477 kcmil, 3M Brand Composite Conductor
Mechanical Properties, Volume 1
Tensile and Stress-Strain Tests

Minnesota Mining and Manufacturing (3M) Company
Purchase Order 0000227040

NEETRAC Project Number: 01-121

March, 2002

National Electric Energy Testing, Research & Applications Center

NEETRAC

BVQi ISO 9001 ANSI-RAB QMS ACCREDITED

A Center of
The Georgia Institute of Technology

Requested by: Mr. Colin McCullough
3M

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

Reviewed by: ______________________
Dale Callaway

477 kcmil, 3M Brand Composite Conductor
Mechanical Properties, Volume 1
Tensile and Stress-Strain Tests

Minnesota Mining and Manufacturing (3M) Company
Purchase Order 0000227040

NEETRAC Project Number: 01-121

March, 2002

Summary:

3M contracted with NEETRAC for a series of tests designed to characterize the mechanical behavior of 477 kcmil 26/7 metal matrix composite (MMC) core aluminum conductor composite reinforced (ACCR). This report provides the test data summary and conductor property coefficients for the tensile test and stress-strain tests.

Samples:

1) Conductor reel containing approximately sixty (60) meters of 477 kcmil, type 16, 3M Composite conductor

References:

1) "Proprietary Information Agreement …." Dated 3/27/01
2) Aluminum Association Guide, Rev. 1999, "A Method of Stress-Strain Testing of Aluminum Conductors and ACSR and A Test Method for Determining the Long Time Creep of Aluminum Conductors in Overhead Lines"
3) 3M Purchase Order 0000227040
4) E-mail dated 6/7/01 from Colin McCullough with details on conductor and core strand properties
5) PRJ 01-121, NEETRAC Project Plan

Equipment Used:

1) MTS Servo-hydraulic tensile machine, Control # CQ 0195
2) Dynamics Research Corporation (DRC)/NEETRAC cable extensometer, Control # CQ 3002
3) National Instruments AT-MIO-16XE-50 computer data acquisition interface

Procedure:

Testing was conducted in accordance with a NEETRAC procedure entitled "PRJ0121, CONFIDENTIAL – MMC Conductor Evaluation". The procedure controls all technical and quality management details for the project. The following tests were performed:

Initial Tensile Test:

A tensile test was performed on the conductor and fitting system to ensure that terminations were sufficiently robust for the stress-strain and creep tests. The tensile sample, stress-strain samples, and creep samples were all prepared using identical fittings and procedures. Each sample was terminated using resin terminations. The procedure requires ring clamps around the conductor free ends during handling, cutting, and end preparation. This preserves the "as-manufactured" placement of the conductor components, and ensures each layer is loaded realistically during load testing. Figure 1 shows a plot of load versus crosshead position for the initial tensile test. The sample free-span length (excluding part in the end fitting) is 3 feet. The sample is identical to the samples used for the stress-strain tests, except those samples all have a free-span length of 19 feet. Good results on a short section are obtained only if all strands are properly loaded.

A sharp break at the end of the data line shows that all components failed suddenly at the peak load. The peak load is 20,400 lbs, or 103% of the ultimate rating provided by 3M. Photograph 1 shows the failed end, which shows that both the MMC core strands and the aluminum strands ruptured at or near the interface between the resin and the free span. Photograph 2 shows the resin plug from opposite the failed end. This test demonstrates that the fittings and installation procedure are suitable for the stress-strain and creep tests.

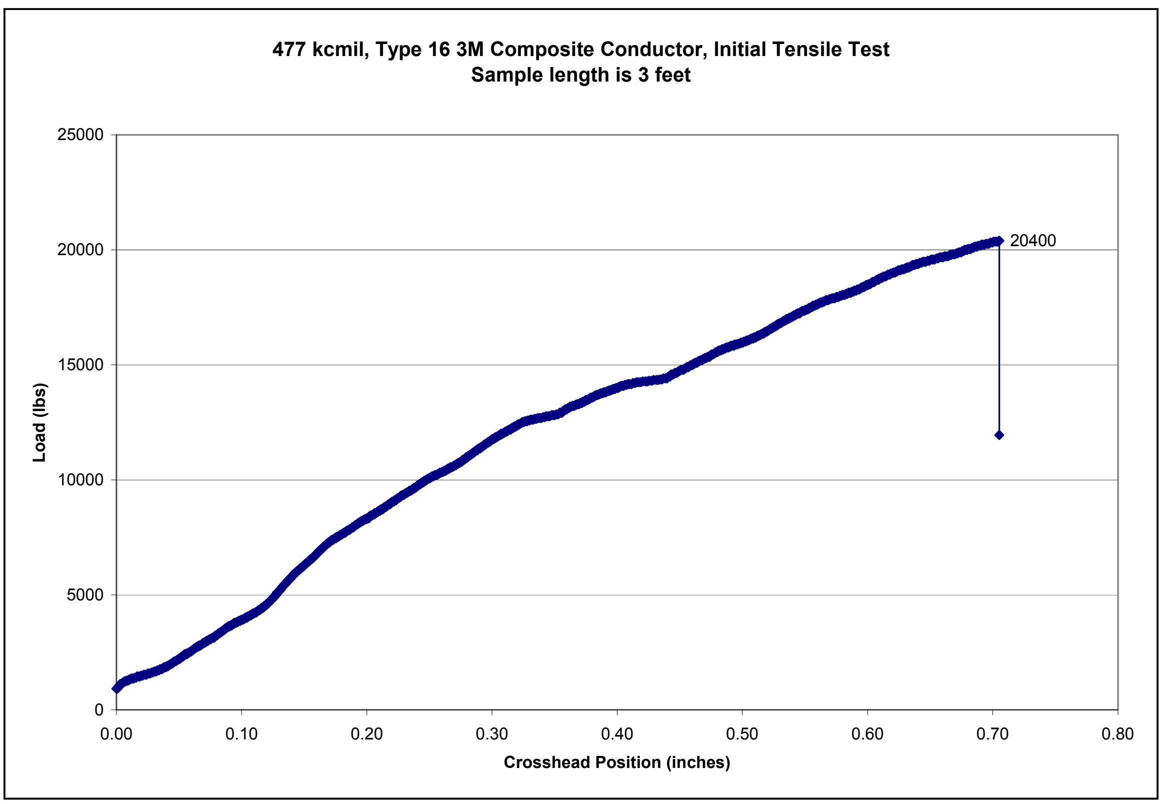


Figure 1, Load versus Crosshead Position for Initial Tensile Test

Photograph 1
Failed End

Photograph 2
Opposite Failed End (Resin Socket)

Samples used for the stress-strain tests were pulled to destruction at the end of the program. Results:

Conductor (19 ft sample)	21,070 lbs (106% RBS)	Core pulled from resin fitting
Core (19 ft sample)	11,750 lbs	Strands failed mid-span

<u>Stress-Strain Tests:</u>

Samples were terminated with resin fittings, and mounted in the MTS hydraulic tensile machine. The free-span conductor length is 19 feet. The active gage section between knife-edges on the cable extensometer is 18 feet, +/- 1/16”. 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 3 shows the long view of the test apparatus. Photograph 4 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. The test profile is in accordance with the Aluminum Association guide, as follows:

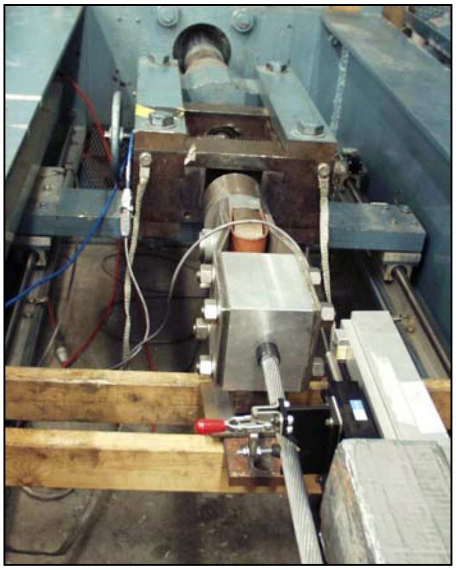
Composite conductor:

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 (5,948 lbs). Hold for 30 minutes.
4) Relax load to 1,000 lbs.
5) Pull to 50% RBS (9,913 lbs). Hold for one hour.
6) Relax load to 1,000 lbs.
7) Pull to 70% RBS (13,878 lbs). Hold for one hour.
8) Relax load to 1,000 lbs.
9) Pull to 75% RBS.
10) Relax load to 1,000 lbs, and remove the extensometer (for its own protection).
11) Pull to destruction.

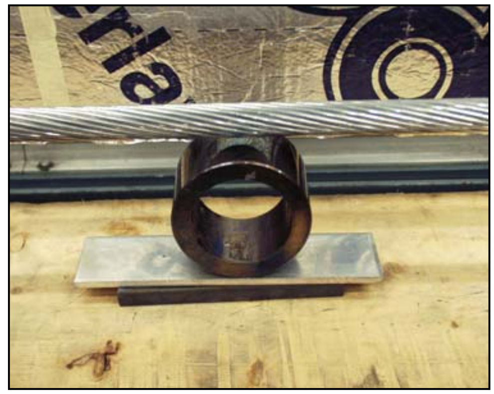
Core strands:

1) Pull to calculated initial tension (in this case, 418 lbs)
2) Install extensometer, and set to zero.
3) Pull to same strain as conductor at start of 30% of RBS test (0.10778%). Hold for 30 minutes.
4) Relax load to 418 lbs.
5) Pull to same strain as conductor at start of 50% of RBS test (0.20670%). Hold for one hour.
6) Relax load to 418 lbs.
7) Pull to same strain as conductor at start of 70% of RBS test (0.33510%). Hold for one hour. Relax load to 418 lbs.
8) Pull to 75% RBS.
9) Relax load to 418 lbs, and remove the extensometer (for its own protection).
10) Pull to destruction.

Photograph 3, Long View of Stress-Strain Test



Photograph 4
Load Actuator and Extensometer



Photograph 5
Mid-span Support to Remove Sag

<u>Results:</u>

Data files containing test data were processed using Microsoft® Excel Spreadsheet with Business Graphics and Database software, to obtain engineering values and graphical presentation. Graphs showing data for each test are shown in Appendix 2.

The following formulas describe the mechanical properties of the conductor, where t is time in hours, stress is in psi, strain is in percent, and T is temperature in degrees Celsius:

Composite Conductor Properties:

Initial Modulus for Stress Strain Curve:	Stress (psi) = -77,110*(Strain%)^2+109,292*(Strain%)+2294
Final Modulus for Stress Strain Curve:	Stress (psi) = 122,361*(Strain%) – 12,902
Elastic Modulus:	10,562,000 psi
Tensile Test, Stress Strain Sample:	21070 lbs (106% RBS), core pulled from resin fitting

Core Properties:

Initial Modulus for Stress Strain Curve:	Stress (psi) = -61,364*(Strain%)2+328,214*(Strain%)+7454
Final Modulus for Stress Strain Curve:	Stress (psi) = 332160*(Strain%) – 1623.4
Tensile Test, Core Stress Strain Sample:	11,750 lbs

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):

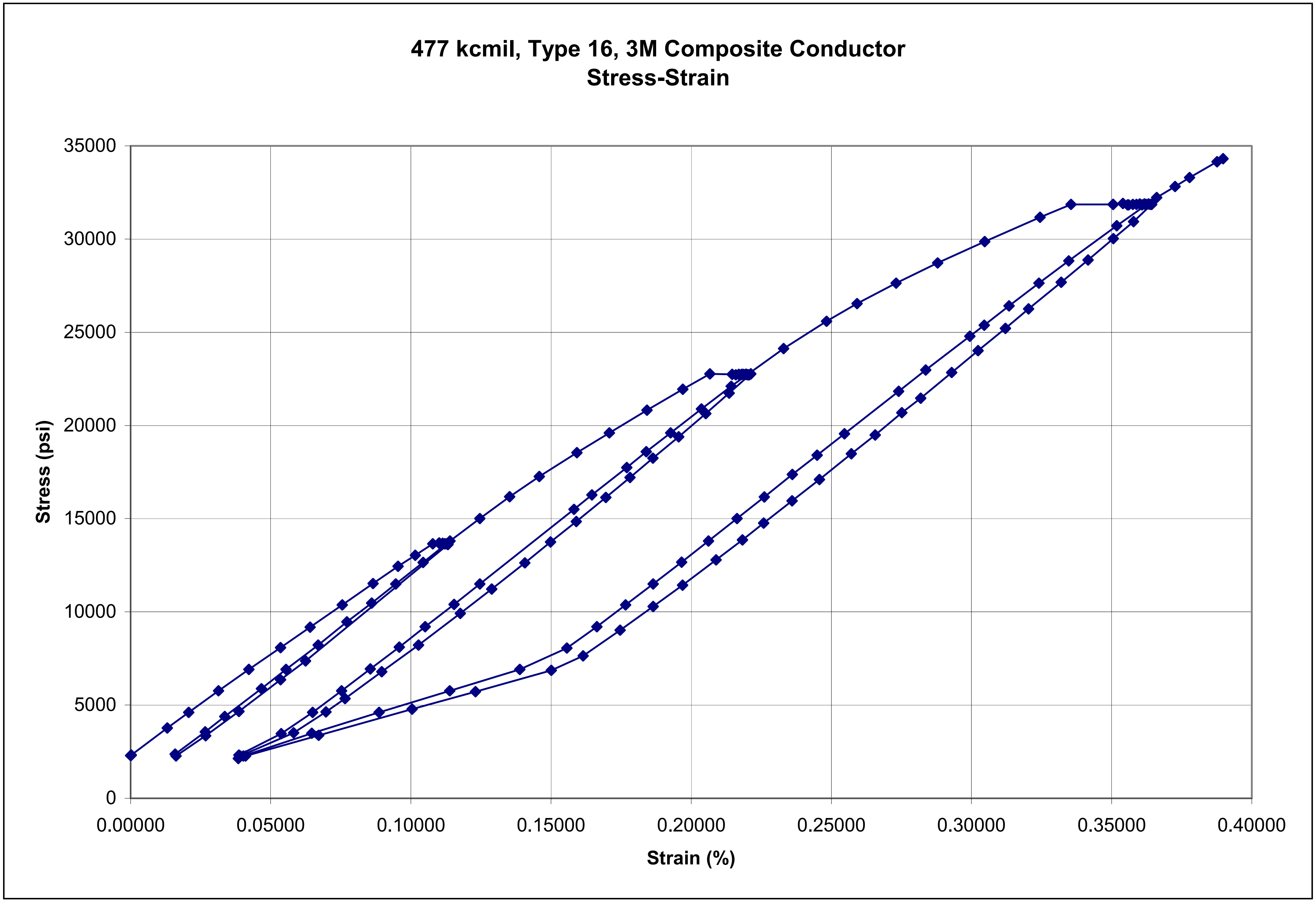
The DRC displacement transducer resolution is +/- 0.0001". For the 18 ft. gage section, resolution is 0.0001"/216", or 0.000046% (0.46 PPM). Sensor accuracy is +/- 0.0002", or 0.92 PPM. This is a digital measurement made with a laser diode reading an etched titanium silicate (glass) rod. The material 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: Lab temperature changed 0.2°C from beginning of the test to the end. Temperature change is partly compensated using a gage reference of the same material as the sample. In this case, the gage rod is aluminum (23 PPM/ ° C), while the sample thermal elongation is estimated to be 16 PPM/ °C. Error in the strain measurement is, therefore, 7 PPM/ °C. For the 0.2 °C temperature variation, the error is 1.4 PPM. The error does not affect the modulus values, because load is changed rapidly relative to rate of temperature change. Thermal affects could affect measurement of short-term creep during load hold periods. However, 1.4 PPM is small relative to measured creep (over 600 PPM during the 30% RBS load hold). Therefore, this error is about 0.2% of reading, and is therefore neglected. No mathematical temperature compensation was used for any of the stress-strain tests.
>
> Effect of starting gage length:
> An error of +/- 1/16" is possible. The maximum error affects the strain measurement by 0.02% of reading.

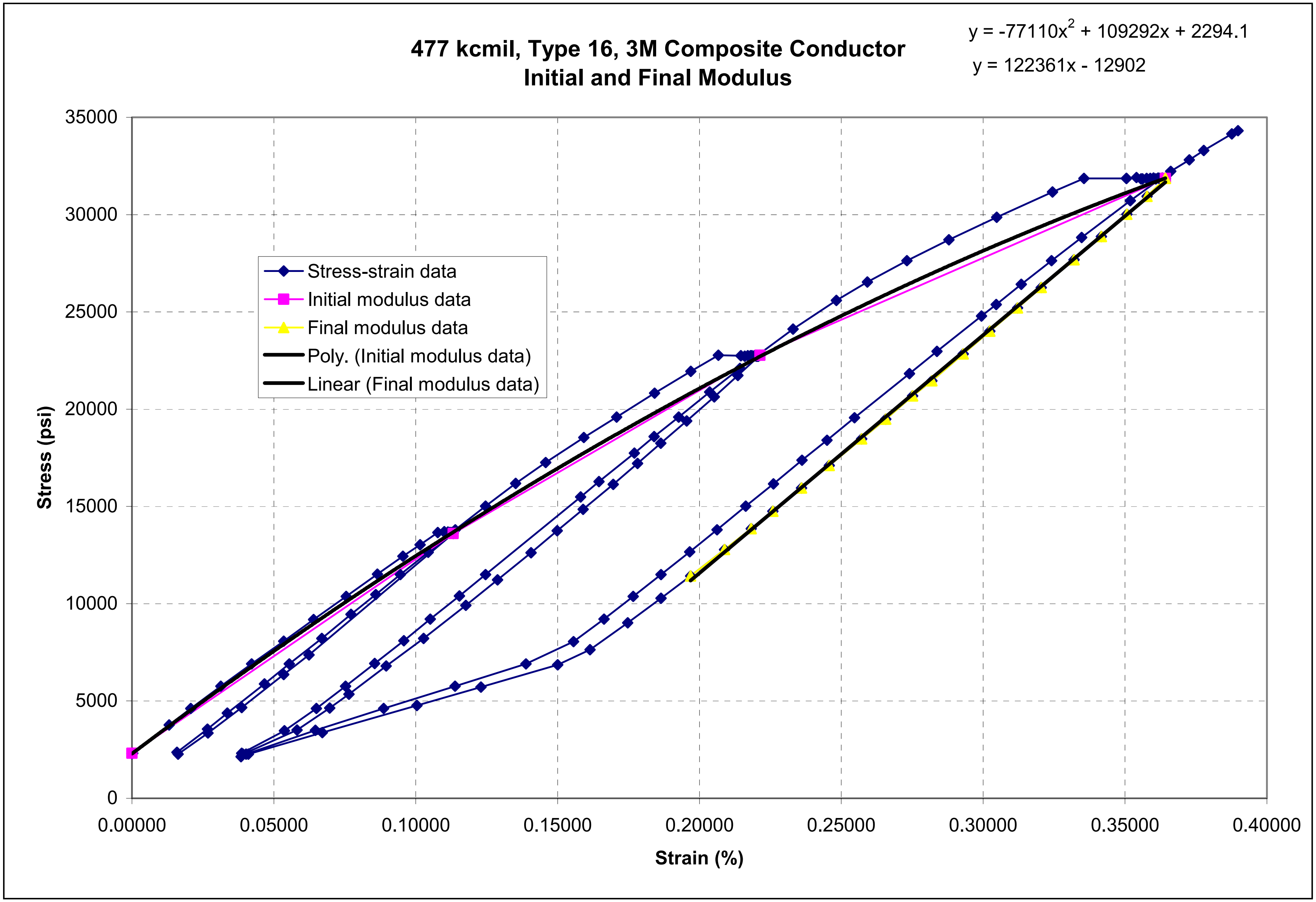
Overall accuracy is calculated based on root-mean squared error estimation. Given the assumptions above, the elongation measurement is considered accurate within 1% of reading, plus or minus 2 parts per million. The Aluminum Association specifications do not provide accuracy requirements, but suggest 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

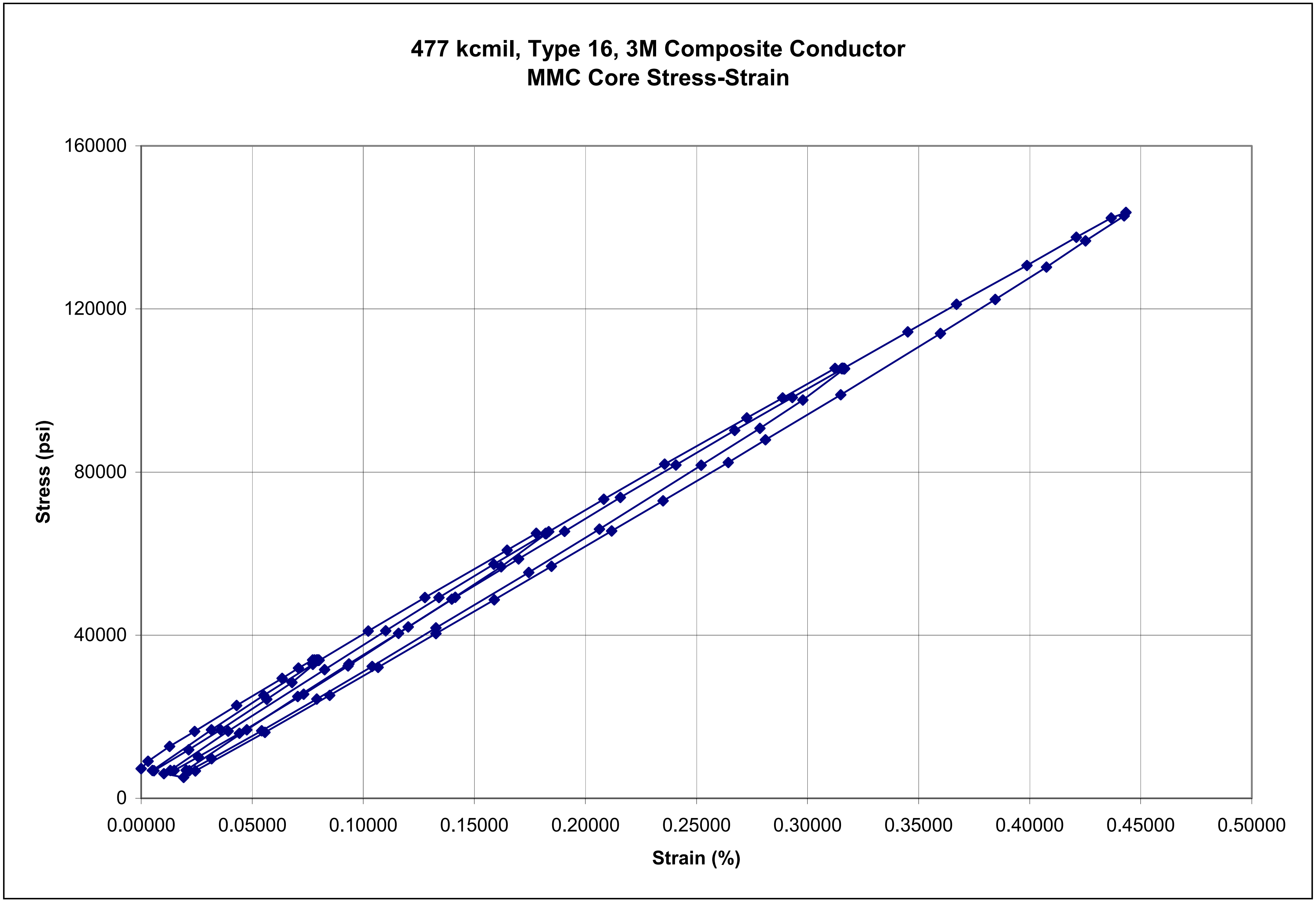
(Data files containing raw and processed data have been sent via e-mail, and are available upon request)



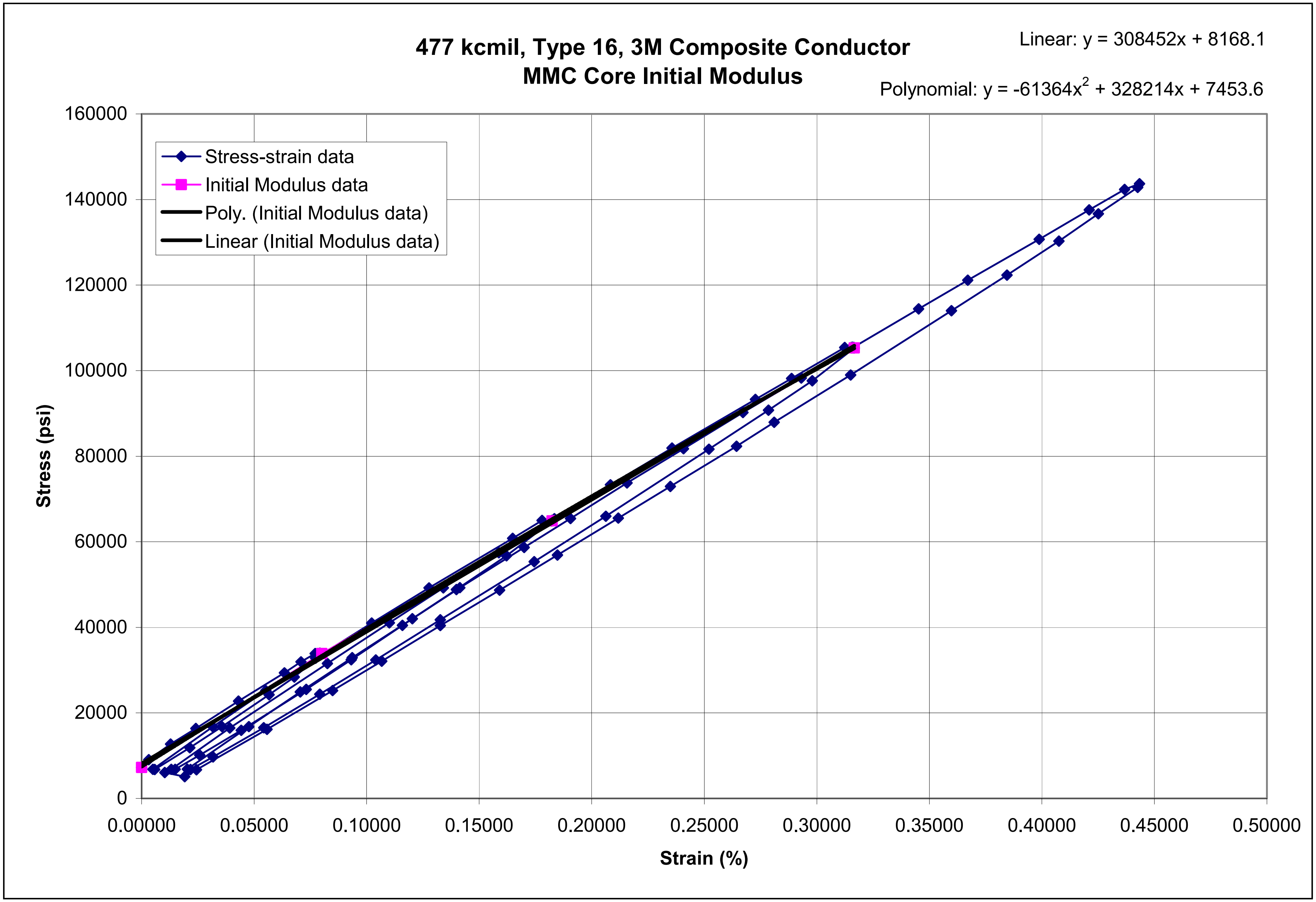
Composite Stress-Strain Plot in Accordance with Aluminum Association Guide



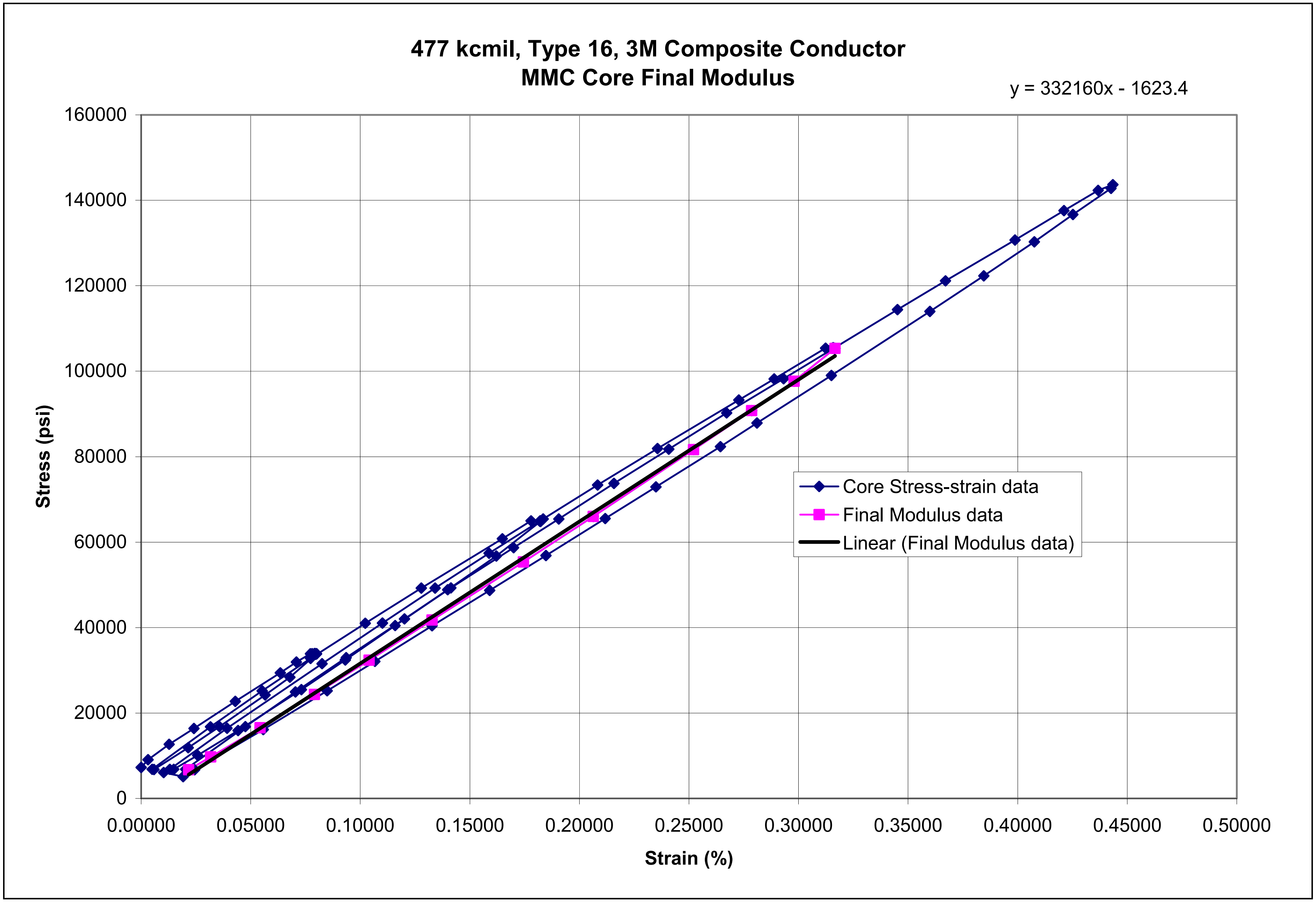
Composite Stress-Strain Plot with Data Fit for Initial and Final Modulus



Core Stress Strain per Aluminum Association Guide



Core Initial Modulus Data



Core Final Modulus Data