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824.0 kcmil ACCR Overhead Conductor Stress-Strain,Creep, and Development of Coefficients for Line Design Software

NEETRAC Project: 24-151

Final Report Rev 1

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National Electric Energy Testing, Research, and Applications Center

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NEETRAC Project 24-151

1.0 BACKGROUND

The introduction of ACSR circa 1907 provided the opportunity for longer spans and shorter structures, but the non-linear response was a challenge for line designers. By the late 1920s, the Alcoa Graphical Method for line design and its variants were in widespread use for overhead line design in North America. The method solves for conductor sag and tension by superimposing laboratory data on the equations for sag and tension. The graphical method was computerized in 1964, when Alcoa introduced Sag10® software, a FORTRAN program that automated the graphical superposition task.

Outside of North America, overhead conductors were modeled as linear springs with empirical factors to account for creep. Both methods are reasonably accurate for ACSR, but the introduction of composite cores circa 2000 revealed that the linear models did not correctly model advanced conductors. Computerized versions of the Graphical Method are now the world-wide standard for overhead line design.

This document reports the results of stress-strain and creep tests for the empirical (based on lab data) conductor model for 3M's 824.0 kcmil ACCR overhead conductor. The stress-strain test was conducted per ASTM B1008 and the creep test was conducted per ASTM WK62464.

While stress-strain and creep are different tests, the results are in a combined report because neither test is standalone. The creep test results depend on the one-hour creep computed from the stress-strain test. The full stress-strain model includes a 10-year creep curve that comes from the creep test.

2.0 TEST SAMPLES

Four (4) 22 ft test samples were removed from a reel provided by Western Area Power Administration (WAPA) through INL. The designation on the reel identified the conductor as 824.0 kcmil ACCR. Bolted clamps were used to ensure the manufacturing pre-stress was preserved in each of the test samples as it was removed from the reel.

Cast-resin lab fittings were used to terminate the samples. The bolted clamps were removed after the resin cured. Two (2) samples were subjected to a 1000-hour creep test, one at 15% RBS tension and the other at 25% RBS tension. Two (2) samples were subjected to a stress strain test. One sample was used for the complete conductor stress-strain procedure, and the other sample was used for the core stress-strain procedure. For the core stress-strain procedure, the aluminum outer strands were carefully cut and removed after the sample was under nominal 400-lb tension in the stress-strain test machine. The process ensures the core is in the same condition as the core in the sample used for the complete conductor stress-strain test. The goal is to impute the aluminum contribution by subtracting the core test results from the complete conductor stress-strain results. The process is explained in more detail in the RESULTS section.

3.0 HISTORICAL DEVELOPMENT OF TEST APPARATUS

3.1 Stress-Strain

Stress-strain machines are adopted from long-bed tensile test machines. Conductor tests supporting the empirical model were performed as early as the 1920s, before the development of controllable motor drives and electronic instrumentation. Load was changed by turning a hand-driven crank. Strain was measured using Vernier scales mounted on the conductor and on a reference (gage) rod. A special instrument telescope was used to read the strain. Figure 1 shows the vintage 1927 Alcoa stress-strain machine at their electrical conductor laboratory in Massena NY. The example chart bears a close resemblance to the stress-strain charts developed in this project.

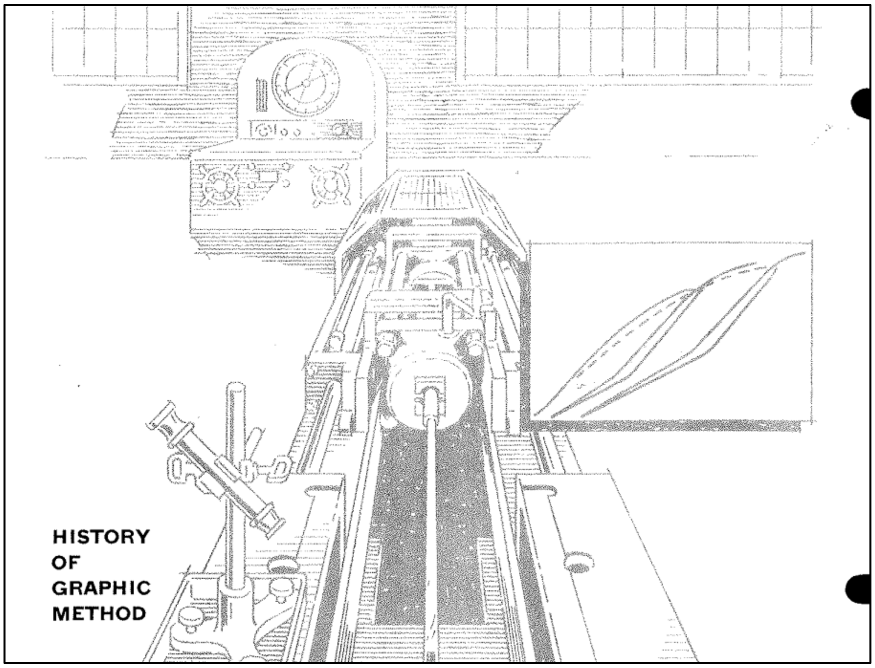


Figure 1: Early Stress-Strain Machine

Circa 1990, NEETRAC developed its stress-strain and creep test capability. By the mid-1990s, NEETRAC was a key contributor to the development of advanced conductors, which were first commercialized circa 2000. NEETRAC's cable extensometer consists of an aluminum gage rod suspended by a lever/counter-weight system. With careful adjustment, knife-edge clamps at each end of the gage rod are located within a millimeter of the conductor. Toggle levers on the clamps lock the knife edges to the conductor to establish a precise 216 inch gage section. For sensitive composite cores, a high friction material is interposed between the knife blades and the conductor. The clamp at one end is fixed to the gage rod. At the opposite end, the clamp is fitted to a precision slide, that allows the clamp to move as the conductor stretches elastically, yields (permanent stretch at loads above the yield stress), or creeps (permanent stretch at loads below the nominal yield stress. An alignment hole is drilled through the slide table to permit the slide to be locked in position with a pin to preserve the gage length. The pin is pulled at the start of the test, and the movement of the ball bearing slide is a precise indication of the conductor strain that is measured with below 0.5 ppm resolution by a linear encoder.

Figure 2: 3M Conductor during Stress-Strain Test

3.2 Creep

A conductor creep test machine is similar to a conductor stress-strain machine, in that both apply tension and measure strain. Creep test machines require several special features to ensure continuity of the test and the data during power interruptions. The test has to run uninterrupted for over 1000 hours.

The early creep test machines used lever/dead weight systems to maintain tension. These systems suffer from stick-slip friction in the lever fulcrum and tend to overshoot the tension due to momentum once the counterweight moves.

NEETRAC's creep benches use motor-driven linear actuators that are self-locking in the event of a power interruption and are energized only when a reload is required. Springs at the opposite end of the machine buffer (soften) the effect of actuator movement and provide stable tension during power interruptions.

A cable extensometer similar to the stress-strain machine extensometer consists of an aluminum beam (gage rod) and an electronic linear encoder. The extensometer is suspended using springs to support the weight. Turnbuckles are used for fine height adjustment. Rollers allow easy horizontal movement of the gage rod. Adjustable anchors in Unistrut beams allow for final positioning of the instrument parallel to the conductor. By careful adjustment of turnbuckles and roller slides, the extensometer is positioned to float in space within a millimeter of contact with the conductor sample. The fixed end of the gage rod is then bolted to a gage block that is bolted around the conductor. The floating end of the gage rod contacts the sample only at the spring-loaded plunger of a digital linear encoder. The digital resolution of the indicator is 0.0001 in. With the 216 in gage section, the strain resolution is 0.00004630% (0.4630 ppm). Figure 3, Figure 4, Figure 5, and Figure 6 show detailed views of the system.

Figure 3 : Buffer Springs and Load Cell (Left), Motor-Driven Actuator (Right)

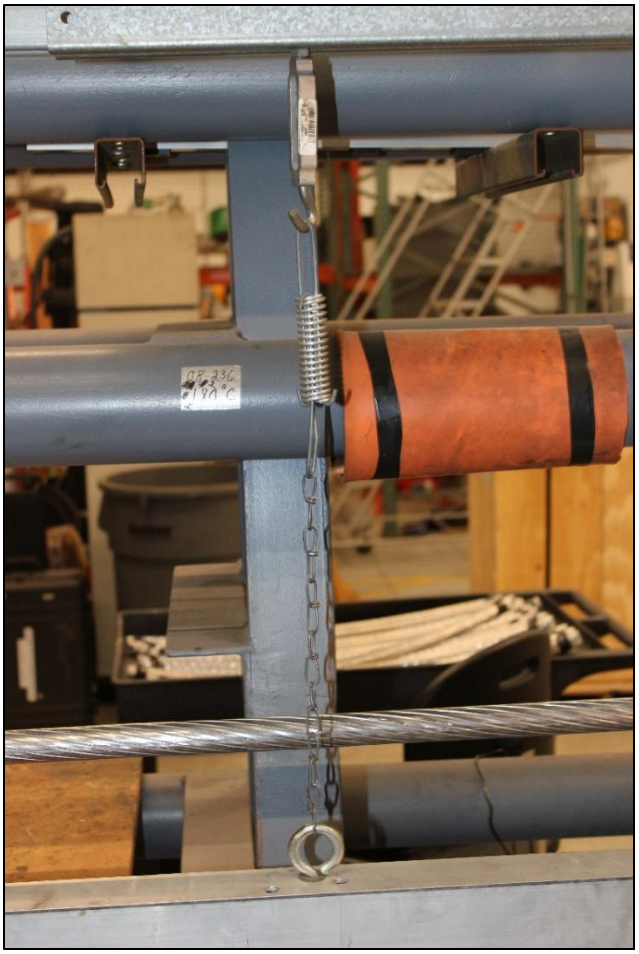


Figure 4: Spring/Turnbuckle Suspension for Gage Rod, Typical Two Places

Figure 5: Digital Indicator at Floating End of Gage Rod

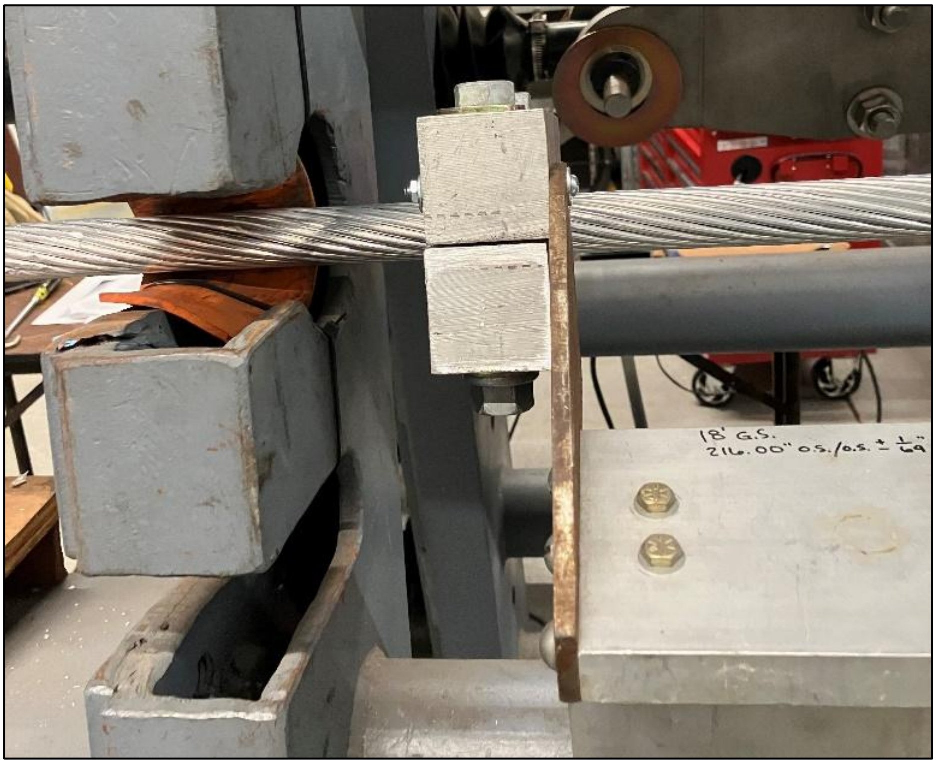


Figure 6: Fixed End of Gage Rod Bolted to Gage Block

The sample and all test equipment are in conditioned lab space to ensure thermal stability. A type T thermocouple was taped to the gage rod surface to measure the ambient temperature. Conductor temperature was not measured, but in the conditioned space it tracks the ambient.

4.0 PROCEDURE

4.1 Stress-Strain

Testing was performed in accordance with ASTM Standard B1008, which is largely based on the NEETRAC practices and contains NEETRAC exemplar data. ASTM B1008 requires two test procedures—one on the complete conductor and one on the core.

Complete conductor test procedure:

1) Apply a load of 1,000 lb. Using a survey laser, ensure the sample and the tensile machine tension elements are level and straight ± 1/8 in. Place rollers at mid-span and under the moving end termination. The sample must be as straight as practical to avoid spurious strain measurement from pulling up sag.
2) Install the extensometer and set the strain reading to zero. Remove the gage pin to allow the slide to move.
3) Pull the sample to 30% of RBS (9,660 lb).
4) Hold for 30 minutes.
5) Relax load to 1,000 lb.
6) Pull the sample to 50% RBS (16,100 lb).
7) Hold for one hour.
8) Relax the load to 1,000 lb.
9) Pull the sample to 70% RBS (22,540 lb).
10) Hold for one hour.
11) Relax the load to 1,000 lb.
12) Pull the sample to 85% RBS (27,370 lb).
13) Relax the load to 1,000 lb, and remove the extensometer (for its own protection).
14) Pull the sample to destruction.

Core test procedure: the sample is prepared as a complete conductor. The aluminum strands are removed only after the sample is in the test machine. The bare core is then subjected to the same time and strain profile it experienced during the complete conductor test:

1) Calculate the initial tension that will achieve the initial strain value using data from the complete conductor procedure. The computed value for this test was 367 lb. Pull the sample to 367 lb.
2) Using a survey laser, ensure the sample and the tensile machine tension elements are level and straight ± 1/8 in. Place rollers at mid-span and under the moving end termination. The sample must be as straight as practical to avoid spurious strain measurement from pulling up sag.
3) Install the extensometer and set the strain reading to zero.
4) Pull to the same strain value as recorded in the complete conductor test at the start of the 30% RBS load hold (0.13264%).
5) Hold for 30 minutes.
6) Relax load to 367 lb.

7) Pull to the same strain value as recorded in the complete conductor test at the start of the 50% RBS load hold (0.22824%)
8) Hold for one hour.
9) Relax load to 367 lb.
10) Pull to the same strain value as recorded in the complete conductor test at the start of the 70% RBS load hold (0.34324%).
11) Hold for one hour
12) Relax load to 367 lb.
13) Pull to the same strain value as recorded in the complete conductor test at the start of the 85% RBS load hold (0.44907%).
14) Relax the load to 367 lb, and remove the extensometer (for its own protection).
15) Pull sample to destruction.

4.2 Creep

The tension is increased at a rate to ensure the target is reached within five (5) minutes as allowed by ASTM Creep Standard Draft WK62464, which is harmonized with the European IEC creep standard and the prior Aluminum Association guide. The tension data was logged by a data acquisition system, but due to scheduling requirements, the load adjustments were performed manually, and the strain data was read directly from the dial indicator and recorded manually.

Tension (stress) and strain were recorded every five (5) minutes for the first hour, and hourly for the remainder of the first day. For the remaining 45 days of the test, the tension and strain were recorded a minimum of twice per day during working days. Reloads and data recording were not typically performed during holidays and weekends, but note that the buffer springs maintained the tension to ensure the continuity of the test.

After a minimum of 1000 hours had elapsed, the data was analyzed.

5.0 RESULTS

5.1 Stress-Strain

<u>Conductor Stress-Strain:</u> Figure 7 shows the tension data recorded during the test. Figure 8 shows the test data as stress versus strain.

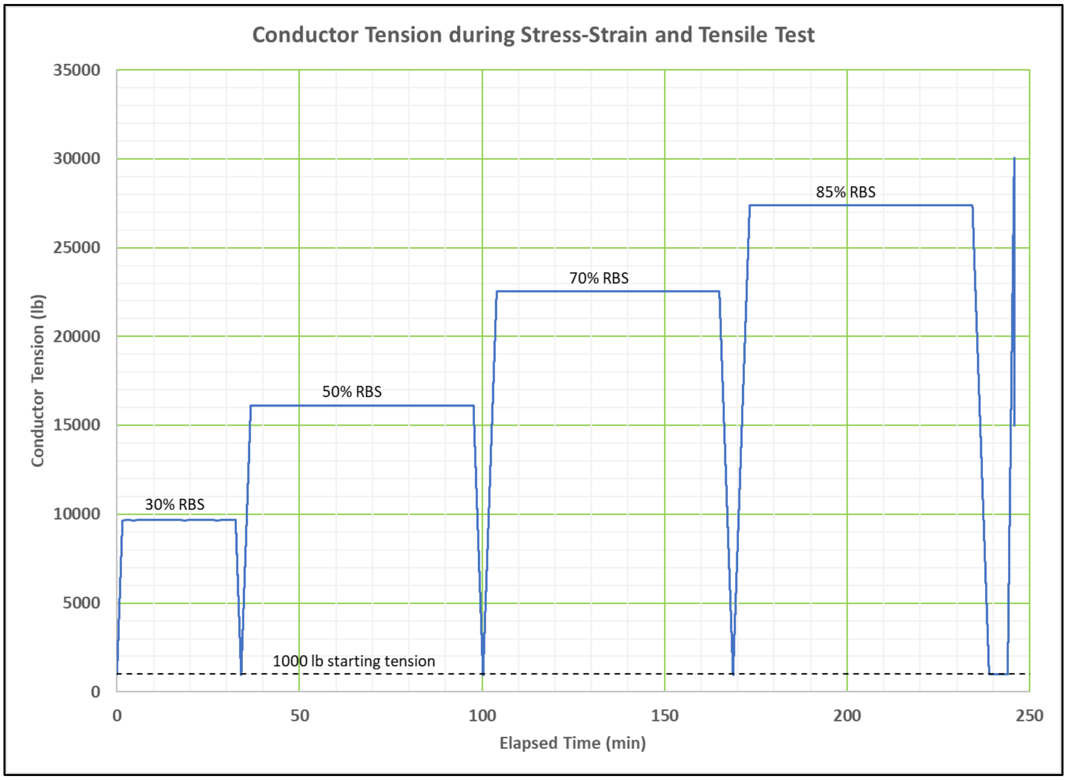


Figure 7: Tension Data from the Conductor Stress-Strain Test

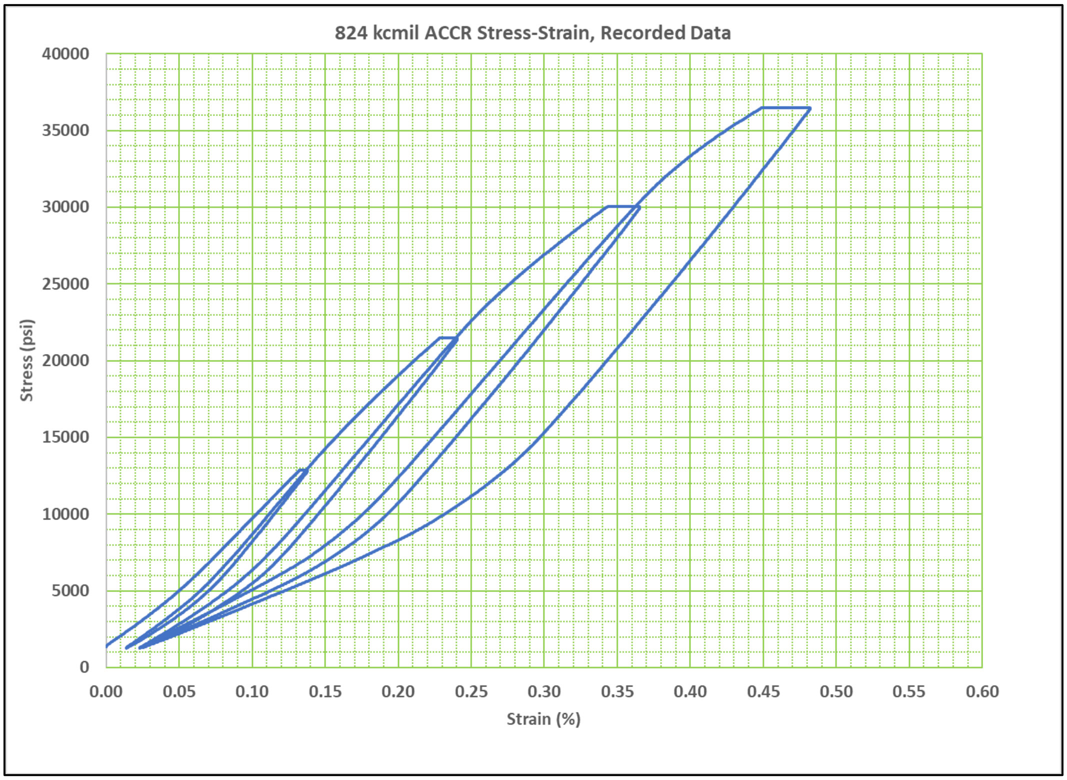


Figure 8: Conductor Stress-Strain Data

Core Stress-Strain: Figure 9 shows the tension data recorded during the core test. Figure 10 shows the core stress-strain response.

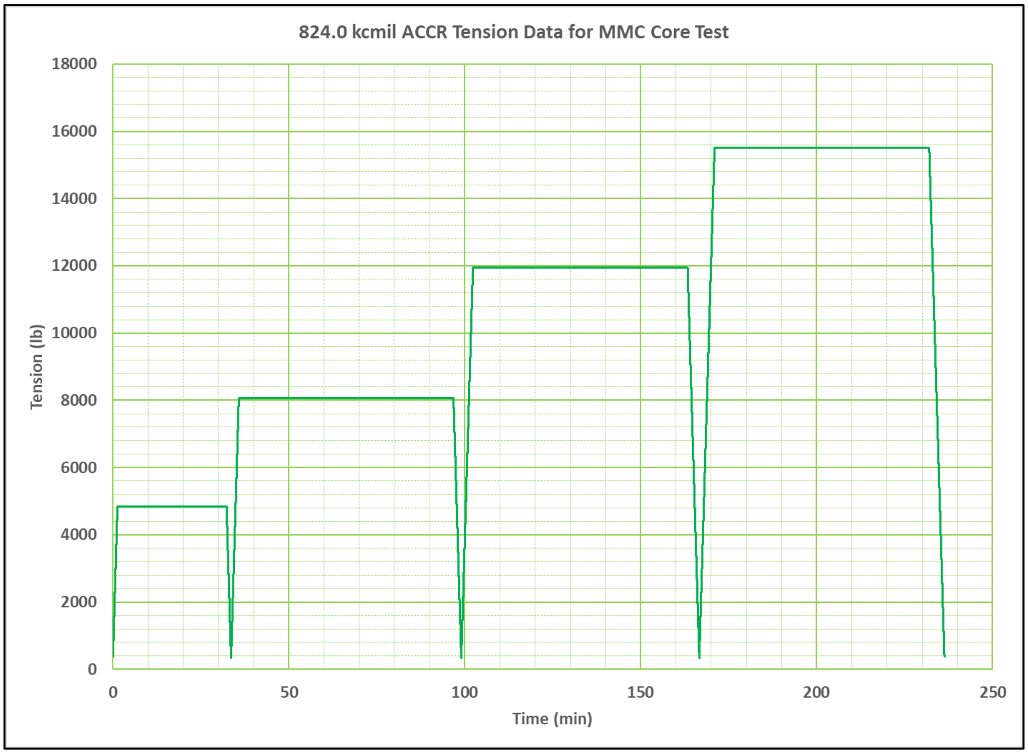


Figure 9: Core Tension Data from the Core Stress-Strain Test

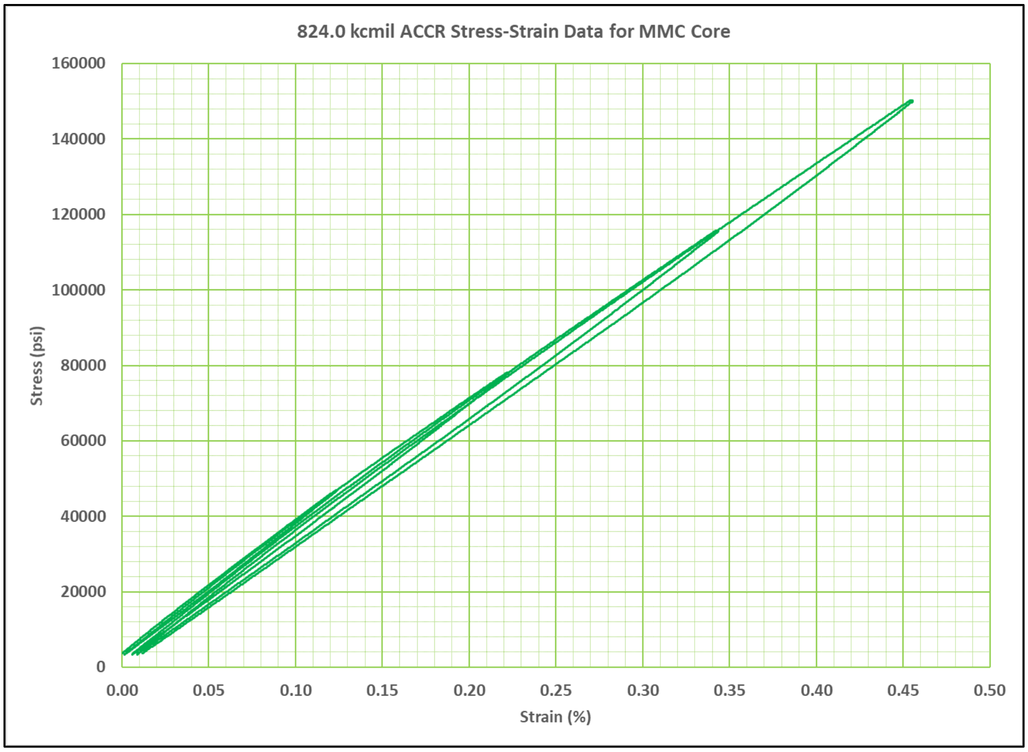


Figure 10:Core Stress-Strain Data

5.2 Creep

Creep data is recorded from the time the sample reaches the target load, but it is well-recognized that samples cannot be pulled to the target load without also allowing time for the high-rate early creep to occur. The solution is to use the 1-hour creep value from the stress-strain test. The first hour of data from the creep test is discarded, and the creep measured after the first hour is added to the 1-hour creep.

Figure 11 shows the process of extracting the 1-hour creep from the stress-strain data.

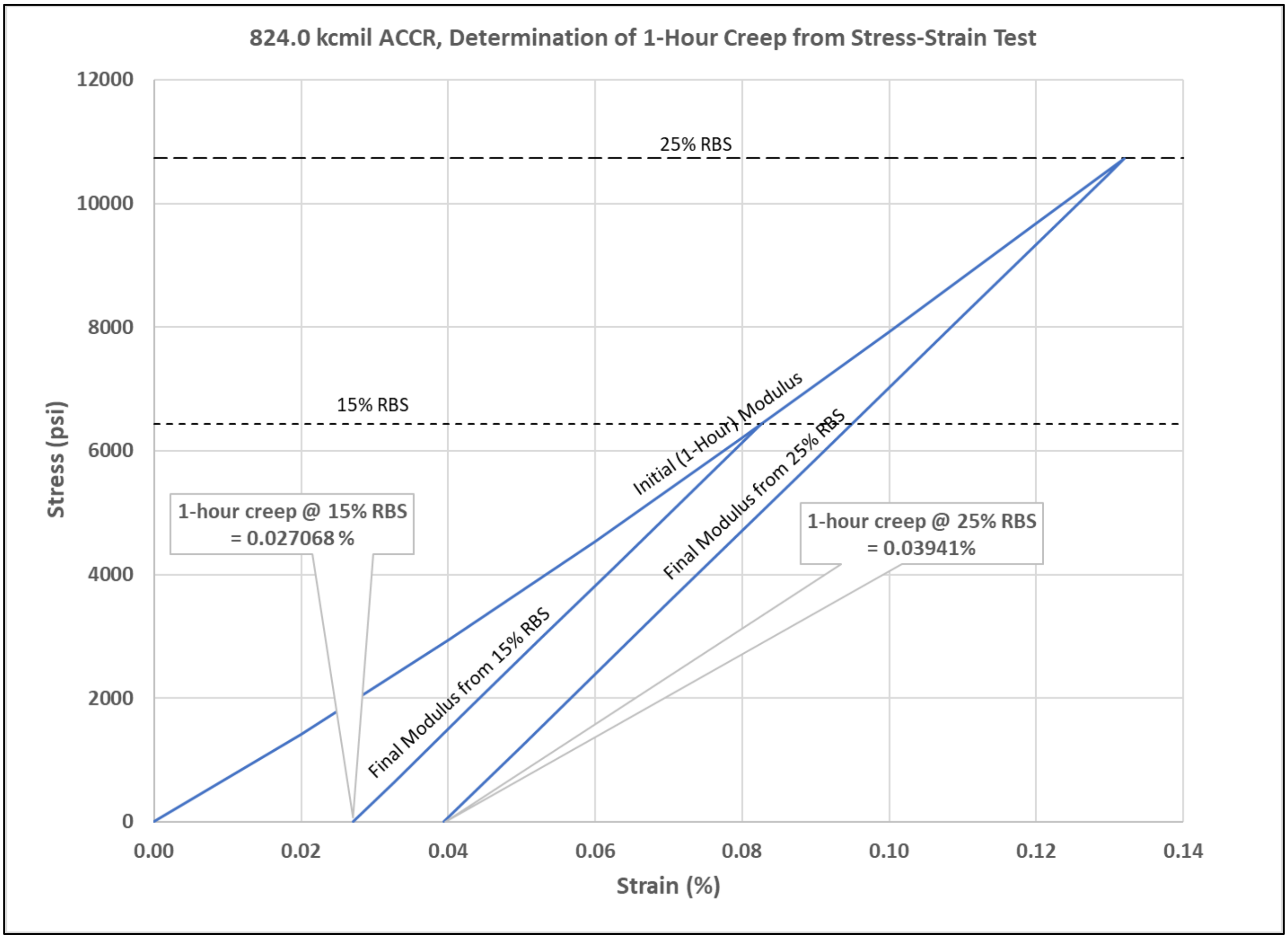


Figure 11: 1-Hour Creep Values from Stress-strain Data

Values for 1-hour creep are:
15% RBS: 0.02707%
25% RBS: 0.03941%

The creep data in the industry-standard format is shown in Figure 12.

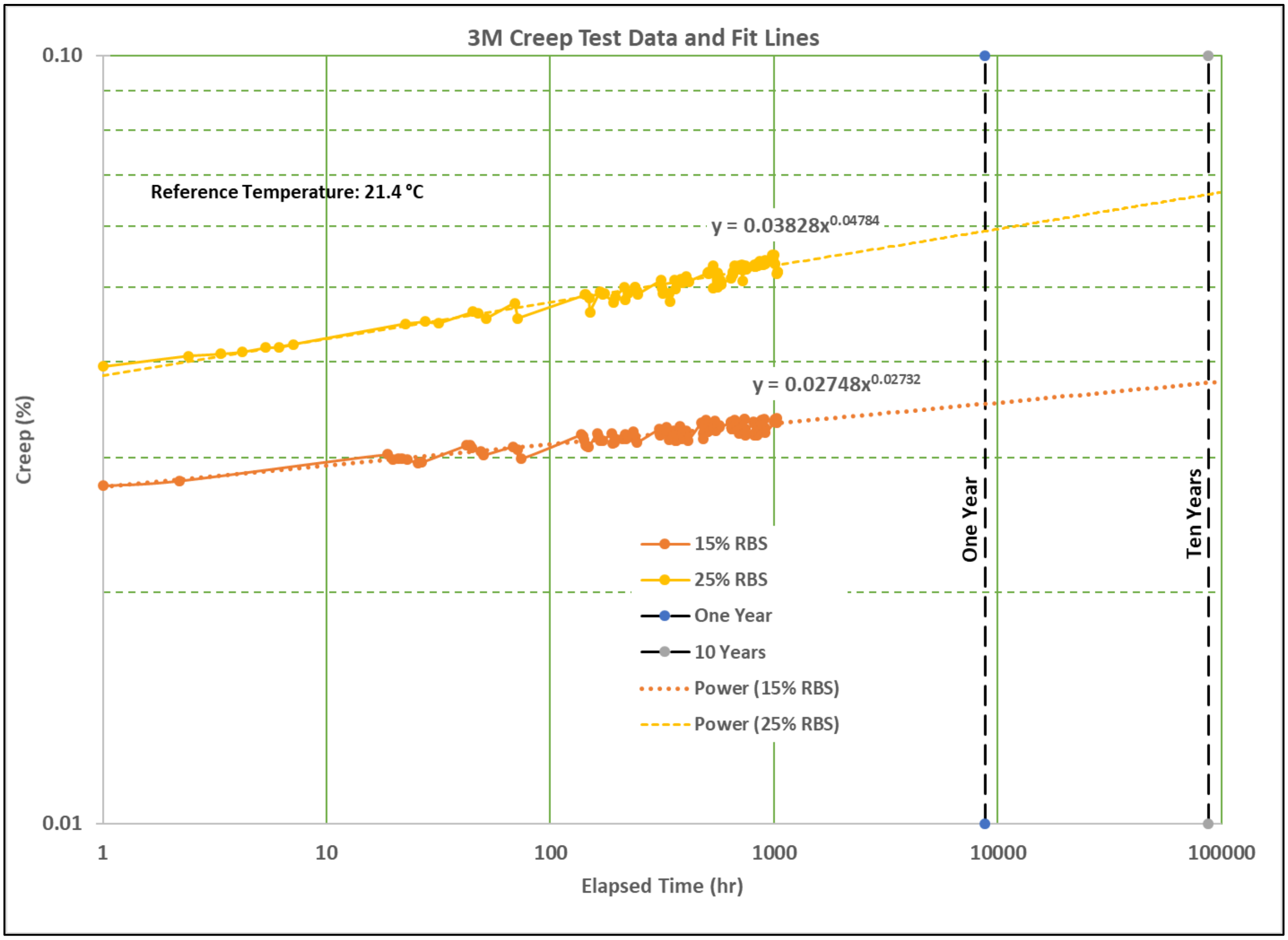


Figure 12: Creep Data and Fit Curves for 15% RBS and 25% RBS

Equations for creep are:

15% RBS: Strain(%) = $0.02748*(\text{hours})^{0.02732}$
25% RBS: Strain(%) = $0.03828*(\text{hours})^{0.04784}$

Values for 10-year creep are:

15% RBS: 0.03750%
25% RBS: 0.06598%

DATA ANALYSIS AND DEVELOPMENT OF CONDUCTOR COEFFICIENTS

5.3 Stress-Strain

The empirical conductor model requires subtraction of the core stress-strain data from the conductor stress-strain data to obtain the stress-strain response of the aluminum component. First the core data is “normalized” by multiplying the values of the coefficients by the area fraction of the core relative to the total conductor area. The resulting aluminum values are the aluminum stress multiplied by the aluminum area fraction. The intent of the method is to treat the conductor as the sum of the properties of the normalized core and the normalized aluminum. This allows for applying elastic strain, creep strain, and thermal strain to the core and aluminum components separately. The conductor sag and tension for different temperatures, ice loads, and creep accumulation are computed by solving for the unique solution that accounts for the changes in the two conductor components.

Figure 13 shows the construction of the initial and final modulus on the conductor stress-strain data.

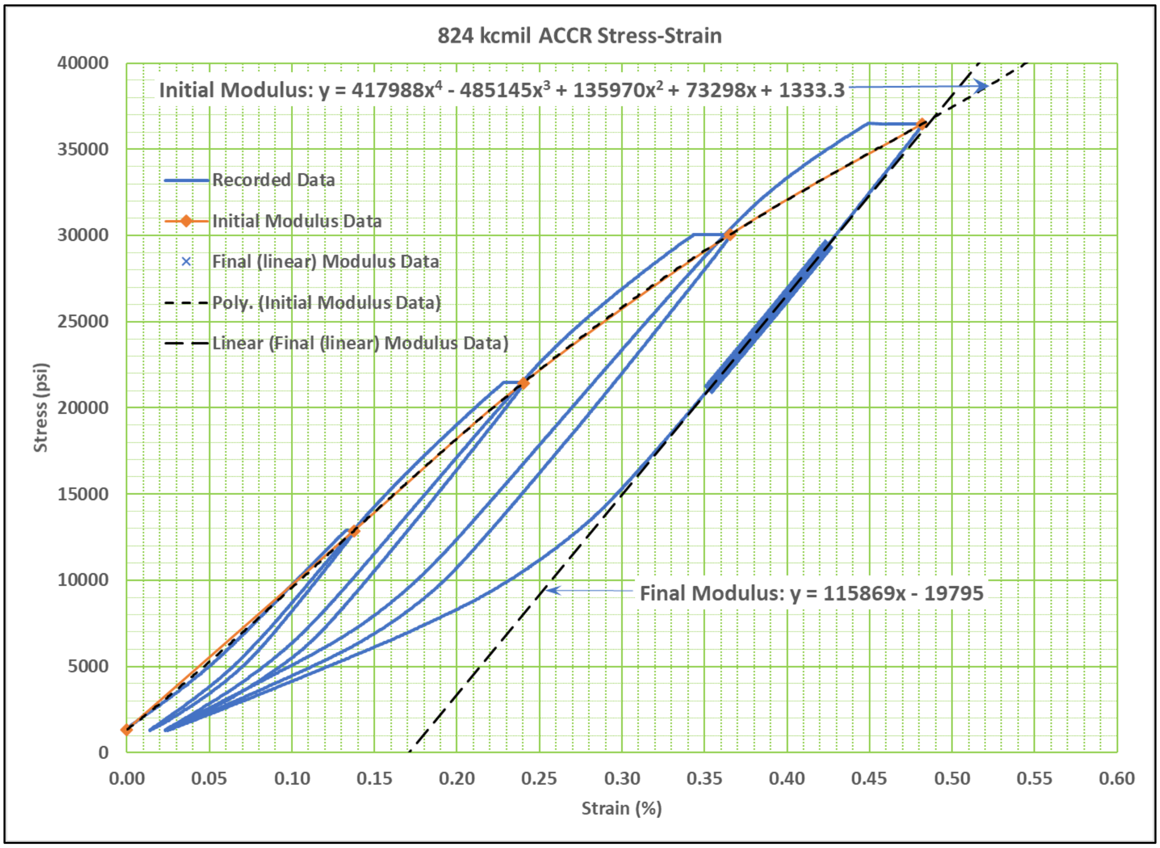


Figure 13: Initial and Final Modulus Equations from the Stress-Strain Data

The equations in Figure 13 are not the conductor coefficients, because they include the strain at the 1000 lb starting tension of the test. Figure 14 shows test data shifted to the right so that the initial modulus intersects the origin at zero stress and zero strain. The coefficients shown in Figure 14 are correct coefficients, but note that the data files and tables (see Table 1) contain coefficients only for the normalized core and normalized aluminum. The sum of the core and aluminum coefficients are the conductor coefficients as shown in Figure 14. The linear modulus remains the same because the slope does not change when the line is translated along the strain axis.

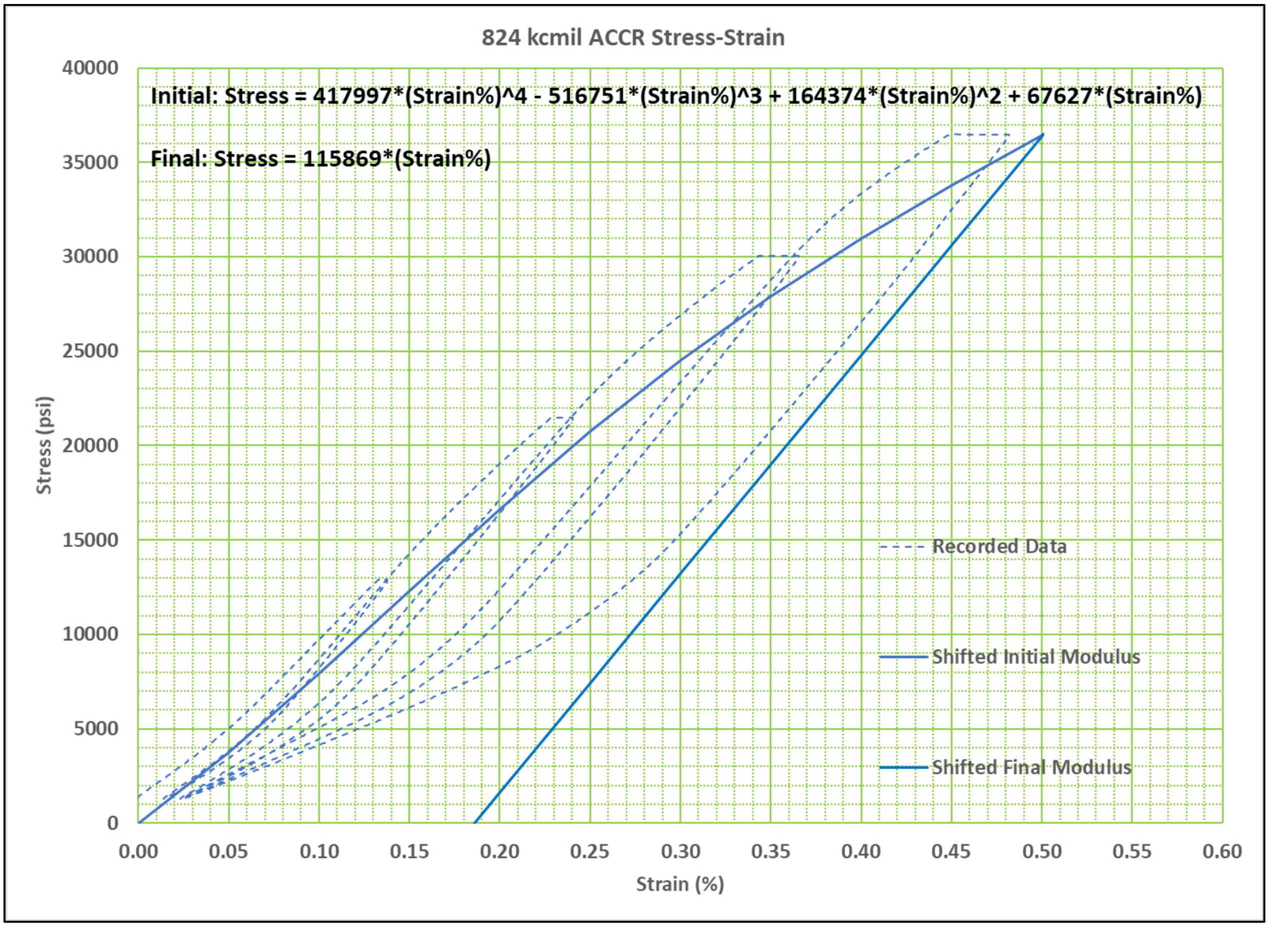


Figure 14: Conductor Initial and Final Modulus after Correcting for Bias Tension

Figure 15 shows the construction of the initial and final core modulus on the core stress-strain data.

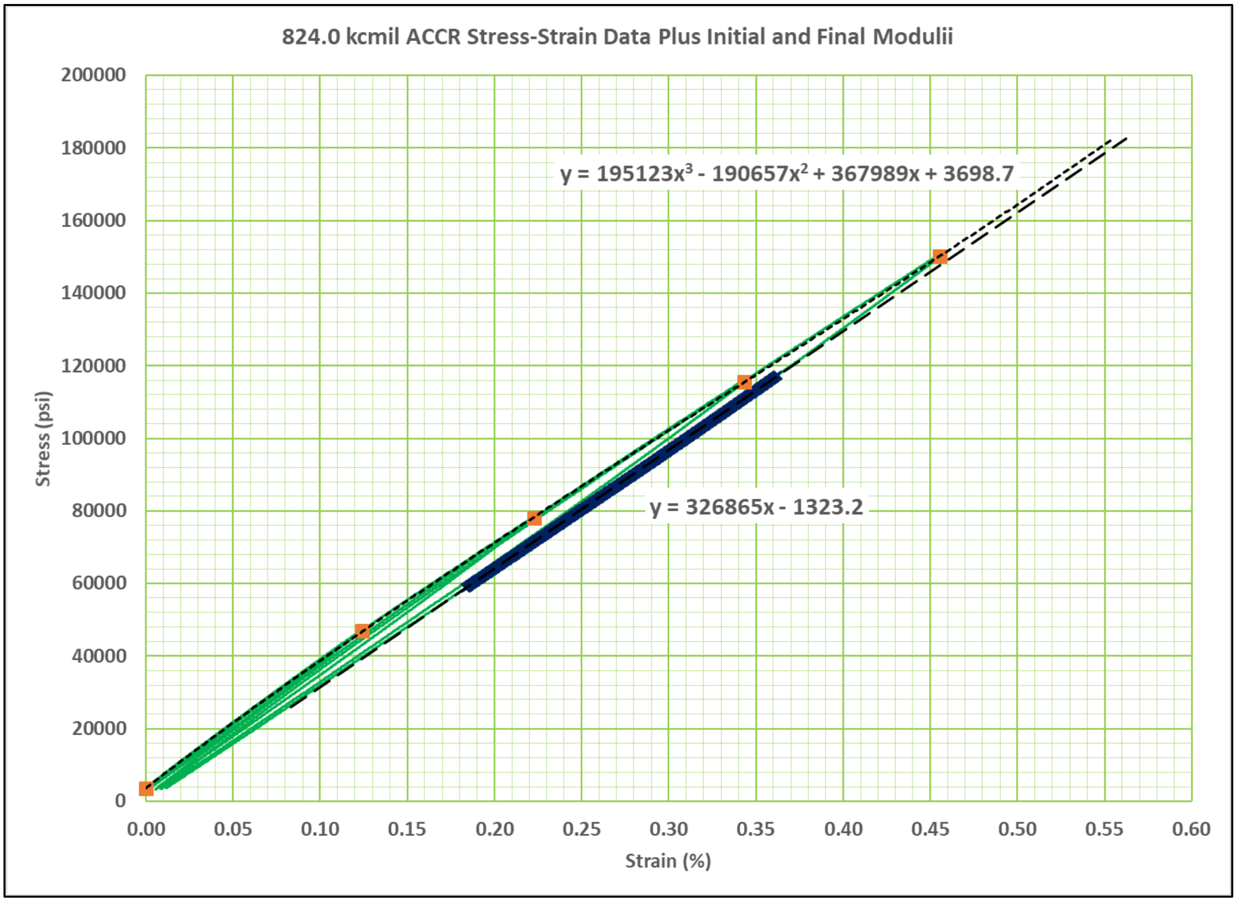


Figure 15: Construction of Initial and Final Modulus Lines for the 3M Core

Figure 16 shows the core moduli shifted along the strain axis to compensate for the bias tension at the start of the test.

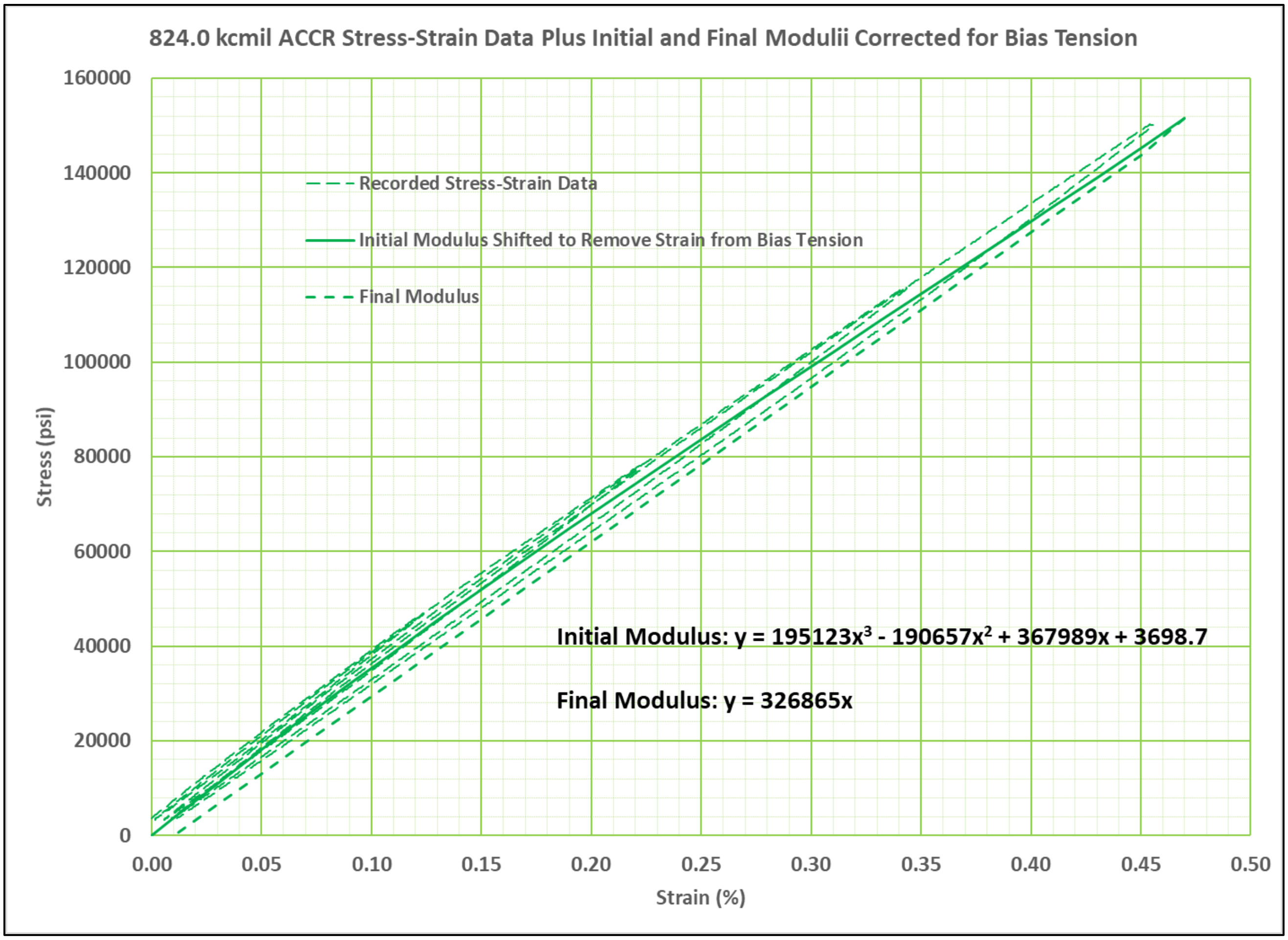


Figure 16: 3M Core Moduli after Compensating for the Bias Tension

Merging the conductor stress-strain data from Figure 14 with the normalized data from Figure 16 results in the industry-standard stress-strain model shown in Figure 17. Note the Y-axis label has changed from “Stress” to “Normalized Stress”, which indicates that both the aluminum data and the core data have been multiplied by their respective area fractions. The blue conductor curves remain the same on the normalized scale because the area fraction of the conductor is always one (1).

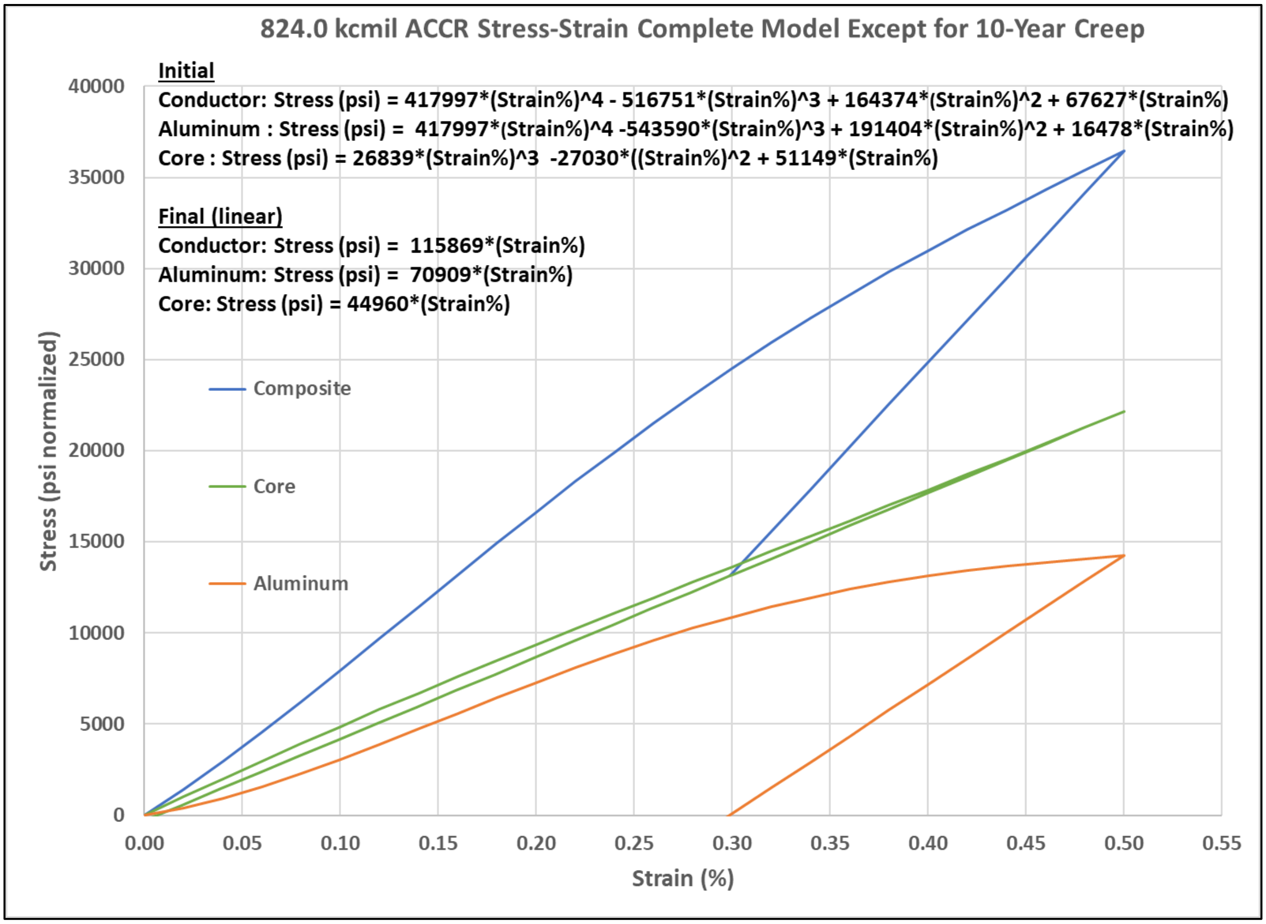


Figure 17: 824.0 ACCR Stress-Strain Model and Fit Equations

The core and aluminum equations in Figure 17 are the coefficients used in the design programs and will match the coefficients displayed in Table 1.

5.4 Creep added to Stress-Strain

The complete model requires a 10-year creep curve and creep coefficients added to the table or computer file. Background creep is assumed to occur at the average annual tension and at the average annual temperature, which is typically assumed to be 60 °F. This is an engineering distinction necessary to separate creep that accumulates gradually over time from creep due to short-time load events. Ice storms and extreme wind are events that cause creep changes on a different time scale than 10-year background creep.

The equation for the creep modulus is created by adding 10-year creep to the 1-hour modulus. Historically, as many and four and even six different tensions were used to estimate the background creep. More recent practice is to rely on the relatively linear behavior of creep vs tension, and use just two stress levels, with a third point at (0,0). In this project, two creep tests were run, one at 15% RBS and the other at 25% RBS. These values bracket the typical installed tensions and provide for accurate interpolation and extrapolation to obtain a value for 10-year creep.

Figure 18 shows the two (2) values for 10-year creep added to the 1-hour modulus to establish the 10-year creep modulus (dashed blue line). Subtracting the normalized core stress-strain line from the conductor creep line imputes the aluminum 10-year creep (dashed orange line).

Historically, creep tests were also run on the core, and separate aluminum creep and core creep coefficients were provided. More recent practice is based on the recognition that core creep is negligible compared to aluminum creep, and therefore the total creep can be represented by just the aluminum coefficients. Any flaw in this underlying assumption is corrected intrinsically, since the conductor creep test captures any small core creep that may occur. Ascribing the small amount of core creep to the aluminum component does not affect the accuracy of the model since all creep is accounted for.

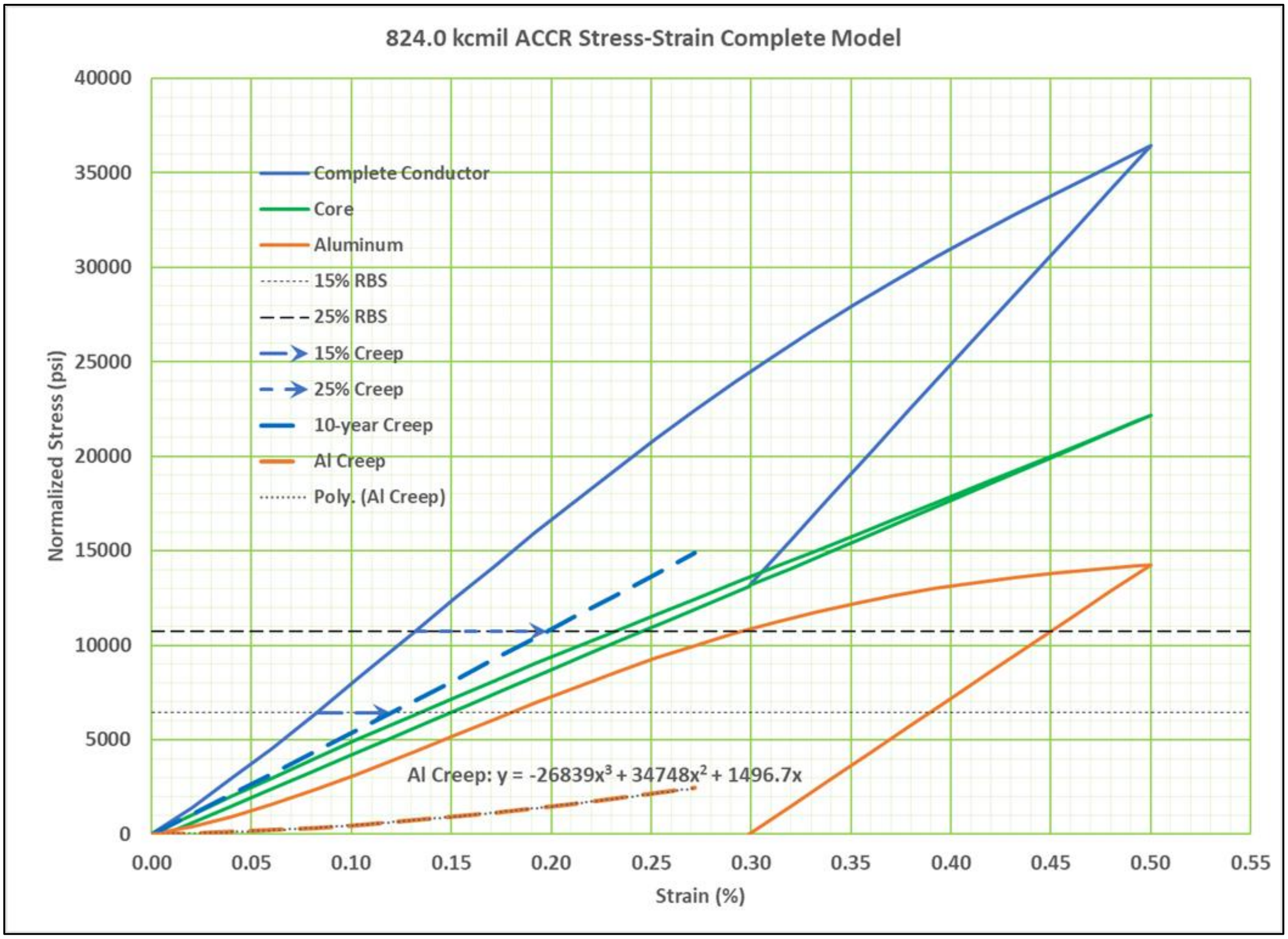


Figure 18: Addition of 10-Year Creep to Stress-Strain Model

Both ASTM Standards are harmonized with IEC (European) and prior guides published by the Aluminum Association.

Table 1 shows the Imperial unit (psi) coefficients derived from the creep and stress-strain tests performed at NEETRAC. Data files are also provided in SI units, but note that the popular software programs operate in Imperial units, and convert any supplied SI units. This means there are two sets of conversion and truncation errors if SI units are provided. While the errors are small, the results are different and have caused confusion.

Table 1: Coefficients for 824.0 kcmil ACCR Conductor, Imperial Units

	K0	K1	K2	K3	K4	71.3	Ref. Temperature (°F)
Al. initial	0	16478	191404	-543590	417997	70909	Al linear modulus (normalized)
Al. creep	0	1496.7	34748	-26839	0	0.00128	Al thermal modulus (%/°F)
Core initial	0	51149	-27030	26839	0	44960	Core linear modulus (normalized)
Core creep	0	51149	-27030	26839	0	0.00035	Core thermal modulus (%/°F)

5.5 Tensile test after stress-strain

Both the conductor sample and the core sample were pulled to destruction upon completion of the stress-strain test. The test is for information only, since the samples have been distressed during the five-hour stress-strain load profile.

The conductor sample failed at 30,061 lb (93.5% of 32,200 lb RBS)

The core sample failed at 18,813 lb (99.7% of 18,878 nominal rating)

6.0 ADDITIONAL MATERIALS ON STRESS-STRAIN AND CREEP

6.1 Stress-strain data referenced to component area

Figure 19 shows the stress-strain data and ultimate stress ratings referenced to the component areas (as opposed to the normalized stress). Note the Y-axis label no longer contains “Normalized”. The blue conductor curve is unchanged because the conductor area fraction is one.

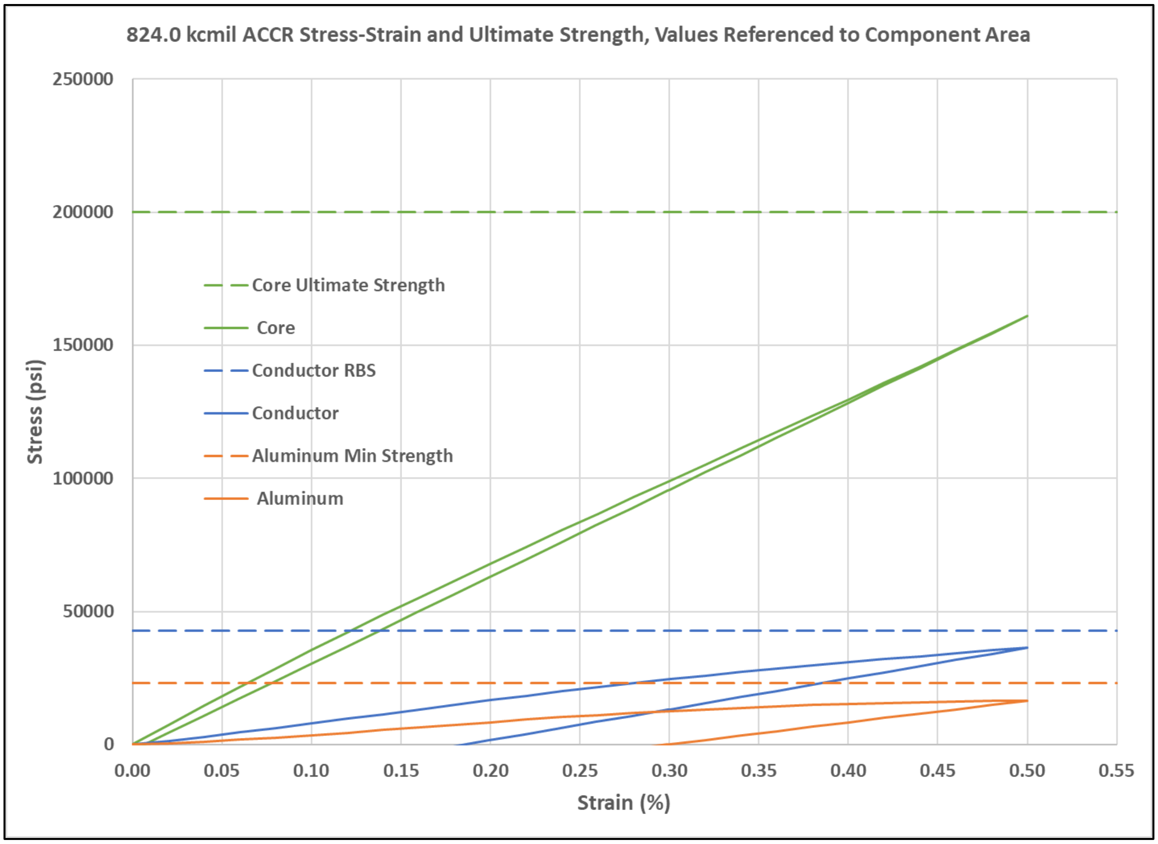
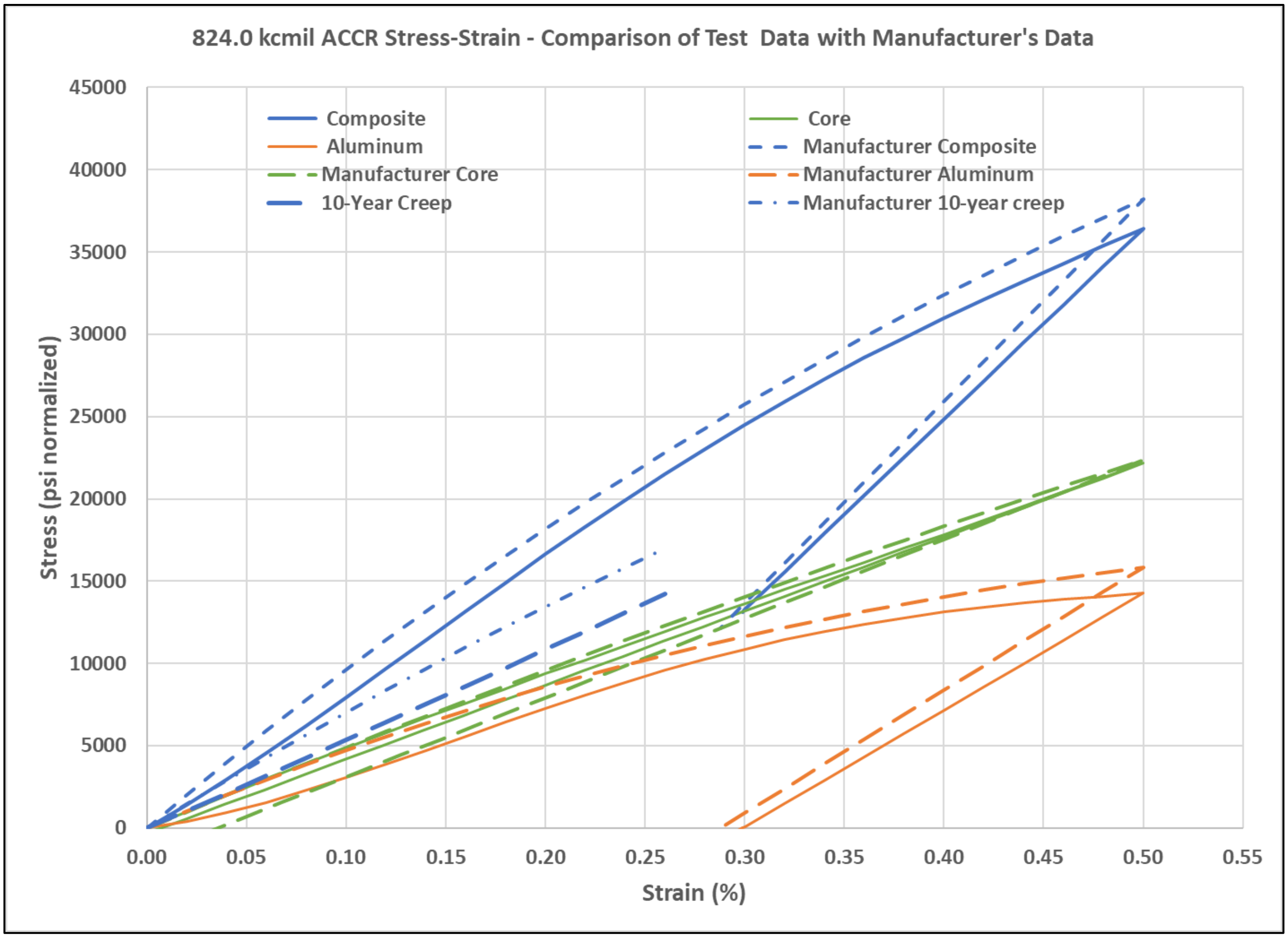


Figure 19: Stress-Strain Chart with Values Referenced to Actual Area



6.2 Comparison with manufacturer data

Figure 20 shows the comparison of NEETRAC's new data (solid lines) and the manufacturers published conductor coefficients (dashed lines).

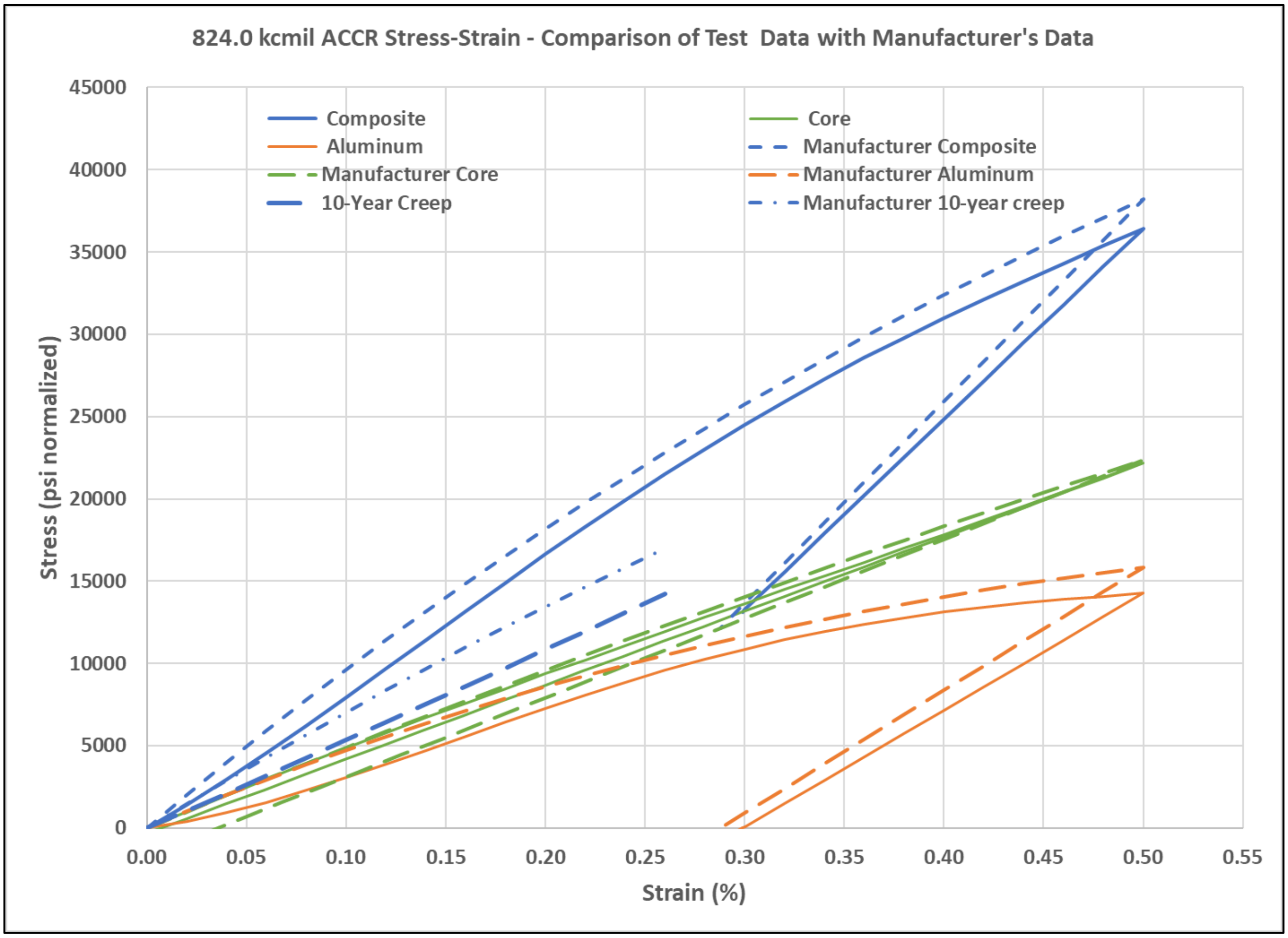


Figure 20: Comparison of NEETRAC Data with Manufacturer's Published Coefficients

Notes:

1. Tests were performed two decades apart, and in different laboratories. The agreement is within the uncertainty of manufacturing variability and interlaboratory variability.

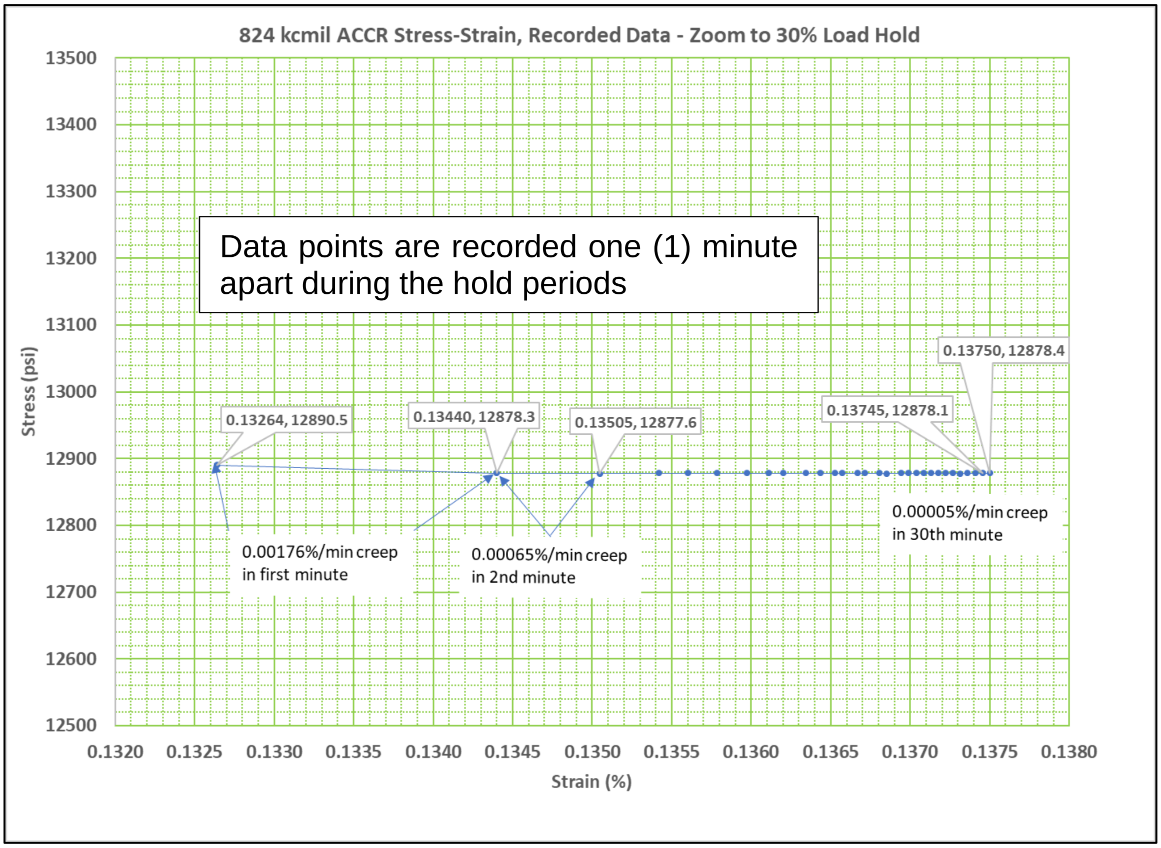
2. The core (green lines) agree, suggesting that the labs are consistent, and the core is consistent. The differences in the aluminum (orange) and complete conductor (blue) curves are manufacturing differences.

3. The slope of the aluminum linear final line is different. The slope is the effective elastic modulus (σ/ε). Since the actual aluminum elastic modulus does not vary, the difference is attributable to lower aluminum content in the sample tested at NEETRAC compared to the sample tested by the manufacturer. See NEETRAC's report on the individual strand tests for confirmation.

4. NEETRAC's creep data is predicting greater creep than the manufacturer data.

6.3 Insights into short-term creep

Figure 21 shows the data points recorded one minute apart during the 30% RBS load hold. The reason short-term creep data is taken from the stress-strain test becomes obvious: creep machines require slow actuators that lock on power-off. A creep machine cannot rapidly load a sample to the target load and keep up with the first few minutes of creep. After just 30 minutes, the creep rate slows to the point that a creep machine can easily maintain the target tension.



Data points are recorded one (1) minute apart during the hold periods

Figure 21: Creep Rate During 30% RBS Load Hold

In the first minute, the creep rate is 0.00176%/min (17.6 ppm/min). In the 2nd minute, the creep rate slows by more than half, to 0.00065%/min (6.5 ppm/min). By the 30th minute of the load hold, the creep rate is 0.00005%/min (0.5 ppm/min, which is at the 0.46 ppm resolution of the NEETRAC extensometer. In lab tests, the creep in the first hour can exceed the creep measured over the next 999 hours of the 1000-hour test.

Figure 22 shows the same 30% load hold data in coordinates of log-time vs. log-creep. The power fit equation is shown, along with an extrapolation to 10 years.

In recent years, presentations by Kinectrics, Southwire, and PLS-CADD have suggested that with high-quality data enabled by digital controls and digital instruments, the creep equations can be determined in far less time than the 1000 hours required by the creep test standards. NEETRAC's data in just 30 minutes establishes an equation that can be extrapolated to 10-year creep. Note that Figure 22 includes the elastic strain from pulling to 30% RBS tension and cannot be compared directly with the 1000-hour creep tests where the strain was zeroed at the start of the test.

Historical research by Alcoa included creep tests that ran for over a decade to evaluate the accuracy of extrapolation of 1000-hour data to 10 years. The results showed that even a 10-hour test with excellent laboratory practices provided sufficient accuracy for engineering purposes. The 1000-hour test remains the standard.

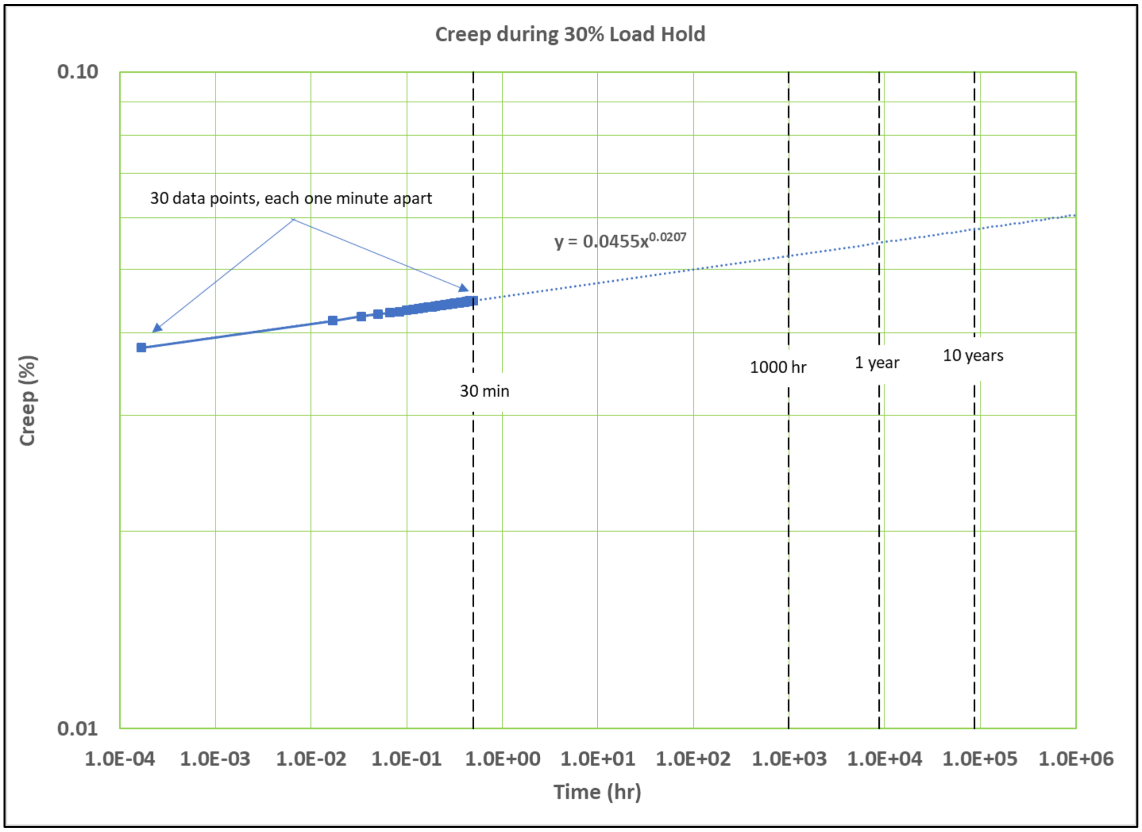


Figure 22: Power Law Fit for 30-min Creep Data, and Extrapolation to 10 Years

7.0 EQUIPMENT

7.1 Stress-Strain

MTS 150,000 lb long-bed horizontal tensile test machine, Calibration Control #	CQ0195
NEETRAC Cable Extensometer, Calibration Control #	CN3002
Omega HH378 Thermocouple Reader, Calibration Control #:	CQ6766
Tinius Olsen stress-strain control and data acquisition system	

7.2 Creep

NEETRAC two-span creep bench	
Mitutoyo dial indicator, Span A, Calibration Control #	CN-7837
Mitutoyo dial indicator, Span B, Calibration Control #	CN-6813
Lebow 25,000 lb rod load cell, Span A, Calibration Control #	CN-7839
Lebow 25,000 lb rod load cell, Span B, Calibration Control #	CN-7838
National Instruments LabView data acquisition software	

8.0 STANDARDS

ASTM B1008, Stress-Strain Testing for Overhead Conductors

ASTM Draft WK62464, Creep Testing for Overhead Conductors

ASTM B941, Heat Resistant Aluminum-Zirconium Alloy Wire for Electrical Purposes

ASTM B976, Aluminum Matrix Composite (AMC) Core Wire for ACCR Conductors

ASTM B978, ACCR Overhead Conductor