596TW Type 13, 3M Brand Composite Conductor
Stress-strain, Tensile, and Resistance

3M Company
Purchase Order 0000866971

NEETRAC Project Number: 03-070

August, 2003

National Electric Energy Testing, Research & Applications Center
NEETRAC
A Research Center of
The Georgia Institute of Technology

Requested by: Mr. Colin McCullough
3M

Principal Investigator: ______________________
Paul Springer III, P.E.

Reviewed by: ______________________
Dale Callaway

596TW Type 13, 3M Brand Composite Conductor
Stress-strain, Tensile, and Resistance

3M Company
Purchase Order 0000866971

NEETRAC Project Number: 03-070

August, 2003

Summary:

3M contracted with NEETRAC for a series of tests designed to characterize the mechanical behavior and DC resistance of 596TW kcmil, 20/7, 3M Brand Composite Conductor. All test results confirm the 3M specifications. The stress-strain data is used for estimating the in-service sag versus tension characteristics.

Samples:

1) Conductor reel with 596TW 3M Composite Conductor received from 3M on April 3, 2003. This has also been called 477 ACCR/TW since it has same diameter as 477 kcmil conductor.

References:

1) "Proprietary Information Agreement …." Dated 3/27/01, and renewed 3/03.
2) Aluminum Association Guide, Rev. 1999, "A Method of Stress-Strain Testing of Aluminum Conductors and ACSR".
3) 3M Purchase Order 0000866971
4) E-mail dated 6/7/01 from Colin McCullough with details on conductor and core strand properties.
5) PRJ 03-070, NEETRAC Project Plan.

Equipment Used:

1) MTS Servo-hydraulic tensile machine, Calibration control # CQ 0195 (load and crosshead data)
2) Dynamics Research Corporation (DRC)/NEETRAC cable extensometer, Calibration control # CQ 3002 (strain data)
3) Yokogawa DC100 data acquisition system, Calibration control # CN 3022 (temperature data)
4) AVO (formerly Biddle) digital low resistance Ohmmeter, calibration control # CQ 1083
5) Brooklyn Reference Standard thermometer, Serial # 86-706, calibration control # CN 0155

Procedure and Results:

I Tensile Tests

Samples were cut from the reel and terminated using a procedure designed to preserve the "as manufactured" position of all conductor layers. Clamps are installed on both sides of any conductor cut, and remain in place throughout the sample preparation process. The process ensures that the test section is representative of the conductor condition as received on the reel.

Cast-resin terminations were installed on each end of three (3) test samples, each with a 20-ft active gage section. Samples were pulled to destruction at a loading rate of 10,000 lb/min. According to the 3M conductor specifications, the rated breaking strength (RBS) for the 596TW Composite Conductor is 21,263 lbs. The following results were obtained:

Sample #	Breaking load (lbs)	%RBS	Failure description
03070001	22,500	106	Tensile break, all strands, in gage section, 2 ft from dead end
03070002	22,950	108	Tensile break, all strands, in gage section, 2 ft from dead end
03070003	22,450	106	Tensile break, all strands, in center of gage section

The stress-strain conductor and core samples were also subject to tensile tests following the stress-strain test. Those results are reported in the section on the stress-strain test. Figure 1 shows data recorded for the initial tensile tests.

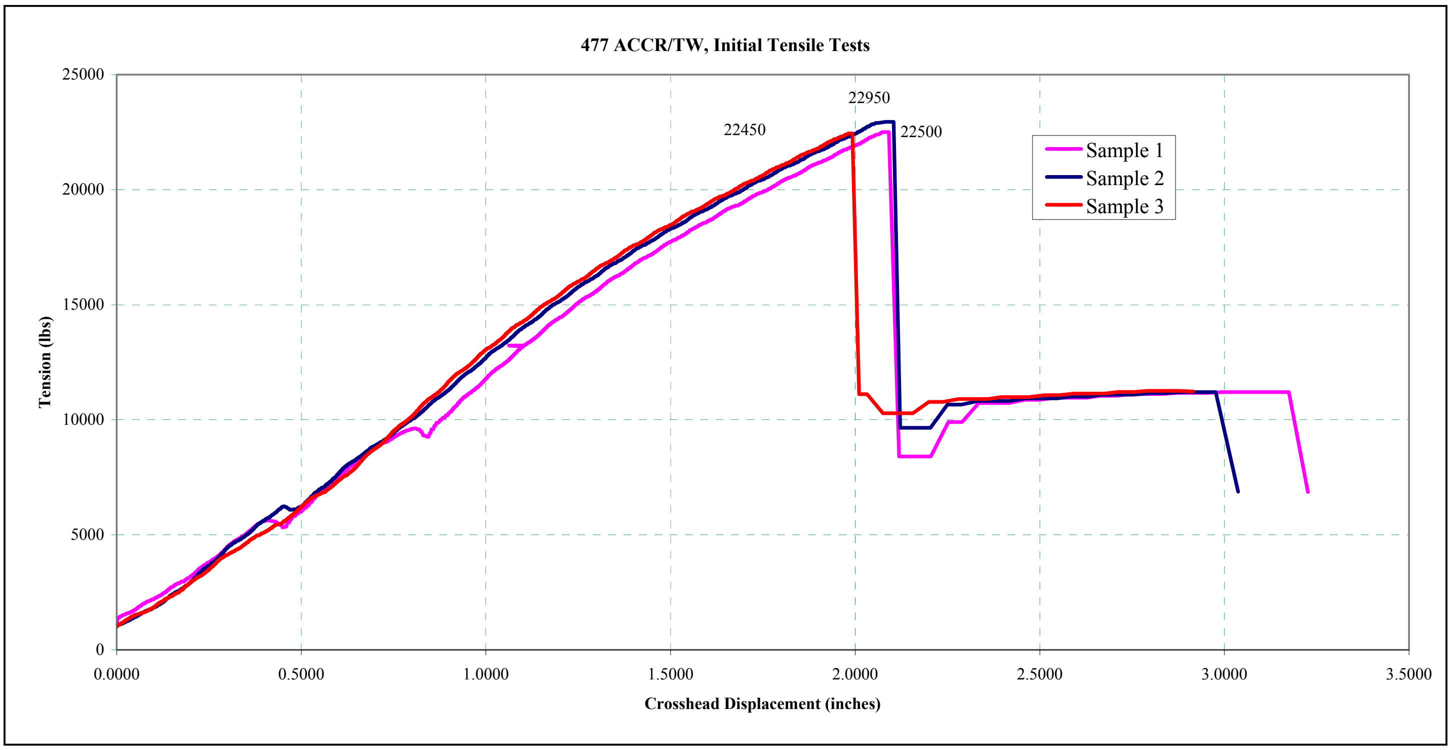


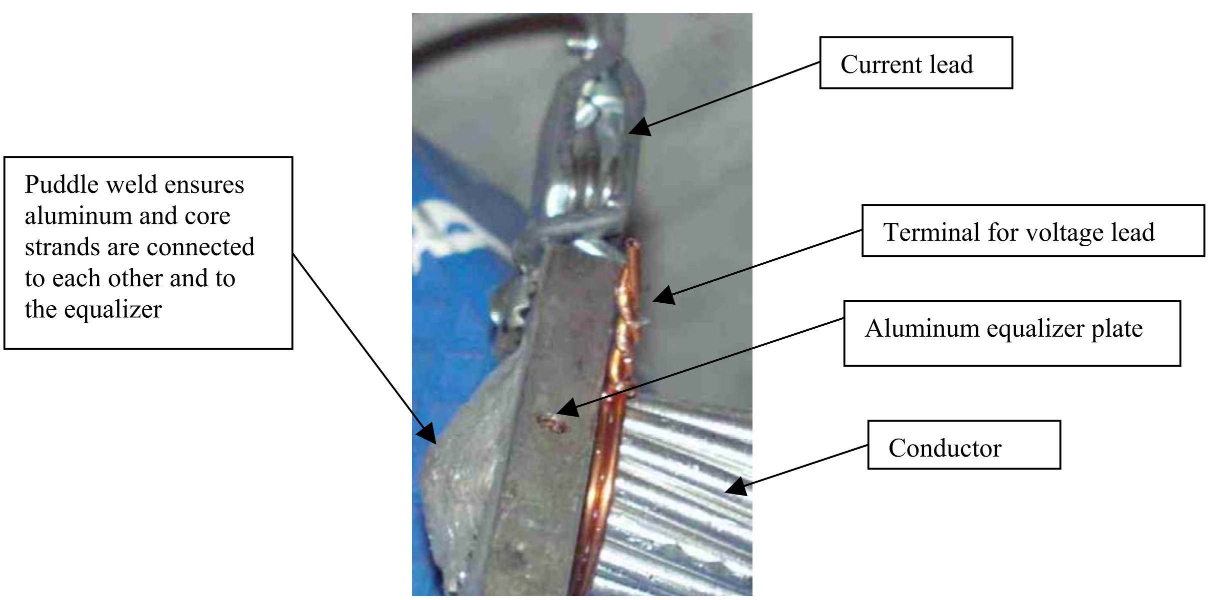
Figure 1, initial tensile test load versus crosshead displacement

II Resistance Measurement

The AVO model DLRO low-resistance Ohmmeter is a proven 4-wire instrument designed to measure extreme low resistance. The instrument is certified accurate within +/- 0.2% of reading for the resistance values measured during this project. Careful sample preparation is required to ensure that conductor resistance measurement is free of extraneous effects caused by voltage gradients within the sample.

The sample for the resistance measurement was cut from the reel using a method that prevents relative movement of any conductor layer. Layers or strands shifting slightly would not significantly affect the resistance measurement, but nonetheless are needed to preserve the remainder of the reel for future stress-strain, creep, and tensile tests. A nominal 20-ft test section was terminated at each end by puddle welding the aluminum and MMC strands into a hole drilled in a 3/8" thick section of aluminum bus bar. The aluminum bus bar and the puddle weld provide an equipotential plane for the current leads, and thereby ensure that all conductor strands carry current free from voltage gradients from localized high current near the current leads. Voltage terminals, which carry negligible current, were placed on the sample by tightly wrapping #14 AWG solid copper strands around the conductor OD. The voltage terminals are located on the conductor inboard of the current leads, and therefore remote from the influence of current flow near the current leads. Resistance readings were repeatable within +/- 0.1 μΩ with this arrangement.

Ambient temperature was recorded using a precision (0.01 °C) thermometer. Conductor temperature was measured using a thermocouple inserted between the strands of the conductor test section. A temperature resistance coefficient of 0.0036/°C (0.36%/°C) was used to correct the resistance measurement to the 20 °C reference standard used for resistance specifications. Temperature was controlled as close to the nominal 20 °C as practical to minimize any error due to temperature correction. Actual conductor temperature was 20.5 °C during resistance measurement. The gage length, or length of conductor between the two voltage terminals, was measured by pulling the conductor as straight as practical with a rope, and then measuring the distance with a metal measuring tape. The gage section length, temperatures, and raw resistance readings are loaded into a spreadsheet that calculates resistance, corrects readings to the 20 °C reference temperature, and scales the results in terms of Ohms/mile. Table 1 shows the spreadsheet with data and calculations. Photograph 1 shows one end of the conductor sample terminated for resistance measurement.



Photograph 1, Current and voltage terminals, typical each sample end
(conductor shown is not the 596TW)

Table 1, Summary of 596TW Resistance Measurements and Calculations				
Parameter		Value	Units	Comments
Temperature		20.5	deg C	Stable +/- 0.5 C for one hour
Test Section		21.563	ft	Actual measurement was 258 ¾”
Resistance Readings		604.3	µΩ	
		604.3	µΩ	
		604.2	µΩ	
Average		604.27	µΩ	Measured at 20.5 C, **not** corrected to 20 C
Ω/ft:		2.8024E-05	Ω/ft	**not** corrected to 20 C
Ω/mi		0.14797	Ω/mi	**not** corrected to 20 C
Ω/mi @ 20C:		**0.14770**	**Ω/mi**	**Corrected to 20 C**
3M nominal resistance		0.14800	Ω/mi	Corrected to 20 C
Discrepancy vs. nominal		-0.20	percent	
Error estimates:	Length	+/- .001	feet	+/- 1/8 inches
	Resistance	+/- 0.2	percent	value from AVO owners manual
	Temperature	+/- 0.5	deg C	Thermometer certified to +/-0.1 °C, but cannot control temperature better than +/- 0.5
RMS Error		0.27%	percent	RMS is typical error. Actual error can be larger.

III Stress-strain

The conductor stress-strain sample was prepared identical to the tensile samples. The stress-strain test is run in the tensile machine, but with the controls set to provide the loading profile specified in the Aluminum Association’s 1999 guide. For the composite conductor, no exceptions to the Aluminum Association’s guide are needed. For the core stress-strain test, the Aluminum Association requires a calculation for the starting condition for the test. The guide provides values for steel core elastic modulus to use in the calculation, but does not provide the values for MMC core. The 3M nominal value for core strand elastic modulus was used. The change is small, and has negligible effect on the test results. The core stress strain sample was prepared by removing all aluminum strands from a conductor sample. The core is wrapped, and clamps are not required to maintain strands in the correct alignment.

The conductor sample was mounted in the MTS hydraulic tensile machine. The active gage section between knife-edges on the cable extensometer is 18 feet, +/- 1/16”. A support is used to remove sag at the mid-point, and thereby minimize slack affects in the strain data. Tension is controlled automatically. Load, crosshead position, elongation, and temperature data were saved to a computer file. The file was processed to produce the stress-strain charts. See Appendix 1 for an error analysis for the test system. The stress-strain plots are in Appendix 2. The modulus data are in "Results" section of this report. Photograph 1 shows the long view of the test apparatus. Photograph 2 is a close-up of the resin socket and extensometer attachment.

Placing a support at 1/2 span minimizes conductor slack. This ensures the conductor is nearly straight, prevents slack from showing up as elongation in the stress-strain data. Photograph 3 shows the mid-span support. The test profile is in accordance with the Aluminum Association guide, as follows:

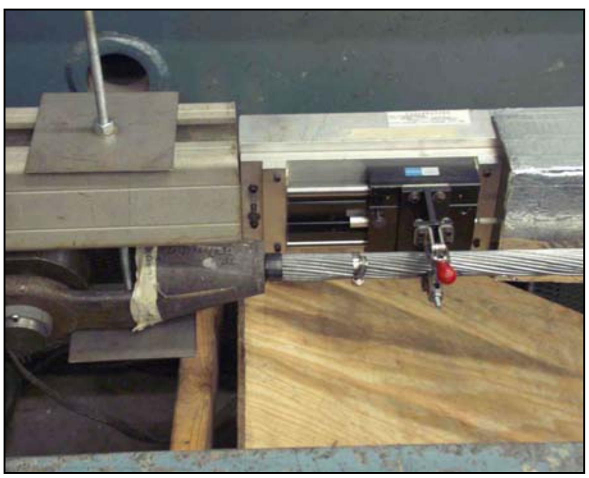
Composite conductor:

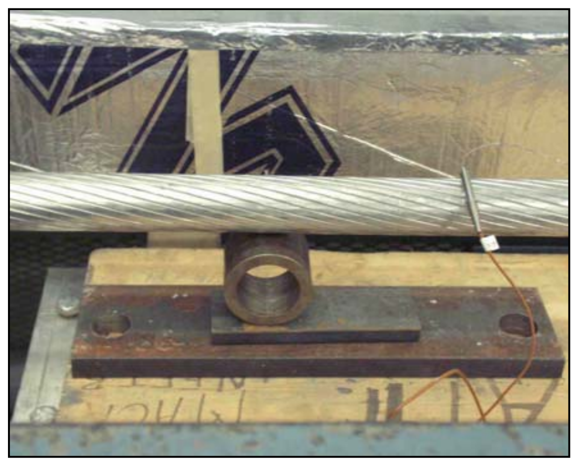
1) Apply load of 1,000 lbs. Remove sag with a mid-span support.
2) Install extensometer, and set to zero.
3) Pull to 30% of RBS (6,380 lbs). Hold for 30 minutes.
4) Relax load to 1,000 lbs.
5) Pull to 50% RBS (10,630 lbs). Hold for one hour.
6) Relax load to 1,000 lbs.
7) Pull to 70% RBS (14,880 lbs). Hold for one hour.
8) Relax load to 1,000 lbs.
9) Pull to 75% RBS (15,950 lbs).
10) Relax load to 1,000 lbs, and remove the extensometer (for its own protection).
11) Pull to destruction.

Core strands:

1) Pull to calculated initial tension (in this case, 349 lbs)
2) Install extensometer, and set to zero.
3) Pull to same strain as conductor at start of 30% of RBS test (0.10074%). Hold for 30 minutes.
4) Relax load to 349 lbs.
5) Pull to same strain as conductor at start of 50% of RBS test (0.19148%). Hold for one hour.
6) Relax load to 349 lbs.
7) Pull to same strain as conductor at start of 70% of RBS test (0.31333%). Hold for one hour.
8) Relax load to 349 lbs.
9) Pull to 75% RBS (8,726 lbs).
10) Relax load to 349 lbs, and remove the extensometer (for its own protection).
11) Pull to destruction.

Photograph 1, Long View of Stress-Strain Test





Photograph 2
Sliding Carriage and Linear Position Instrument

Photograph 3
Mid-span Support to Remove Sag

(Conductor in photographs is <u>not</u> 596TW, but does illustrate the test configuration)

Data files containing test data were processed using Excel® to obtain engineering values and graphical presentation. Graphs showing data for each test are shown in Appendix 2. The stress-strain test requires approximately 3 hours to complete. Cycling of the room temperature controls resulted in a temperature shift of 0.8°C during the conductor stress strain test, and 1.4 °C during the core test. The strain data were compensated for known effects of thermal expansion of the sample and the strain instrument. Details are in Appendix 1, "Error Analysis".

The following formulas describe the mechanical properties of the conductor, where t is time in hours, stress is in psi, strain is in percent. Data are temperature compensated. The polynomial equations are translated along the strain axis using a numerical technique. Curve translation and temperature compensation of the raw data change the value of strain predictions by no more than 0.5%, or approximately half of the estimated error for the measurement.

Conductor Properties:

Initial modulus:	Stress (psi) = 213,952*(Strain%)^3-206,730*(Strain%)^2 +125,242*(Strain%)
Final modulus:	Stress (psi) = 113,595*(Strain%) – 13,513
Residual tensile strength:	22,020 lbs (104% RBS), failure in gage section, mid-span

Core Properties:

Initial modulus:	Stress (psi) = -42,678*(Strain%)^2 +326,075*(Strain%)
Final modulus:	Stress (psi) = 70,666*(Strain%)^2 +298,212*(Strain%) - 5004
Residual tensile strength:	11,380 lbs (98% RBS), failure in gage section, multiple locations

Aluminum Properties:

Initial modulus:	Stress (psi) = 241839*(Strain%)^3 -228,113*(Strain%)^2 + 99,065*(Strain%)
Final modulus:	Stress (psi) = 85,018*(Strain%) – 12,340

Acknowledgement:

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

Appendix 1, Calibration and Error Analysis for Stress-Strain Tests

Mechanical load (stress):

Measurement equipment is certified to exceed requirements of ASTM E4-1998 (+/-1%). MTS Tensile Machine "as-found" calibration data show accuracy is typically better than 0.5%. Stress is calculated based on the nominal (as opposed to measured) conductor dimensions.

Conductor Elongation (strain):

The DRC displacement transducer resolution is +/- 0.0001". For the 18 ft. gage section, resolution is 0.0001"/216", or 0.000046% (0.46 PPM). Sensor accuracy is +/- 0.0002", or 0.92 PPM. This is a digital measurement made with a laser diode reading an etched titanium silicate (glass) rod. The material has near-zero thermal coefficient. Data are transmitted via digital communication with an interface board in a PC data acquisition system. Therefore, there is no calibration drift or temperature sensitivity for the transducer. However, the elongation instrument has other error sources that need to be counted. Here is an estimate for those errors:

Effect of load measurement errors: strain error is linear wrt load error. Error is 0.5% of reading.

Effect of mechanical deflections of the gage rod: The gage rod is a 2" x 6" x 1/8" x 19 ft aluminum box beam, which is extremely stiff. The only bending force is friction in the guide bearings and wiper seals for the displacement sensor. Starting and running friction were measured as 0.3 lbs, and 0.2 lbs respectively. The error is less than 0.5 PPM.

Effect of thermal expansion of the sample and gage rod:

i. Conductor: Lab temperature changed 0.8^{o}C during the conductor stress-strain test. Assuming the conductor thermal elongation is 17 ppm/^{o}C, and the gage rod thermal expansion is 23 ppm/^{o}C, the possible error is 4.8 ppm. Temperature compensation was employed, and it is estimated that the residual error is 0.5 ppm.

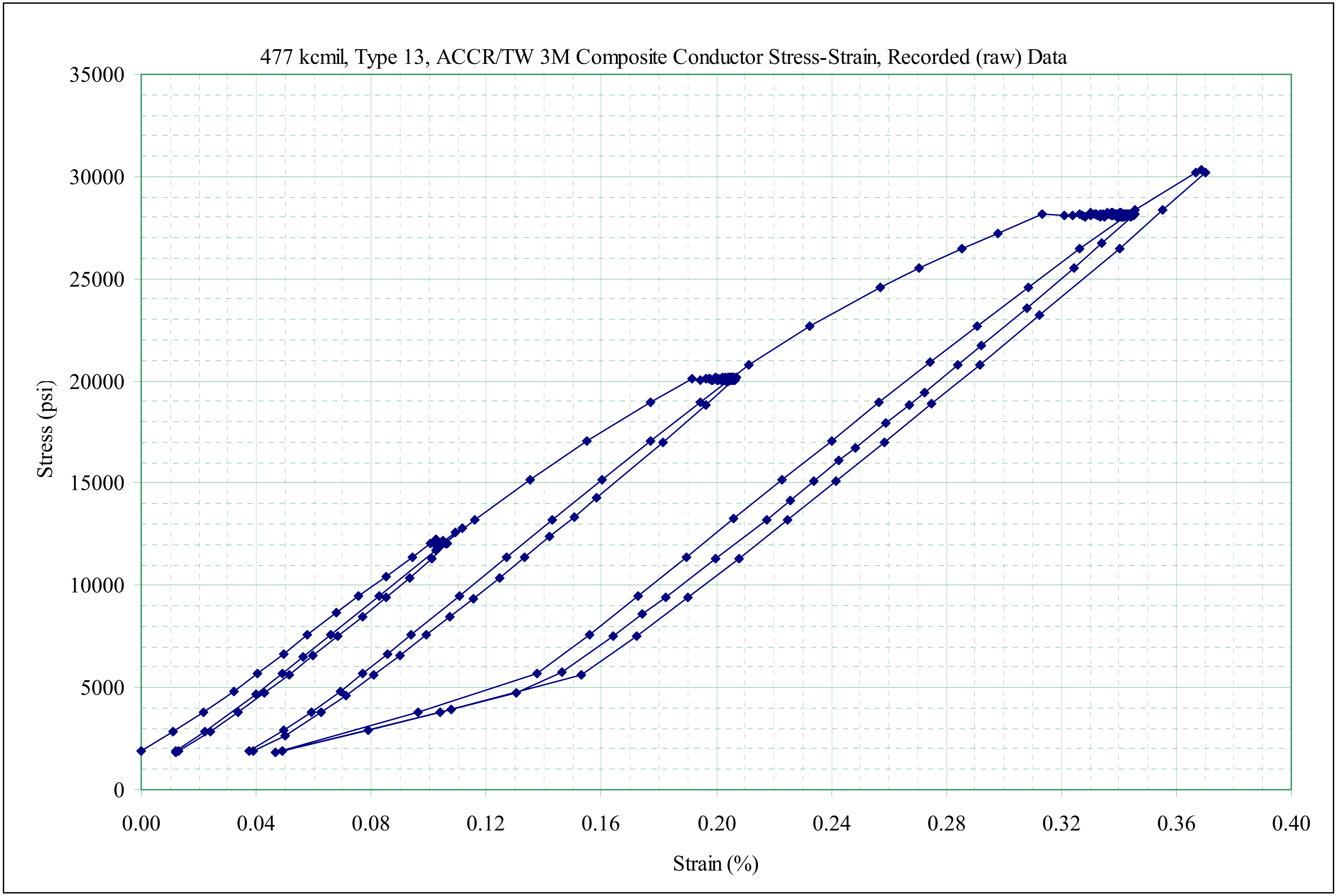
ii. Core: See appendix 2 for a graph showing gage rod temperature, recorded strain, and compensated strain. Lab temperature changed 1.4^{o}C during the core stress-strain test. Assuming the core thermal elongation is 6 ppm/^{o}C, and the gage rod thermal expansion is 23 ppm/^{o}C, the possible error is 23.8 ppm. Note however that the temperature was cycling with the operation of the building air conditioning system, and the more significant data points at the end of the load hold periods are compensated by less than half this amount. Errors in the compensated data are caused by uncertainty in the temperature data and thermal modulus values. With compensation, the error due to thermal expansion effects is estimated at 2 ppm.

Effect of starting gage length:
An error of +/- 1/16" is possible. The maximum error affects the strain measurement by 0.02% of reading.

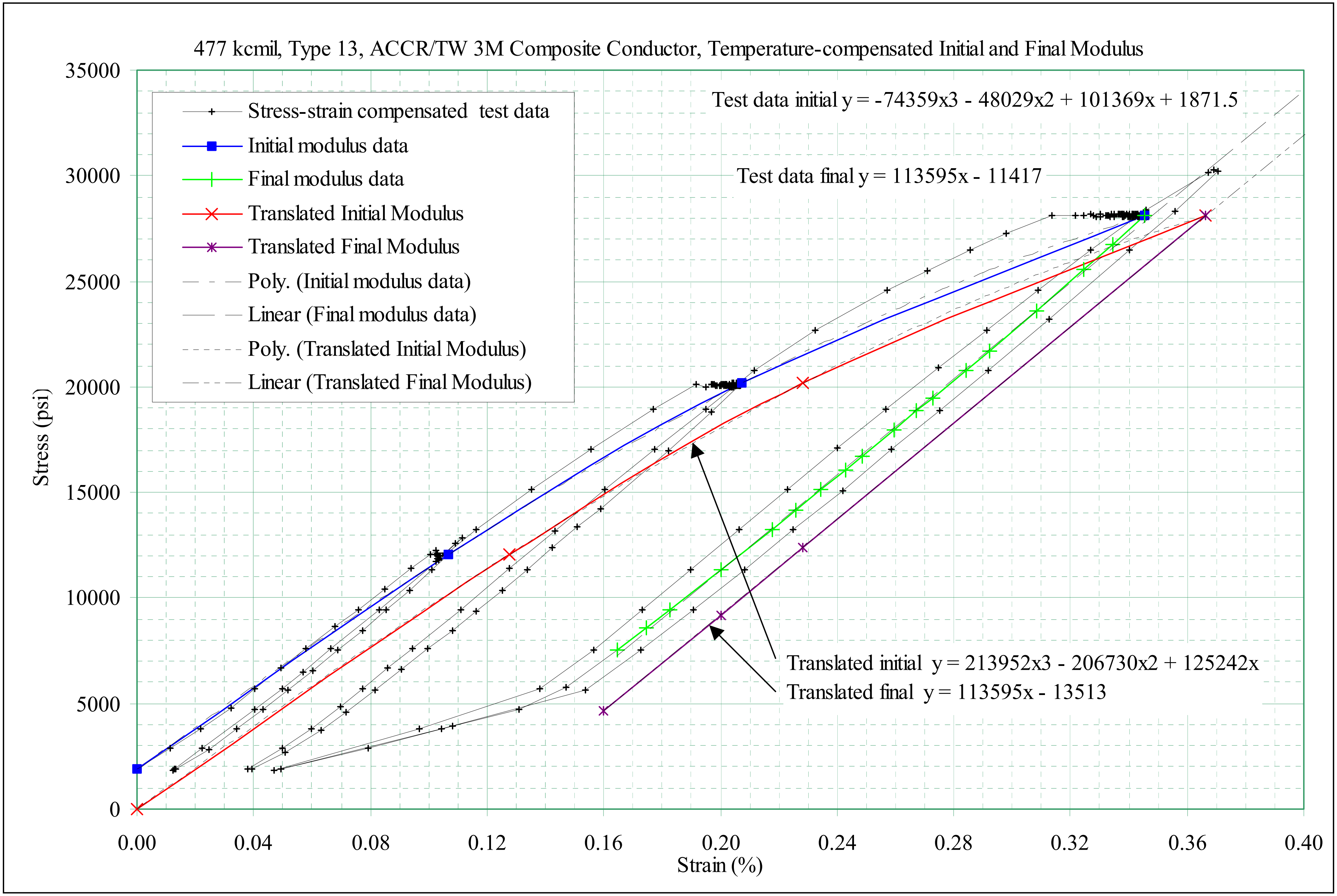
Overall accuracy is calculated based on root-mean squared error estimation. Given the assumptions above, the elongation measurement is considered accurate within 1% of reading, plus or minus 2 parts per million. RMS error is considered a typical error, not a maximum error. Actual error can be greater than the RMS error. The Aluminum Association specifications do not provide accuracy requirements, but suggest that the resolution of the measurement should be 10 PPM. The system employed has resolution of 0.46 PPM (0.0001 inches in 18 ft).

Appendix 2
Stress-Strain Graphs

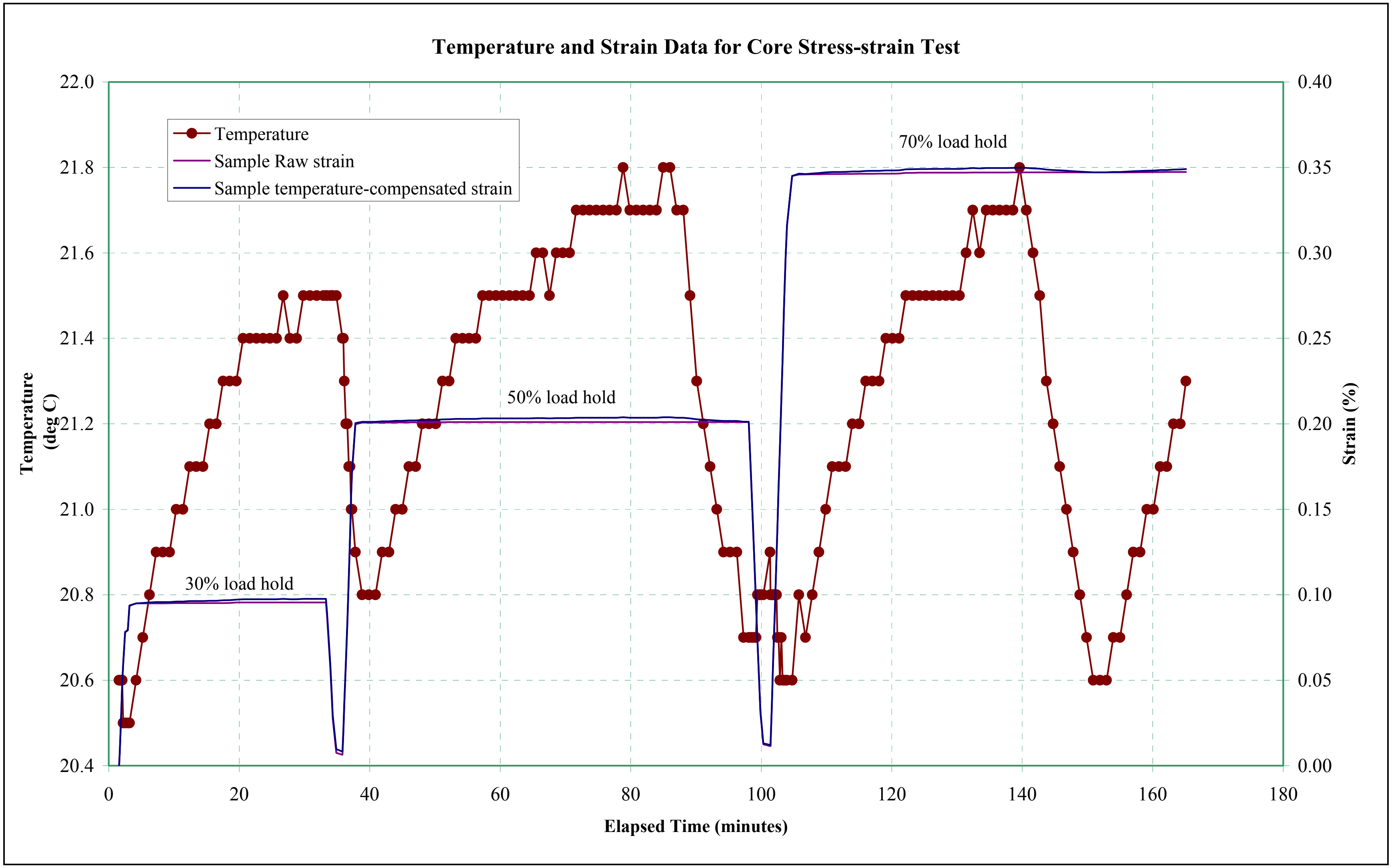
(Data files containing raw and processed data have been sent via e-mail, and are available upon request)



Composite Stress-Strain Plot in Accordance with Aluminum Association Guide

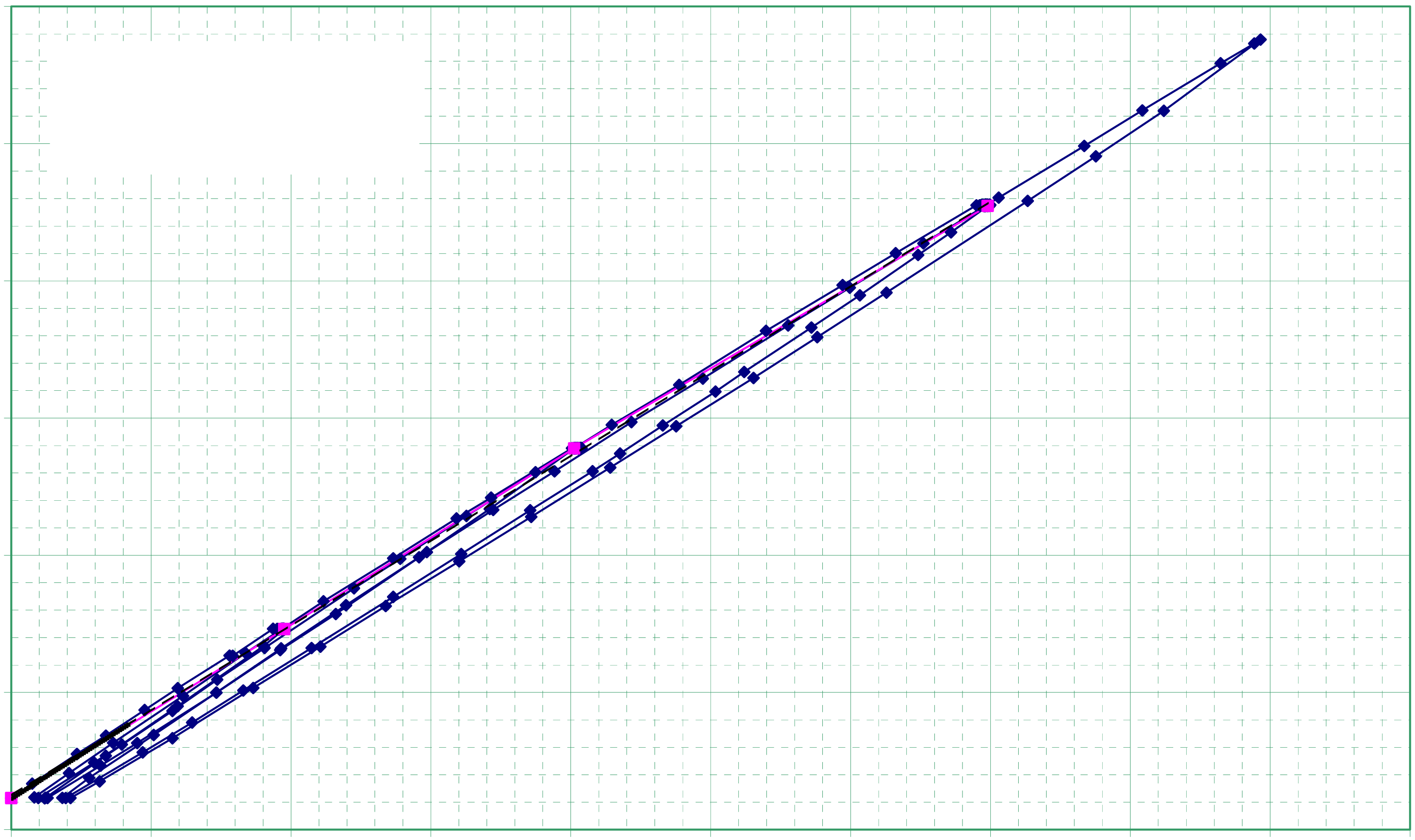


Temperature-corrected Composite Stress-Strain Plot with Data Fit for Initial and Final Modulus

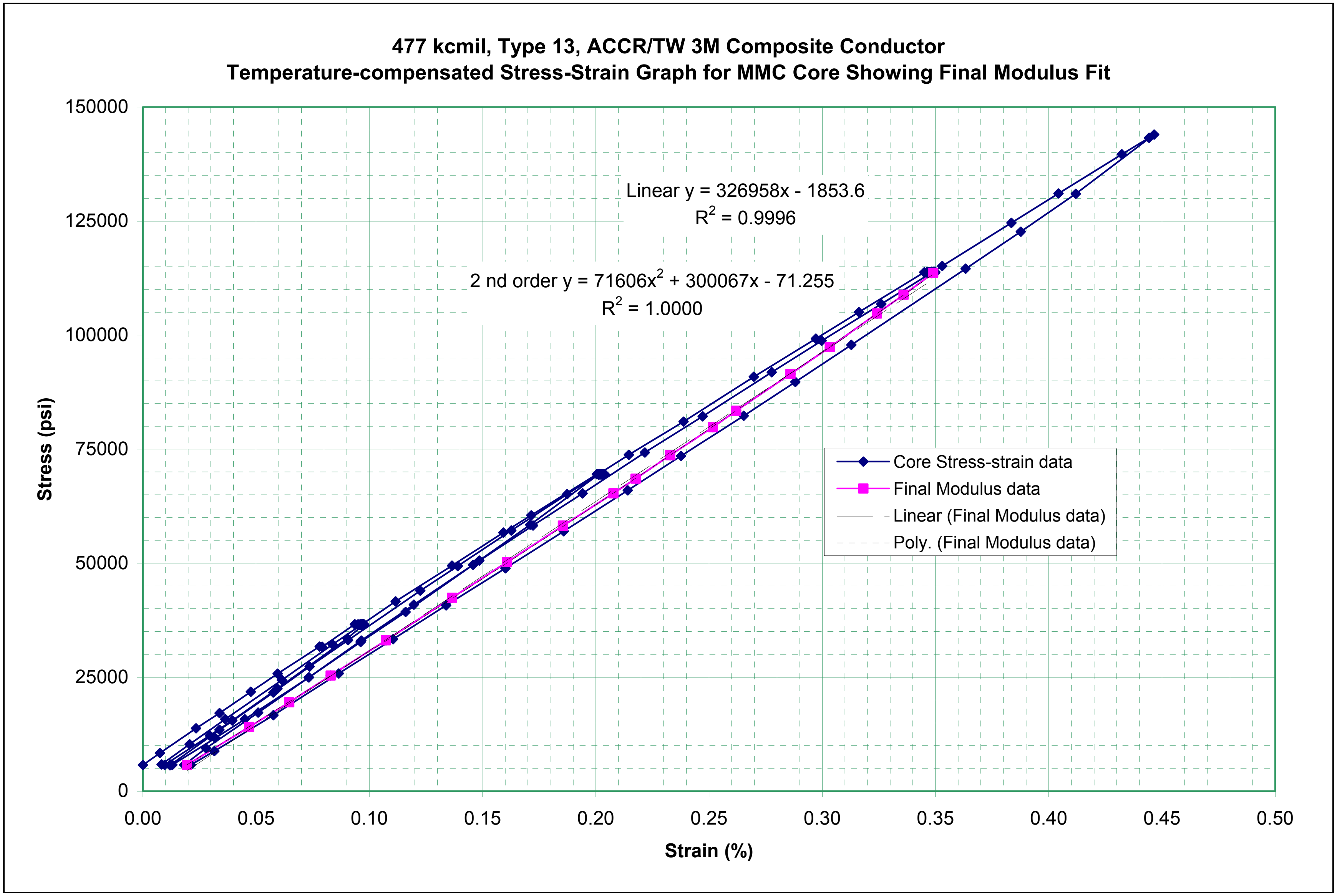


Time profile for gage rod temperature, recorded strain, and compensated strain for the MMC core stress-strain test

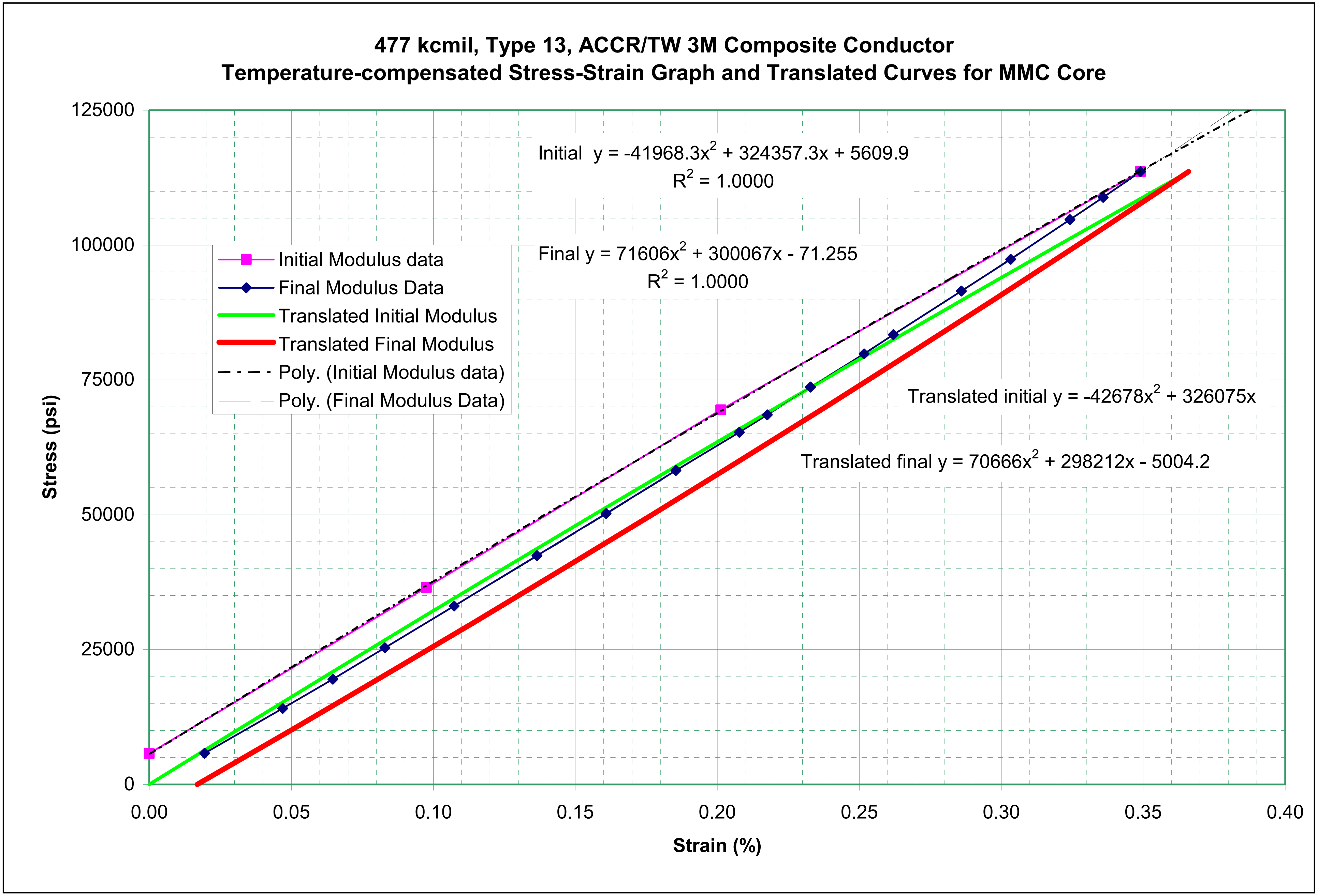
Chart shows cycling of air conditioning system. Chart also shows the fortuitous circumstance that the temperature change is small at the end of each hold period, and therefore compensation is not significant at the more important points in the test.



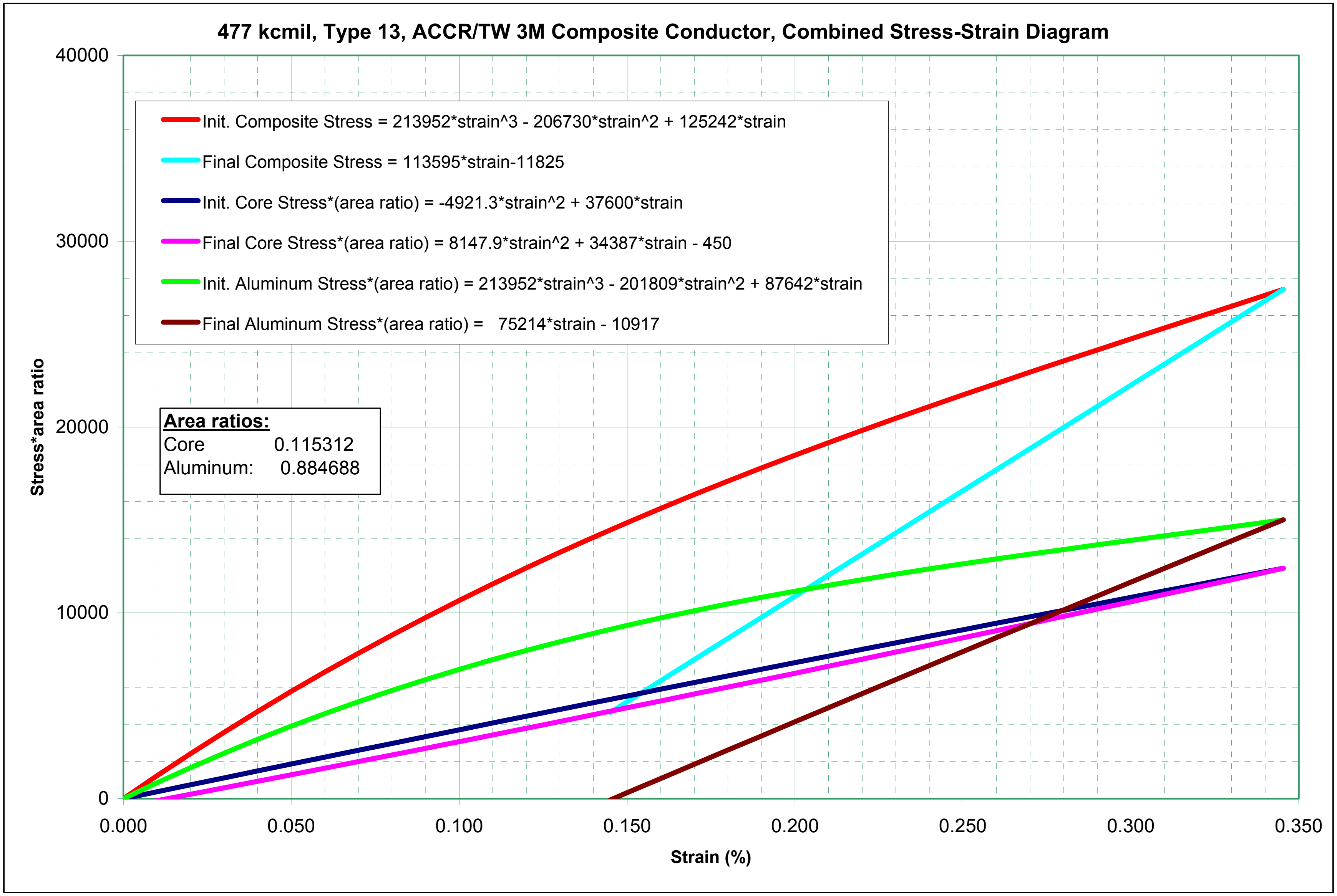
Temperature-compensated Core Stress Strain per Aluminum Association Guidelines, and Initial Modulus Fit



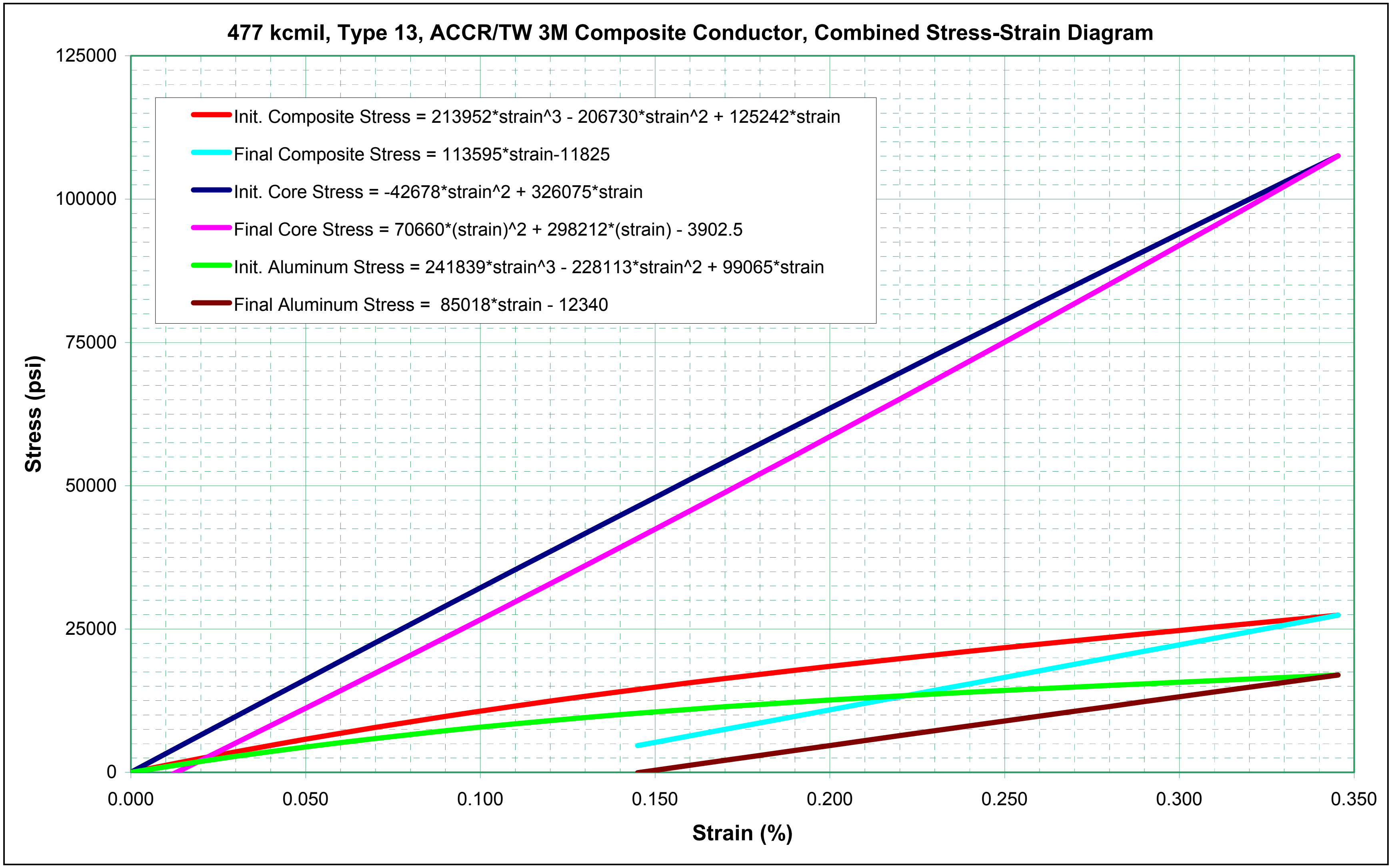
Core Stress Strain per Aluminum Association Guidelines, and Final Modulus Fit



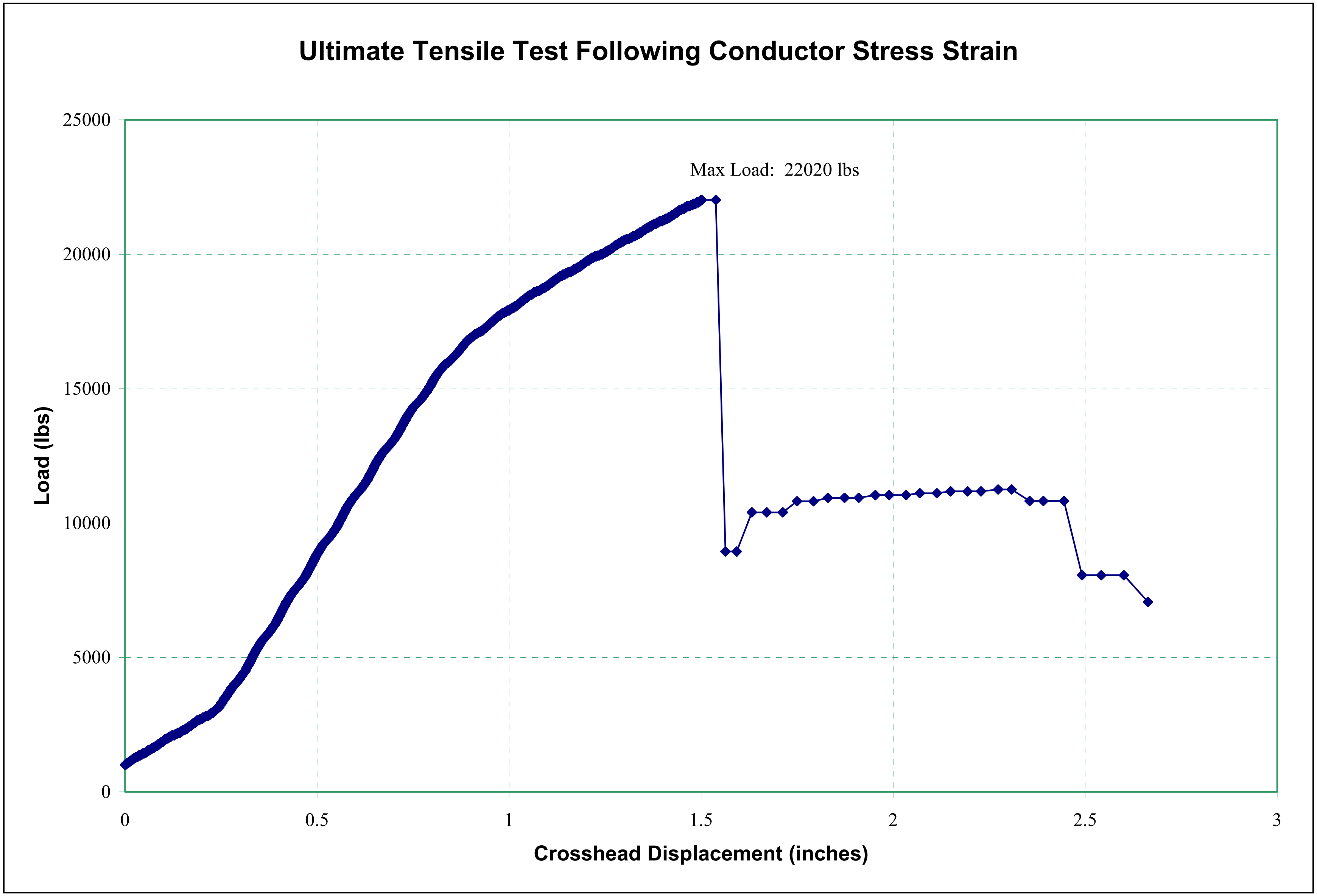
Initial and final modulus data, data fits, and data fits translated along the strain (x) axis



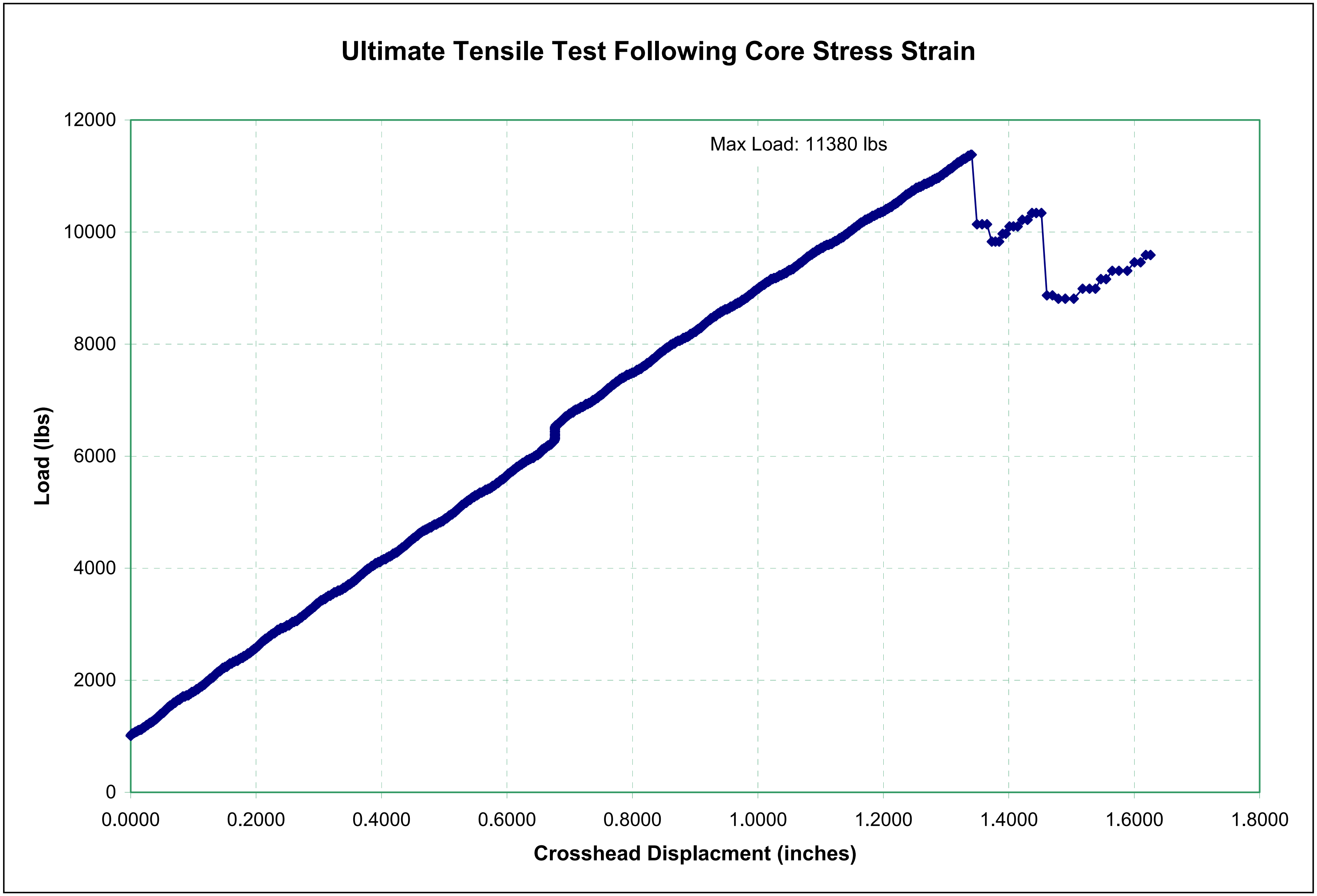
Stress-strain construction, temperature-corrected, normalized to area ratio, and translated along the strain axis



Construction of stress-strain curves, not normalized for area ratio



Plot of Crosshead Displacement versus Load, Tensile Test Following Stress Strain Test



Crosshead Displacement versus Load, Tensile Test Following Core Stress Strain Test