Fortunately the load changes are averaged around the set point, so averaging naturally occurs when trends are calculated.

Spurious temperature and load changes are small. Their effect on the data and property coefficients is small. The raw data and coefficients based on the raw values are shown in the graphs only when there is a visible difference between the raw data plot and the compensated data plot. Compensated data is considered reliable, because compensation removes known errors in the data.

Conclusions:

Coefficients for each test performed are as follows:

Condition	Elastic modulus (msi)
Room temperature, load increasing from 4% RBS to 30 % RBS (day 1)	34.79
Room temperature, load decreasing from 30% RBS to 4 % RBS (day1)	34.65
Room temperature, load decreasing from 15% RBS to 4 % RBS (day 2)	35.24
75 C, load increasing from 4% RBS to 30 % RBS	34.68
75 C, load decreasing from 30% RBS to 4 % RBS	35.14
125 C, load increasing from 4% RBS to 30 % RBS	34.25
125 C, load decreasing from 30% RBS to 4 % RBS	35.42
175 C, load increasing from 4% RBS to 30 % RBS	33.17
175 C, load decreasing from 30% RBS to 4 % RBS	34.07
225 C, load increasing from 4% RBS to 30 % RBS	32.92
225 C, load decreasing from 30% RBS to 4 % RBS	33.33

Condition	Thermal modulus (ppm/C)

4 % RBS, 22 C to 75 C heating	6.45
4% RBS, 75 C to 125 C heating	6.51
30% RBS, 125 C to 22 C cooling	6.68
30% RBS, 22 C to 175C heating	7.64
30% RBS, 175C to 88C cooling	8.80
4% RBS, 175 C to 225 C heating	7.23
15% RBS, 225 C to 22 C cooling	7.63

Coefficients appear to have some dependency on temperature, stress, and sample conditioning. Figures 3 and 4 show plots of the coefficients as a function of temperature and stress.

Figure 3, elastic modulus versus temperature (room temp data from day 2)

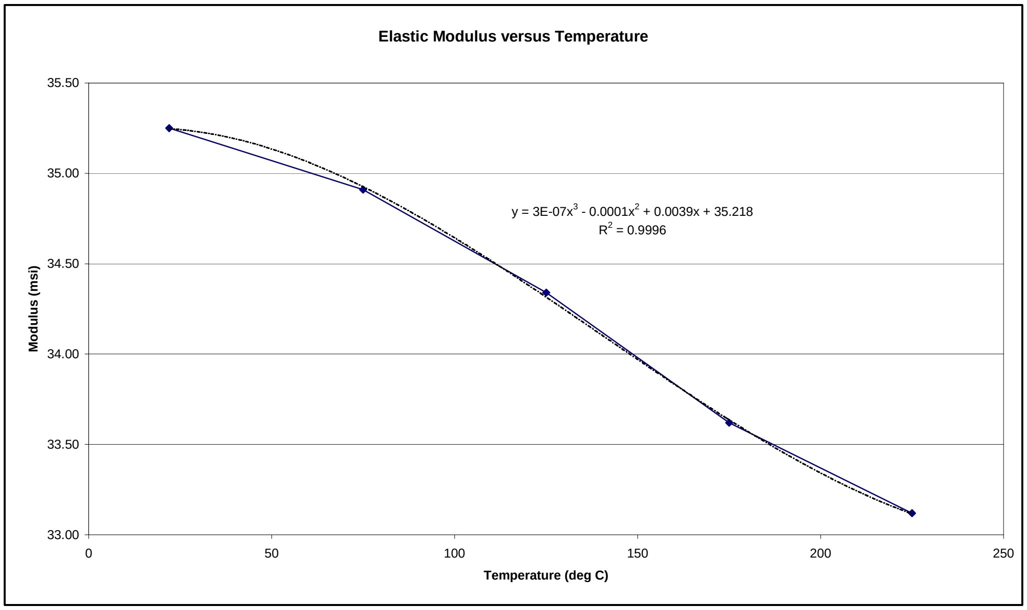
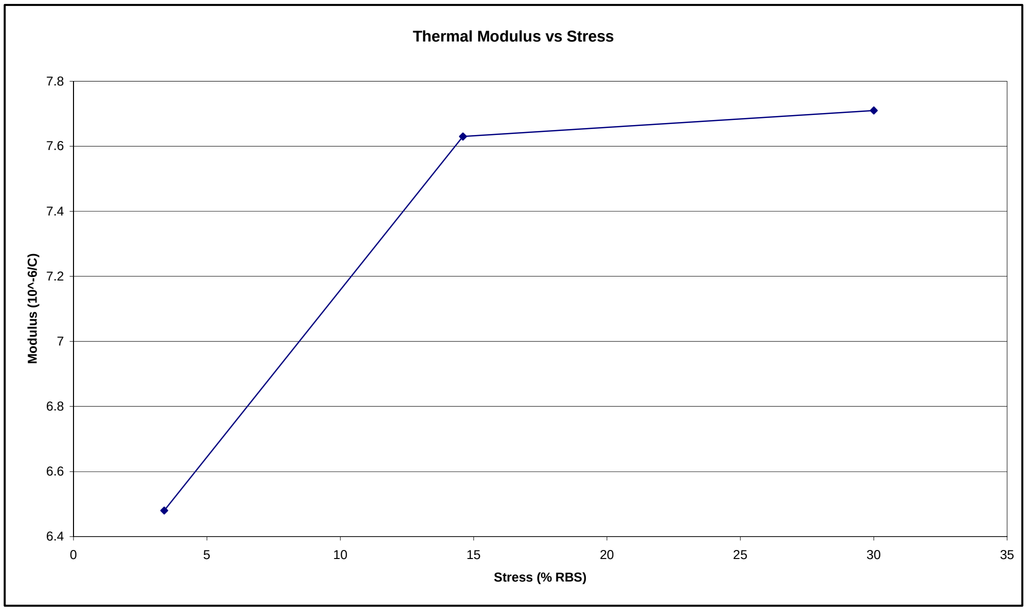


Figure 4, thermal modulus versus stress



Data to characterize the dependencies is limited. The third-order fit to the elastic modulus data shown on the chart works well for the test temperatures, but extrapolation outside that range may not be valid. A linear fit may work better for extrapolation. In any case, the effect is small in relation to other uncertainties affecting conductor sag and tension. Therefore, an averaged value should be considered for all conditions. There is hysteresis in both mechanical and thermal strain. An average of the increasing modulus and decreasing modulus is appropriate for field conditions, where load and temperature constantly cycle. A coefficient at the maximum expected conductor temperature will give conservative (higher) ground clearance estimates. Based on these considerations, an elastic modulus of 33.3 msi seems reasonable. A thermal modulus of 7.4 ppm/C should provide reasonable predictions.

An expression for the length of core as a function of temperature and stress is proposed, based on "average" values determined for the coefficients:

$$L_{tn,\,sn} = L_{to,\,so} + L_{to,\,so} * (t_n - t_o) * 7.6E\text{-}6 + L_{to,\,so} * (s_n - s_o)/33.3E6$$

where:

$L_{to,\,so}$ = length at reference temperature t_o and reference stress s_o (any unit)

$L_{tn,\,sn}$ = length at new temperature t_n and stress s_n (same units as $L_{to,\,so}$)

t_o = reference temperature in degrees C
t_n = new temperature in degrees C

s_o = reference stress in psi
s_n = new stress in psi

Setting t_o and s_o to a value of zero will simplify the expression for all positive values of temperature and stress.

A further independent Analysis is provided by Stephen Barrett of Barrett Research and is attached in Appendix 3.

Acknowledgement:

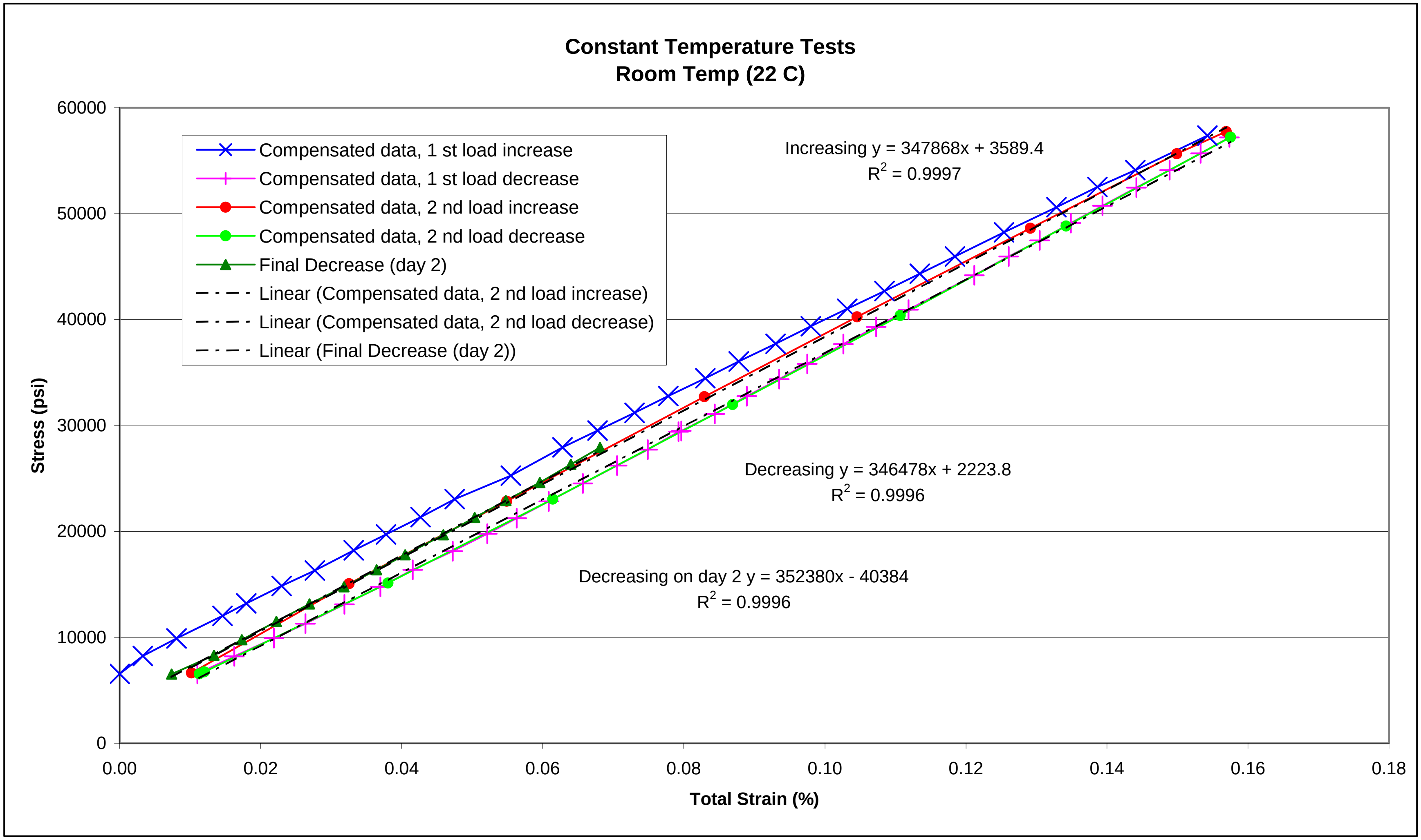
This material is based upon work supported by the U.S. Department of Energy under Award No. DE-FC02-02CH11111.

Disclaimer:

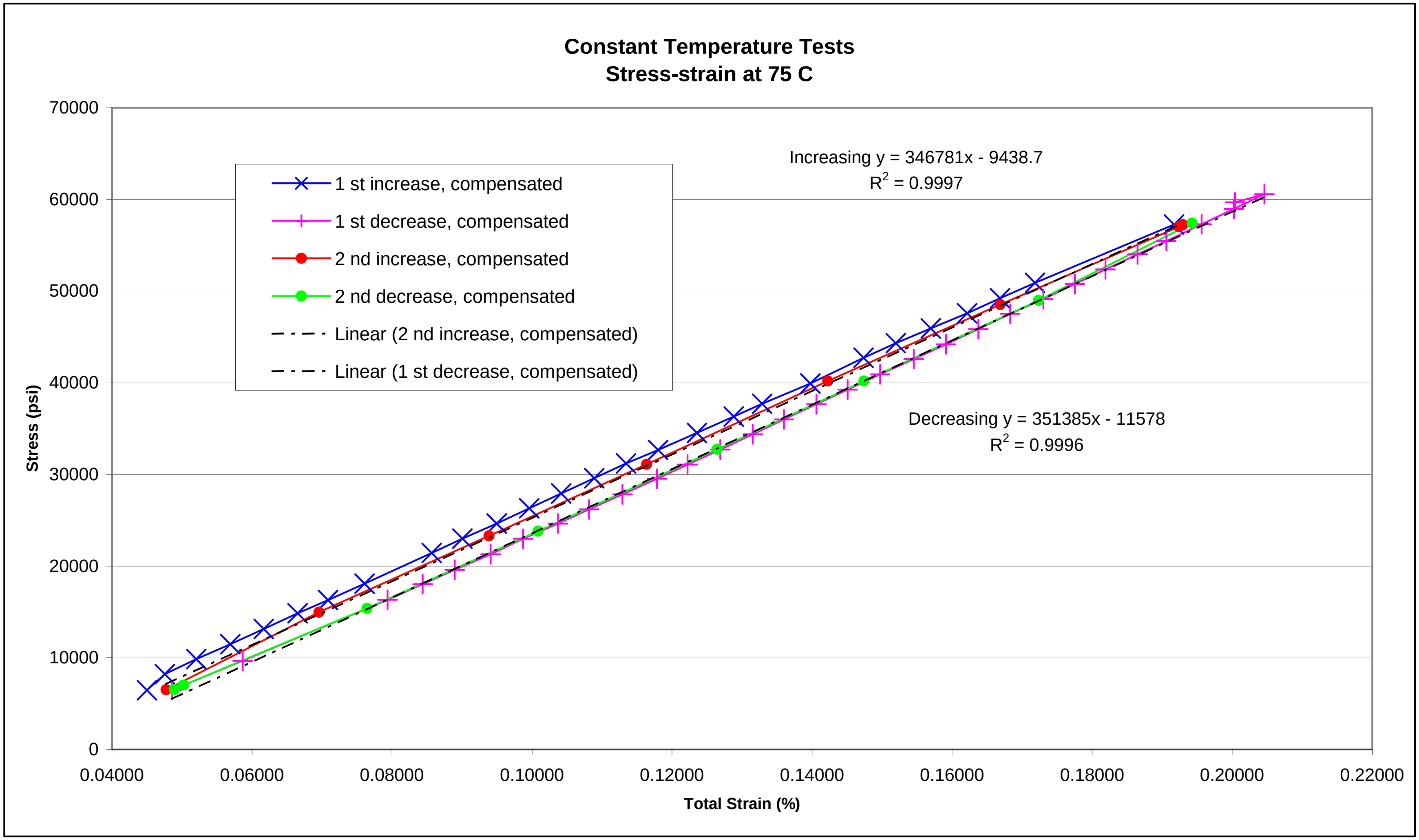
Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Department of Energy.

Appendix 1

Graphs showing stress-strain at room temperature and elevated temperature

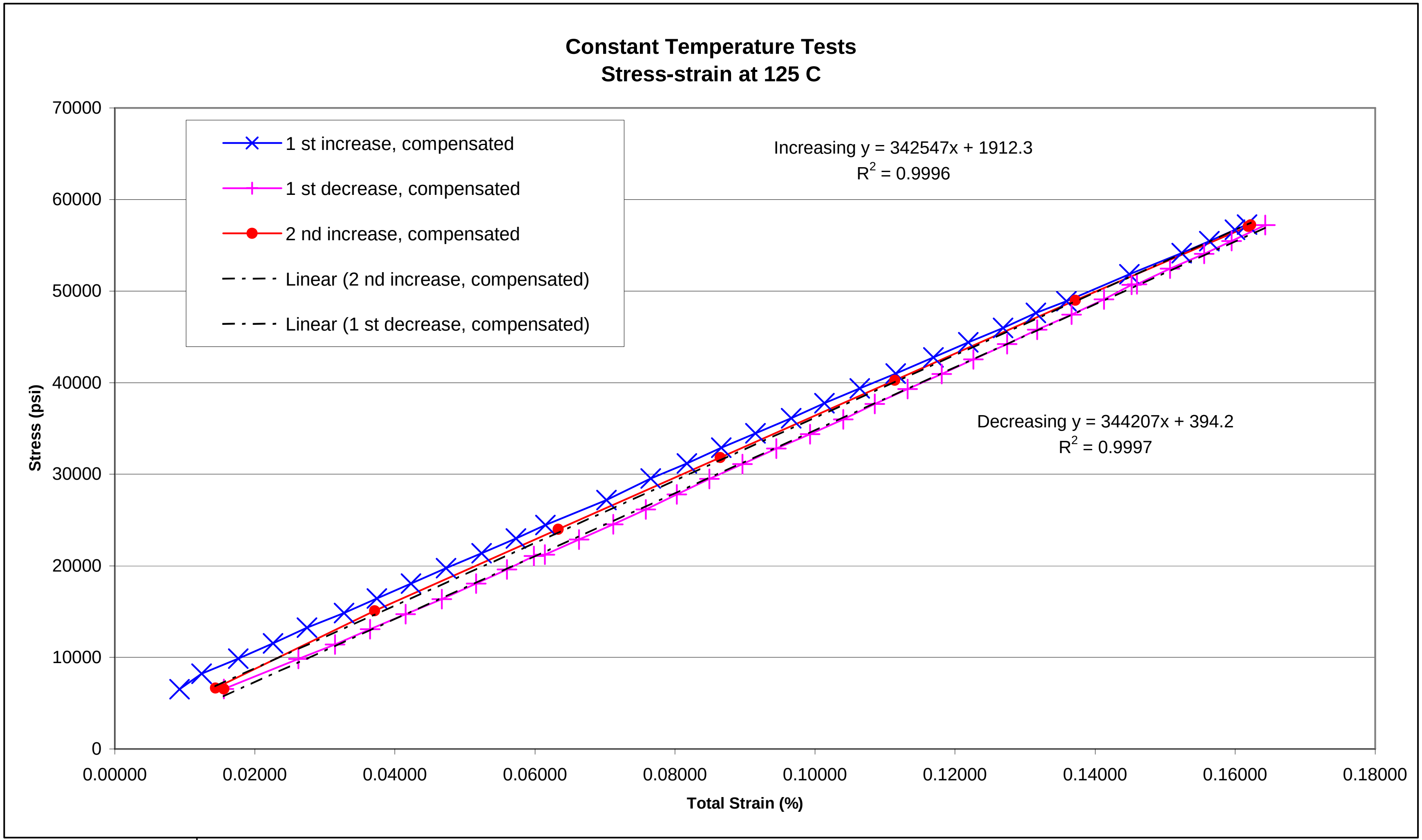


Notes: Top curve is first-time sample was loaded. Slope appears to be affected by initial creep and other conditioning effects.
The second load cycle is used for modulus calculation.
Compensation is in effect, but this is a room-temperature test and the raw data are nearly identical.
Repeatability is good except for the first increase load, where initial creep effects are present.
Decreasing load curve at end of day 2 shows effect of sample conditioning on elastic modulus. Measured creep over the two-day period totals 0.0074%, after temperature and stress compensation. This chart shows almost all creep occurred during initial loading (top blue curve).

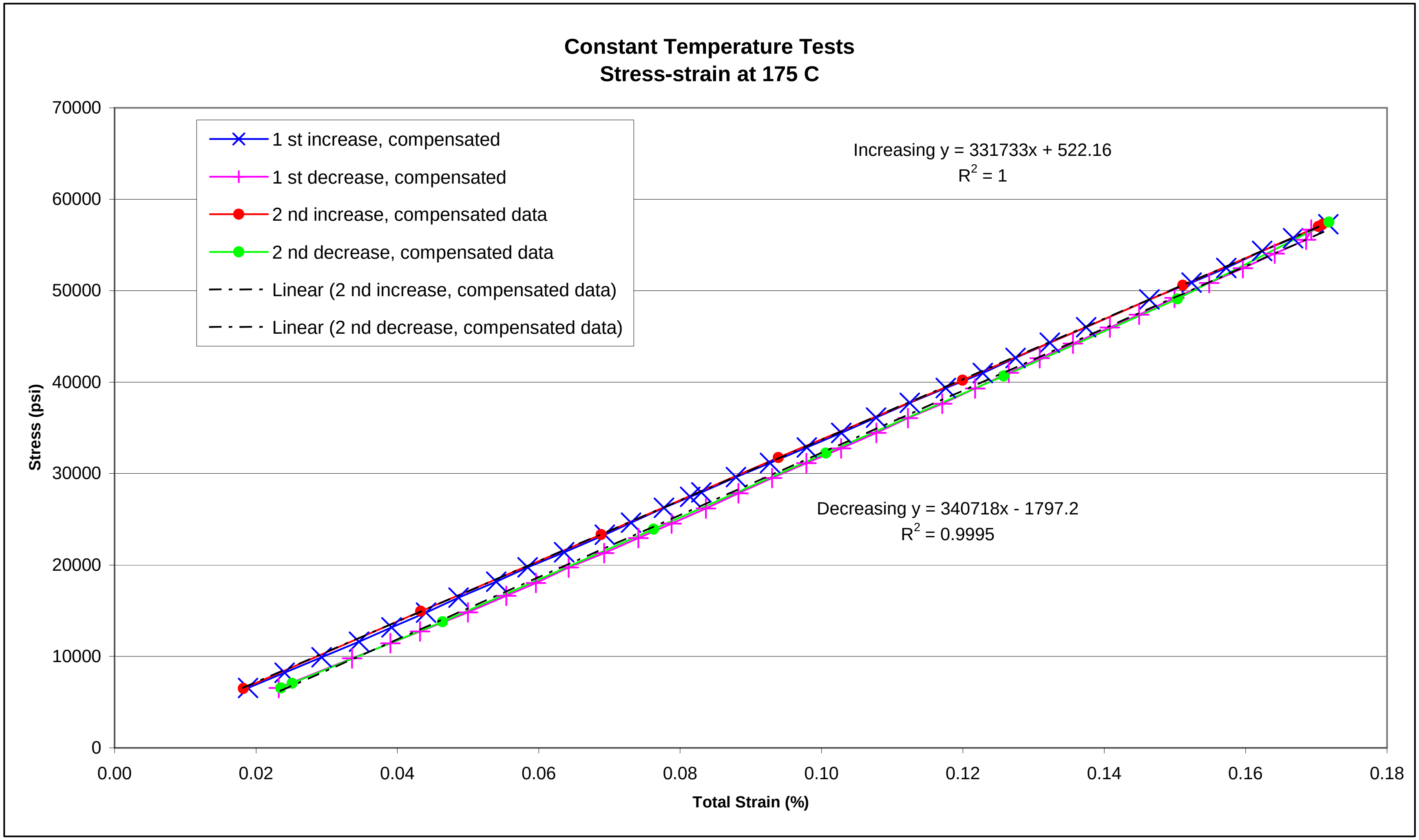


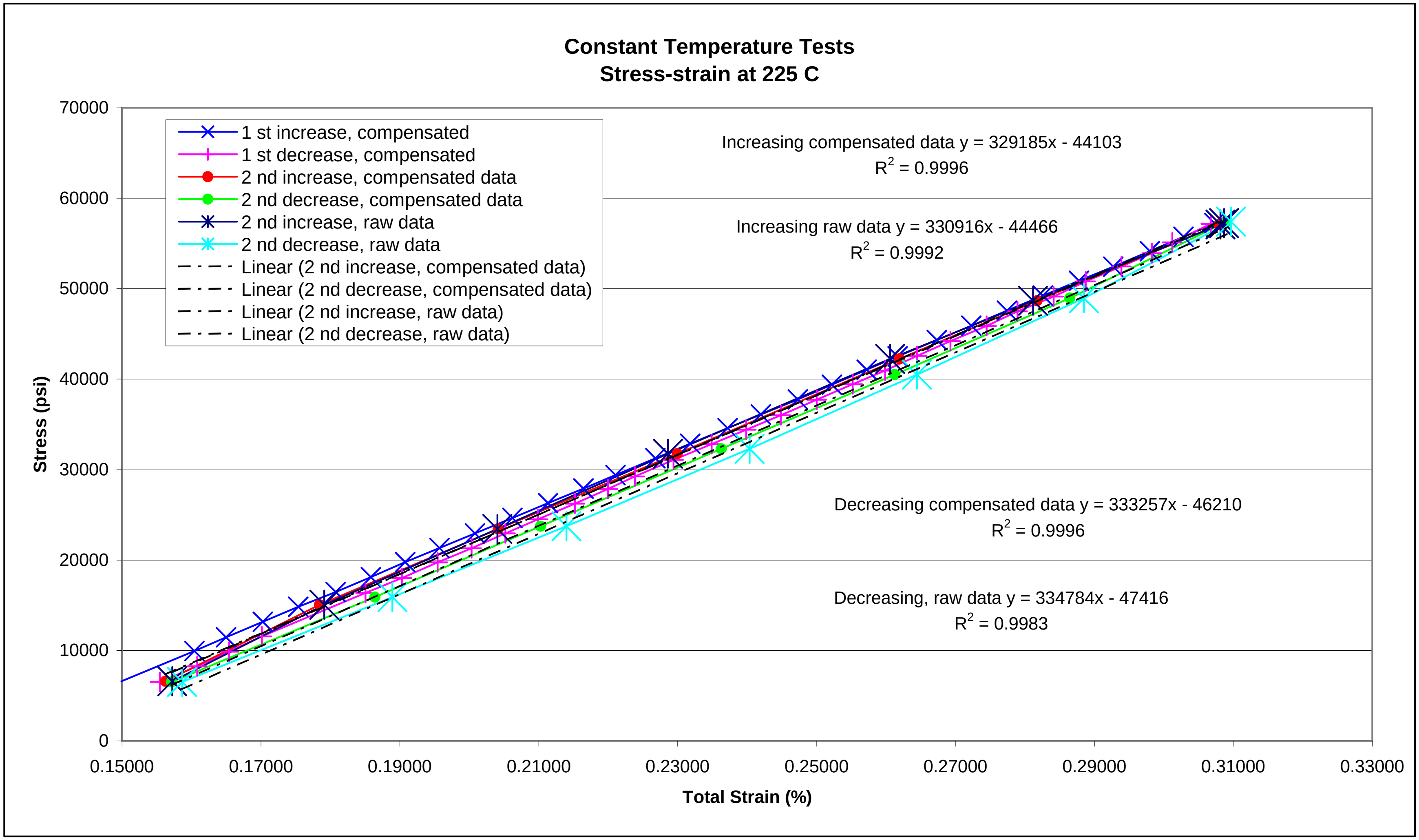
Notes:

Extension of the '"1st decrease" was caused by sticking load control valve. Load excursion was to 33% RBS, and should not affect the test.



Notes: There is no "2nd decrease" line. The sample was left at 30% RBS overnight for a complete cool-down curve.


Constant Temperature Tests
Stress-strain at 175 C
1 st increase, compensated
1 st decrease, compensated
2 nd increase, compensated data
2 nd decrease, compensated data
Linear (2 nd increase, compensated data)
Linear (2 nd decrease, compensated data)
Increasing y = 331733x + 522.16
R2 = 1
Decreasing y = 340718x - 1797.2
R2 = 0.9995
Stress (psi)
Total Strain (%)
0
10000
20000
30000
40000
50000
60000
70000
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18



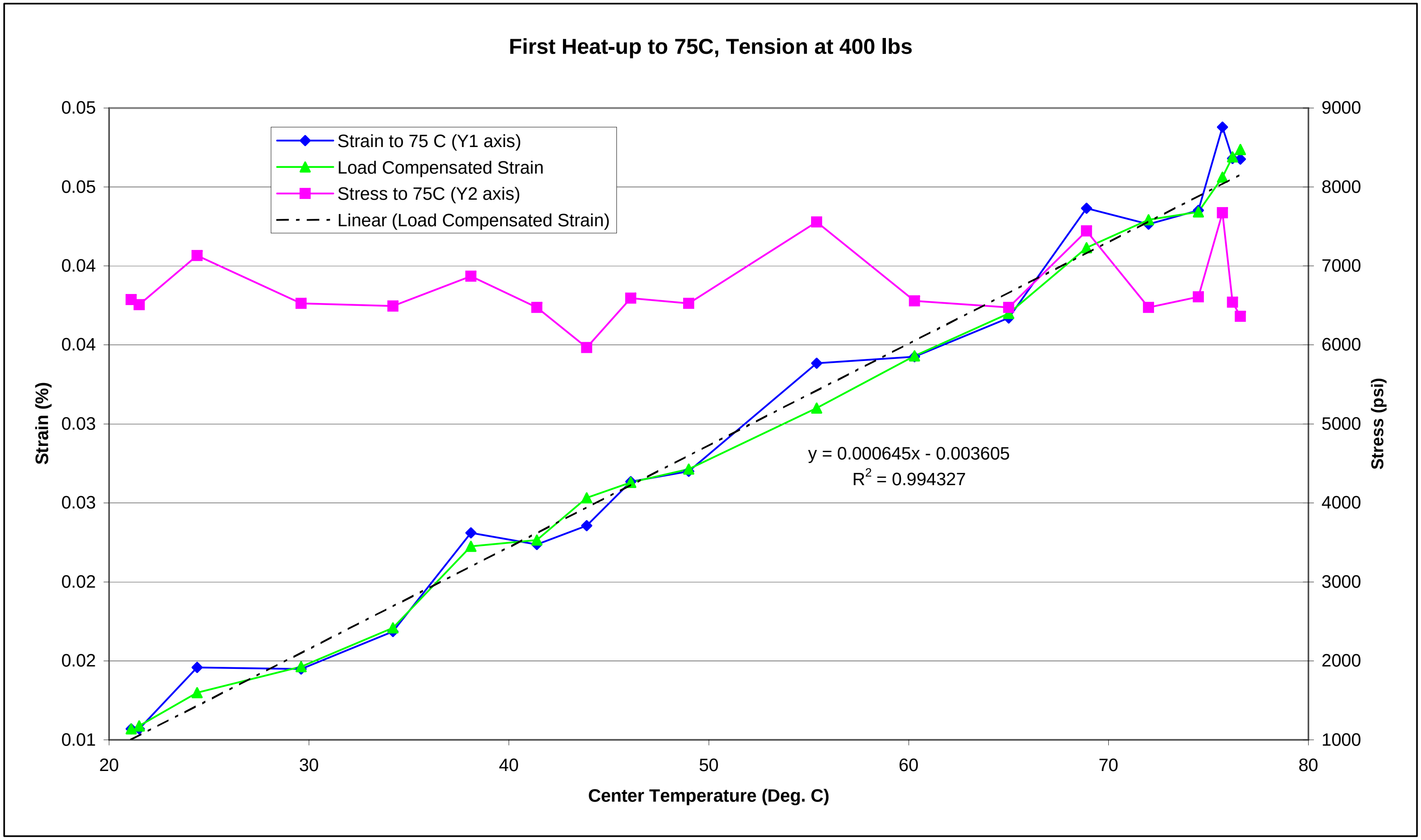
Notes:

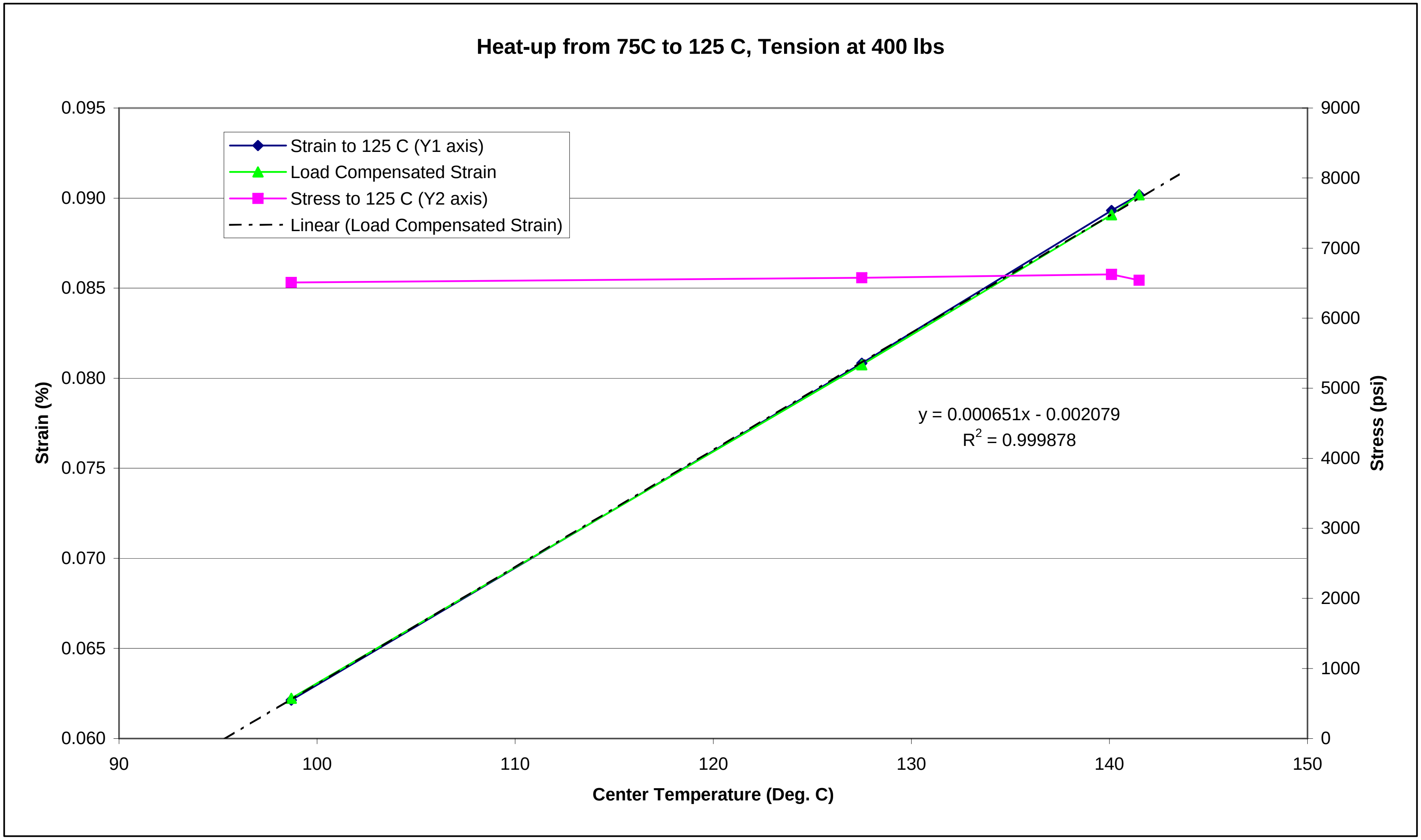
Temperature increased 11.3 degrees from start to the hottest part of the test. In this graph, the raw data are plotted to show the effect of the compensation process. A coefficient of 6.3 ppm/C was used to compensate the strain for temperature change after the test started.

Appendix 2

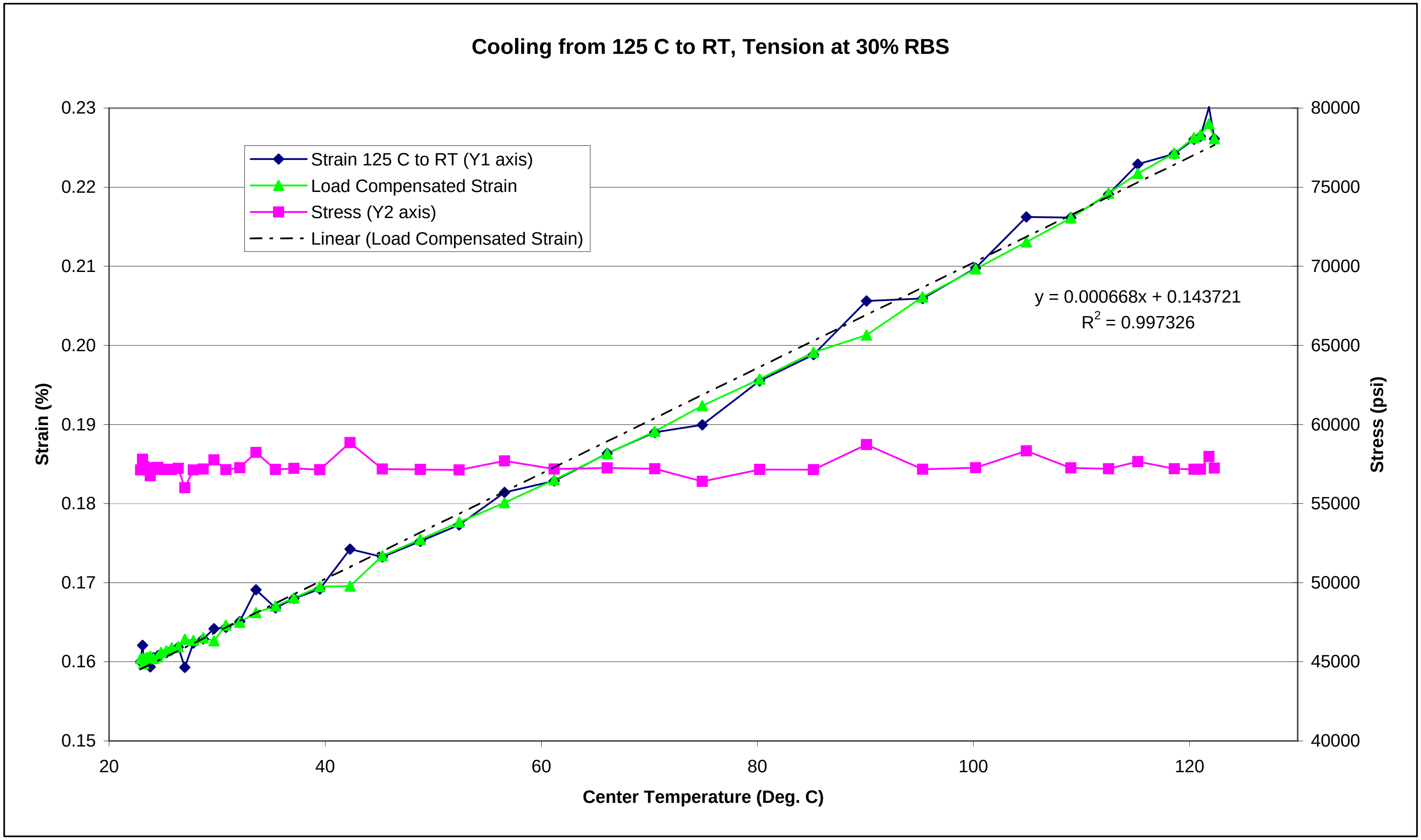
Graphs showing thermal strain at constant mechanical load

Graphs ordered by time sequence

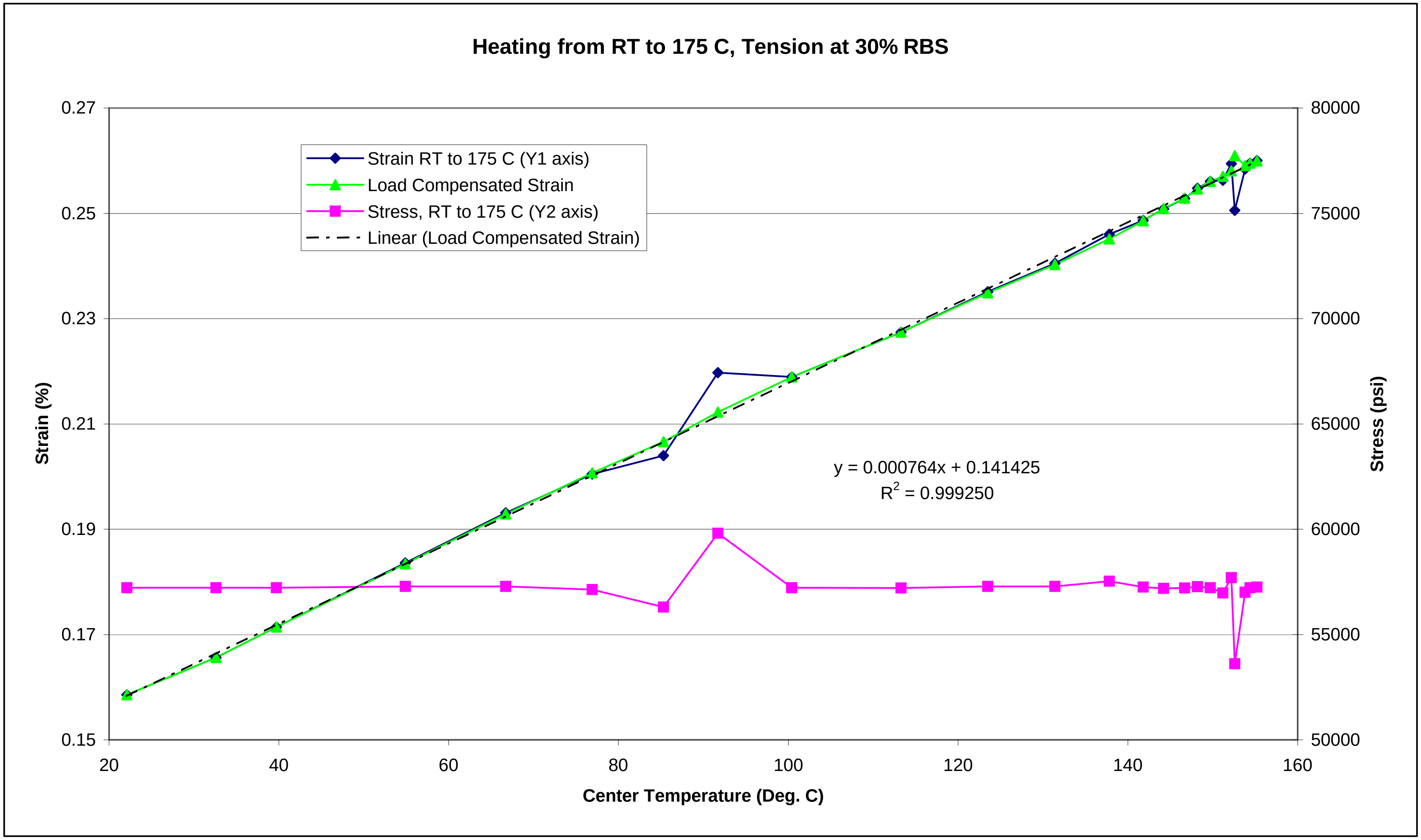

First Heat-up to 75C, Tension at 400 lbs
Strain to 75 C (Y1 axis)
Load Compensated Strain
Stress to 75C (Y2 axis)
Linear (Load Compensated Strain)
y = 0.000645x - 0.003605
R2 = 0.994327
Strain (%)
Stress (psi)
Center Temperature (Deg. C)
0.05
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
9000
8000
7000
6000
5000
4000
3000
2000
1000
20
30
40
50
60
70
80

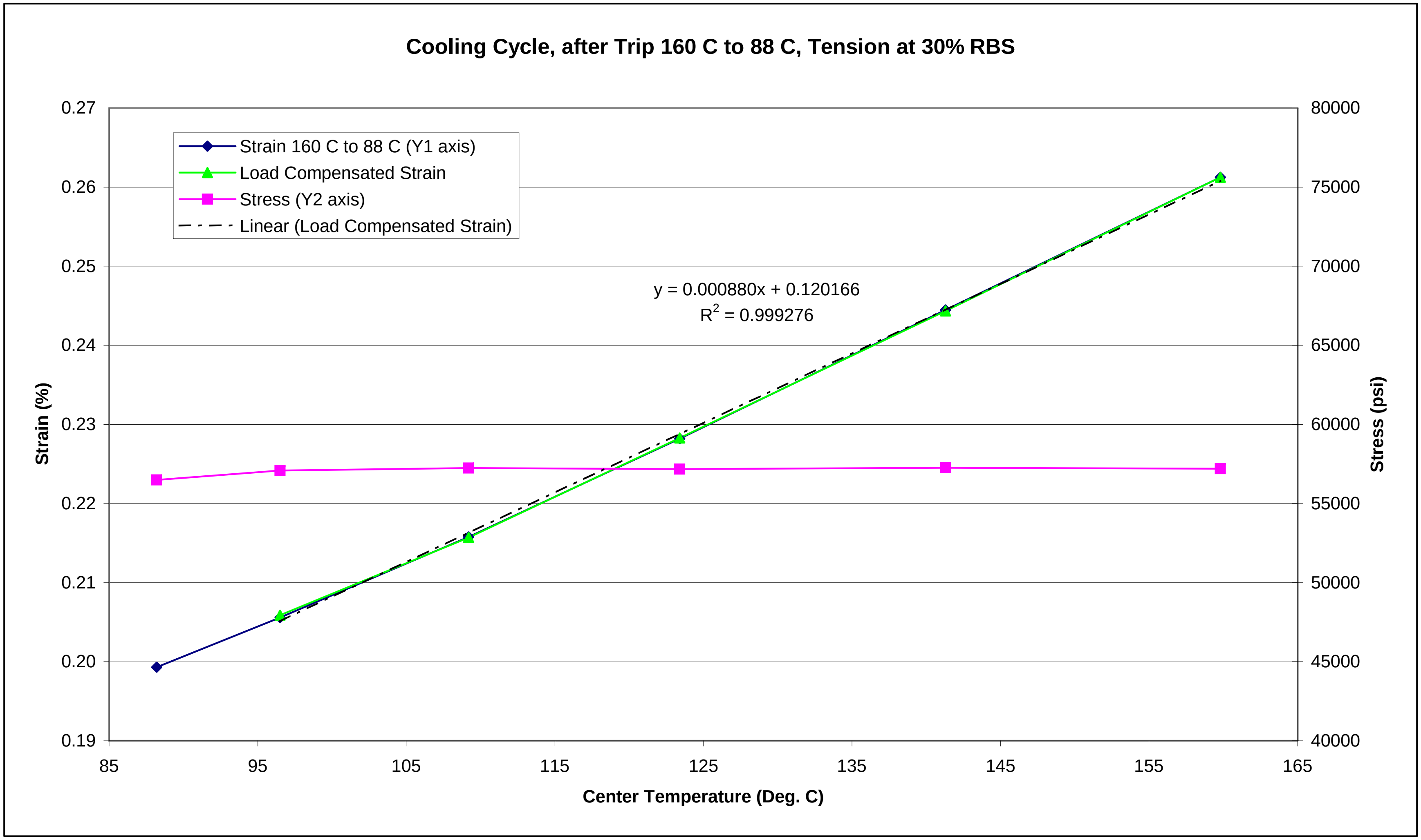


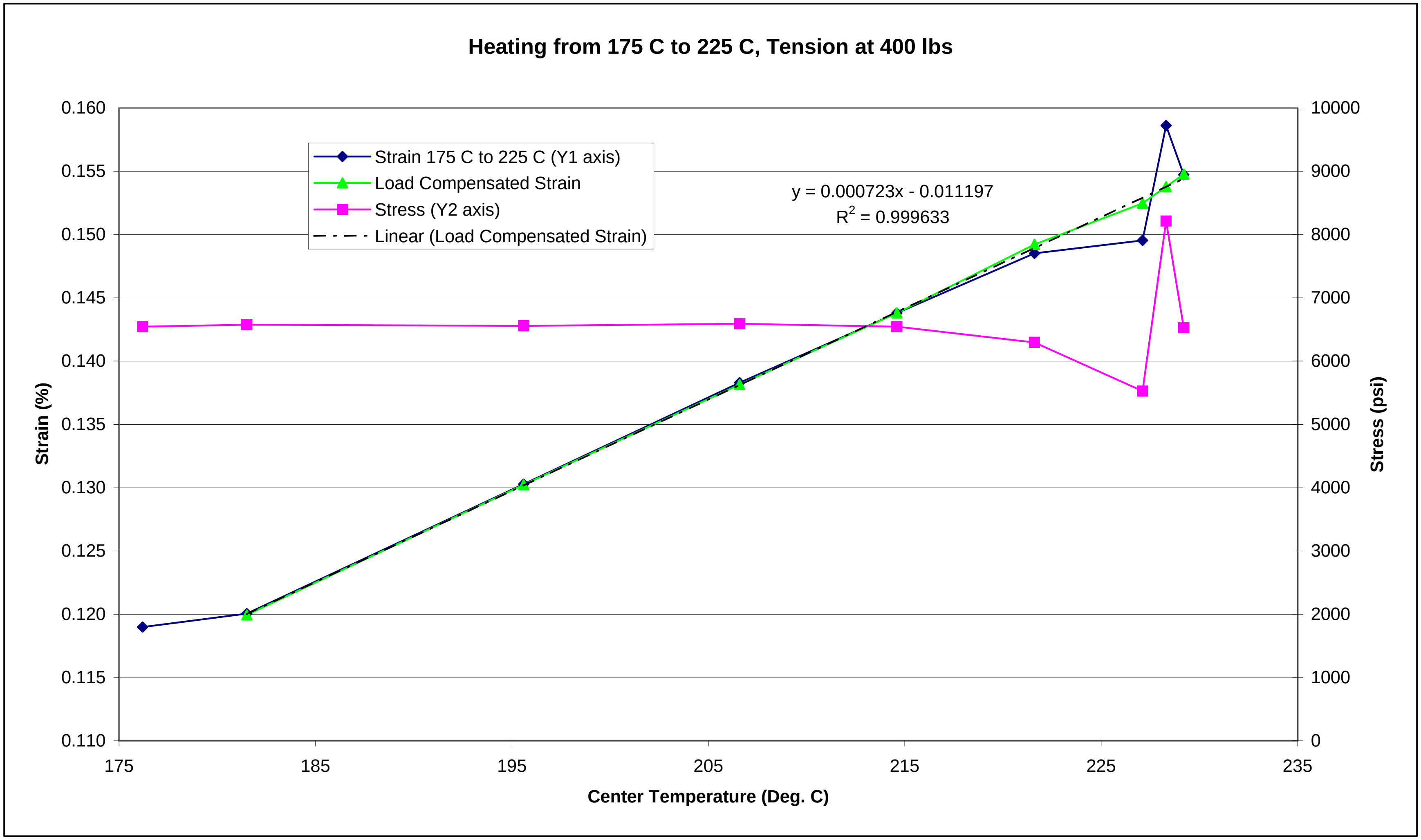
Note: Load control was nearly perfect. Data are smoother, but the coefficient value is consistent with tests where load control was “hunting”.

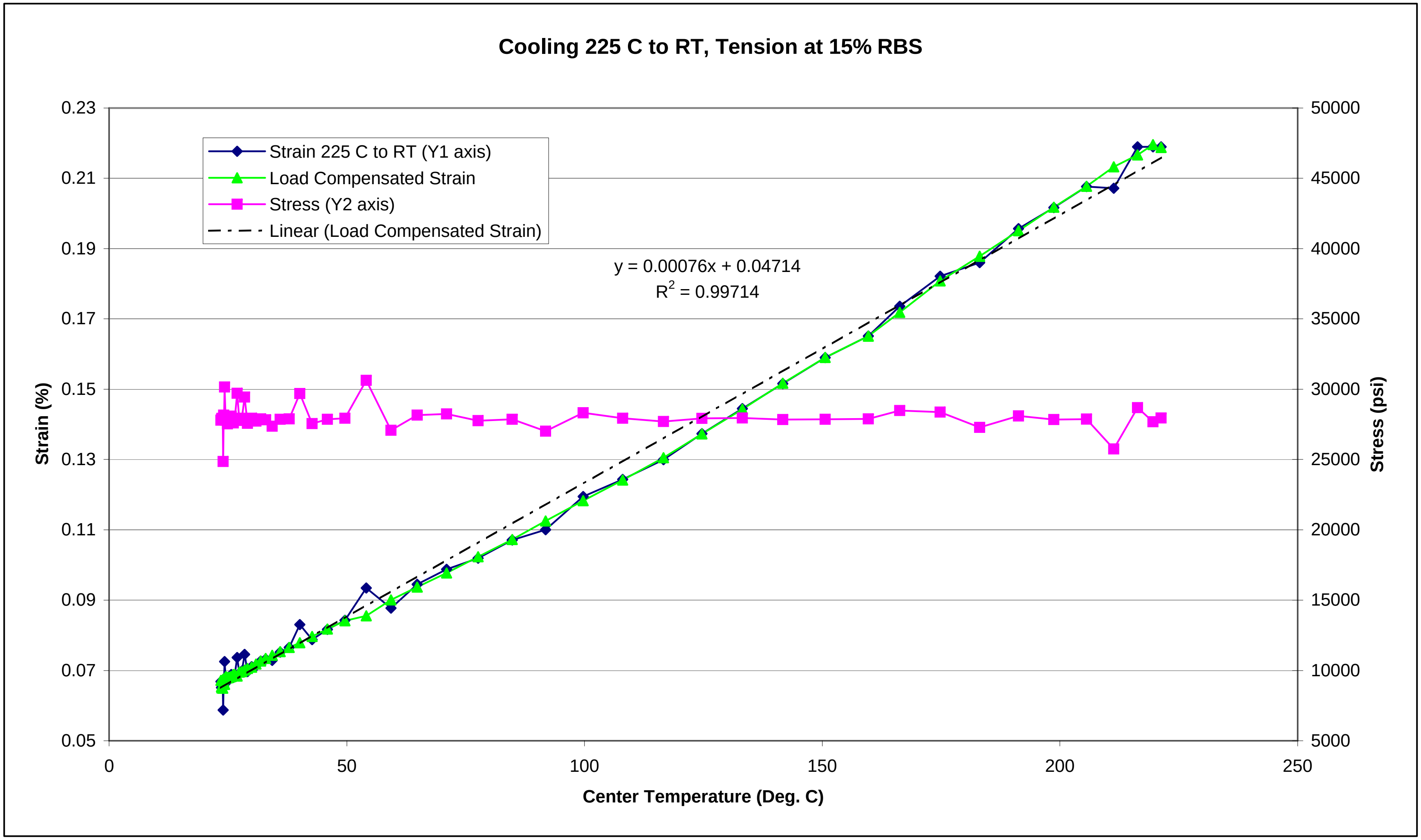


Note: Curvature in the data suggests slight temperature dependency of the thermal coefficient. Slope appears to be higher at higher temperature, but effect is small.


Heating from RT to 175 C, Tension at 30% RBS
Strain RT to 175 C (Y1 axis)
Load Compensated Strain
Stress, RT to 175 C (Y2 axis)
Linear (Load Compensated Strain)
y = 0.000764x + 0.141425
R2 = 0.999250
Strain (%)
Stress (psi)
Center Temperature (Deg. C)
0.27
0.25
0.23
0.21
0.19
0.17
0.15
80000
75000
70000
65000
60000
55000
50000
20
40
60
80
100
120
140
160


Cooling Cycle, after Trip 160 C to 88 C, Tension at 30% RBS
Strain 160 C to 88 C (Y1 axis)
Load Compensated Strain
Stress (Y2 axis)
Linear (Load Compensated Strain)
y = 0.000880x + 0.120166
R2 = 0.999276
Strain (%)
Stress (psi)
Center Temperature (Deg. C)
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
80000
75000
70000
65000
60000
55000
50000
45000
40000
85
95
105
115
125
135
145
155
165


Heating from 175 C to 225 C, Tension at 400 lbs
Strain 175 C to 225 C (Y1 axis)
Load Compensated Strain
Stress (Y2 axis)
Linear (Load Compensated Strain)
y = 0.000723x - 0.011197
R2 = 0.999633
Strain (%)
0.160
0.155
0.150
0.145
0.140
0.135
0.130
0.125
0.120
0.115
0.110
Stress (psi)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
175
185
195
205
215
225
235
Center Temperature (Deg. C)



Note: Again, curvature in the data suggests slight temperature dependency of the thermal coefficient.

Appendix 3

Analysis of NEETRAC's Thermal and Elastic Strain-Mapping Test on the Core of 477 kcmil (26/7) ACCR

by

Stephen Barrett
Barrett Research

Analysis of NEETRAC's Thermal and Elastic Strain-Mapping Test on the Core of 477 kcmil (26/7) ACCR

Purpose of the Test

Elastic moduli are known to decrease as temperature increases. Likewise, the thermal expansion properties depend on stress. Because the composite core is intended to be used at temperatures up to approximately 250 °C, it is necessary to determine core strain as a function of both temperature and stress.

NEETRAC's Test

NEETRAC measured the elastic strain as a function of core tension at a series of temperatures, nominally 20, 75, 125, 175 and 225 °C. The tension varied between 400 lb and 3490 lb (core area = 0.0610 in^2). The reference strain (zero) was at Tension = 400 lb at room temperature. The reference strain and gauge markers were never changed during the series of tests so that any plastic elongation could be distinguished from elastic and thermal elongation.

The order of tests was:

- Room Temperature With Hold
- Room Temperature Without Hold
- 75 °C With Hold
- 75 °C Without Hold
- 125 °C With Hold
- 125 °C Without Hold
- Room Temperature creep for approx 15 hours at approx. 3490 lb.
- 175 °C With Hold
- 175 °C Without Hold
- 225 °C With Hold
- 225 °C Without Hold
- Return to 400 lb at room temperature

Plastic Elongation

Each of the 10 stress-strain loops had a width of 0.01% strain. One might expect that the total plastic strain at the end of the test would therefore be approximately 0.10% strain. This was not the case, however. At the end of the test, the strain was –0.001% at 22 °C. The plastic strain was not accumulating with each test. This can be seen in NEETRAC's graph of "Load Cycles Without Hold" (in file 02224MAP.xls), where the data are superimposed on the "Load Cycles With Hold". There is virtually no difference between the pairs of tests at each temperature. The
0.01% plastic strain on each cycle is recoverable when the tension is reduced to low levels. The recovery can be seen in the "final" decreasing portion of each cycle as a slight toeing in of the curve. The plastic strain in the elastic portion of each cycle (decreasing tension) is effectively constant at approximately 0.01% for all of the cycles, which simplified the analysis.

Elastic Modulus

The normal practice when fitting the elastic modulus is to use the upper portion of the curve.

In the NEETRAC test, the "final" curves are highly linear, even though a slight non-linearity is evident. The error in the fit at low tensions is approximately 0.003%, which is negligible. A very good fit to the upper slopes of all the final curve was obtained with:

$$\text{Tension} = (21870 - 3.3\ T) \times \%\text{Strain}$$

where T is temperature in C°.

The core area is 0.0610 in^2.

1) The Elastic Modulus is therefore given by:

$$\mathbf{E = 35.85 - 0.0054\ T}$$

where E is the Elastic Modulus in Msi
T is temperature in C°.

2) The Thermal elongation at Tension = zero was fitted by:

$$\mathbf{\%Strain = 0.00063\ T + 2.5 \times 10^{-7}\ T^2}$$

The Sag-Tension Programs Strain-Sum and STESS, which use the Strain Summation Method, employ temperature-dependent elastic moduli and quadratic thermal expansion data in the format given above, so no modification will be required to enter these fits.

3) A constant term of -0.015% strain was required to fit the data. This includes the plastic strain of approximately +0.01% and a negative offset to transfer the reference strain (zero) to zero tension at 0°C. (The experiment reference strain was 400 lb tension at room temperature.)

All of the elastic curves of NEETRAC's graph "Load Cycles With Hold" were fitted without change, using the "temperatures at the centre of the sample when the upper, decreasing-tension portions of the cycle were measured.

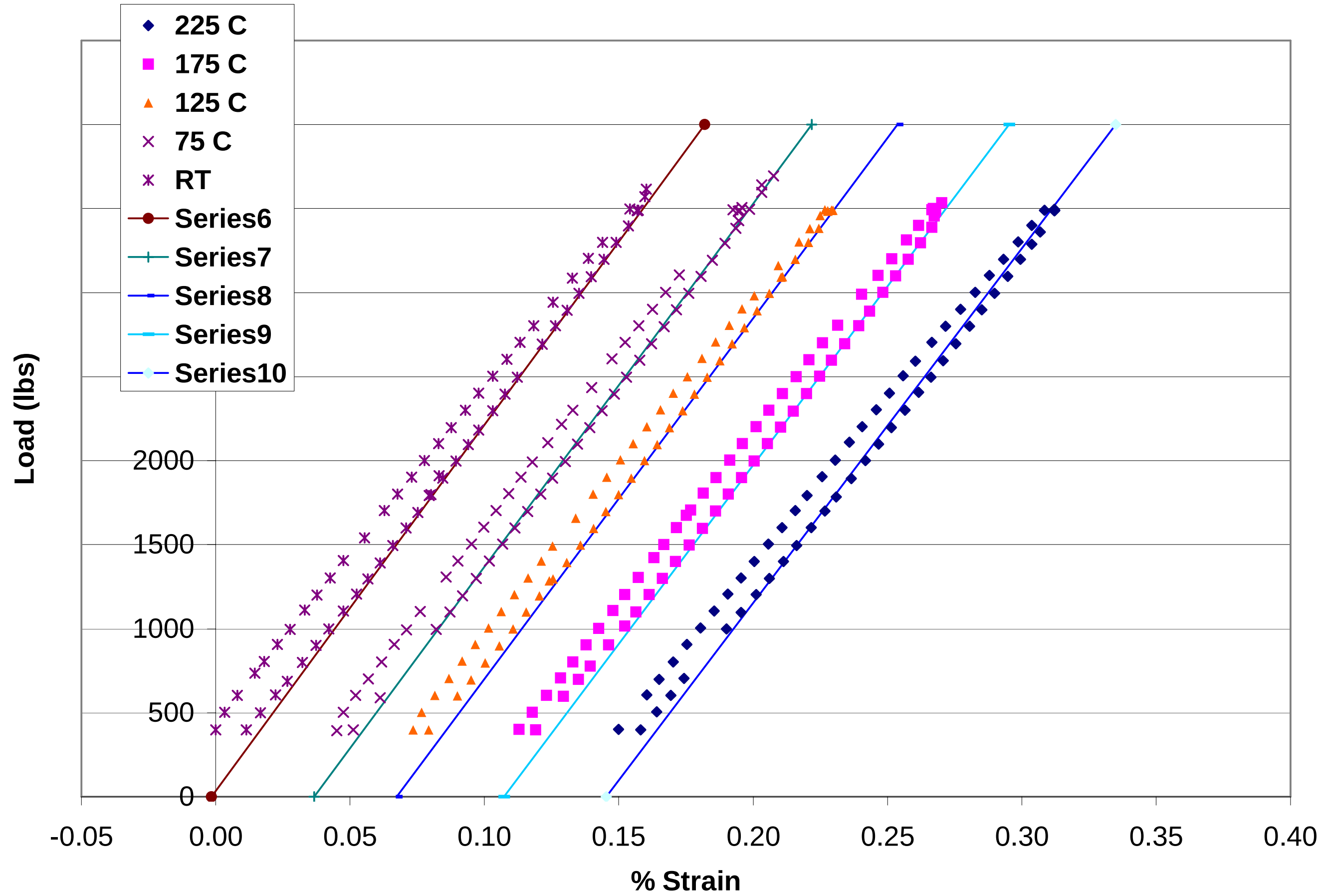
The temperatures used in the fit were:

21.2 °C, 79.5 °C, 124.5 °C, 181.0 °C and 232.0 °C

4) The equation used to fit the data was:

$$\mathbf{\%Strain = -0.015 + [0.00063\ T + 2.5 \times 10^{-7}\ T^2] + [Tension/(21870 - 3.3\ T)]}$$

Fit to NEETRAC's Data using a single Equation (Equation 4, above):



"Load Cycles With Hold" from NEETRAC's 02224MAP.xls

The fit is very good. It is within 0.003% strain at the low end of each cycle. The error at the top of the 225 °C cycle is about the same and could be a result of the average temperature of the sample being about 3 C° hotter than the "centre" temperature that was used for the fit.

Comment on the Stress Dependence of the Thermal Expansion

The equations given above may be used to derive equations for thermal expansion at constant stresses other than zero, but it is unnecessary to do this in order to compute the sum of thermal and elastic strain. The approach used to analyze the NEETRAC test and used in the Strain-Summation Method of Sag-Tension Calculation is probably the easiest to visualize:

The thermo-elastic strain may be visualized on a 3-dimensional plot of strain ε as a function of temperature T and stress σ, where the origin is ($T=0$, $\sigma=0$, $\varepsilon=0$). The strain solution may be approached from the origin by first going to temperature T along the temperature axis (i.e. at zero stress). Once the temperature has been reached, the point (T,σ,ε) is approached by moving towards it parallel to the stress axis (i.e. at constant temperature).

Comment on the Quality of the Data

NEETRAC is to be commended on the superb quality of their experimental procedure and data reporting. With the cycle performed twice at each temperature, the reproducibility was better than 0.003%, which is remarkable. Plastic elongation was shown to be approximately 0.01% throughout the testing and a creep period at the highest tension level had negligible effect. These are valuable things to know, in addition to the thermo-elastic properties.

Stephen Barrett
Barrett Research
April 4, 2003