Technical Information

3M

Composite Conductor

1272-kcmil

Stress-Strain Polynomial Coefficients for Design Software

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Date of Report: August 2, 2005

1272-kcmil 3M™ Composite Conductor: Stress-Strain Polynomial Coefficients for Design Software

Summary

An analysis of the Stress-Strain and Creep raw data generated at Neetrac for 1272 ACCR generated the coefficients for transmission design that may be incorporated into Alcoa Sag10™ design software. The Sag10™ software coefficients are summarized in Table 1.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	48046	-26995	-10555	5473	73263	70.5	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	24838	-28111	4108	-2141	0.00128		
C0	C1	C2	C3	C4	CF		Core
0	41786	-8620	-4095	2134	39718		
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	41786	-8620	-4095	2134	0.000353		

Table 1. Complete Sag10™ design coefficients for 1272 ACCR.

The methodology to derive these coefficients from the raw data is documented in the sections below. Reports detailing the experiments to obtain all the relevant raw data are found in the following three references:
"1272-kcmil, 3M Brand Composite Conductor, Tensile Tests, Stress-Strain Tests", NEETRAC Project Number: 02-327, March 2003.
"1272-kcmil, 3M Brand Composite Conductor Room-temperature Creep", NEETRAC Project Number: 03-068, September 2003.
"1272-kcmil 3M™ Composite Conductor: Derivation of Power-Law Creep Parameters", 3M Technical Report, August 2005.

Initial Loading Curves

Derivations start with the raw data from Neetrac for 1272-kcmil ACCR Conductor (both core and aluminum layers). The raw data was obtained from Neetrac in the form of Microsoft Excel® Spreadsheets, and all the subsequent analysis was performed using Microsoft Excel® Software. The specification for the 1272-kcmil ACCR Conductor is provided in Appendix A.

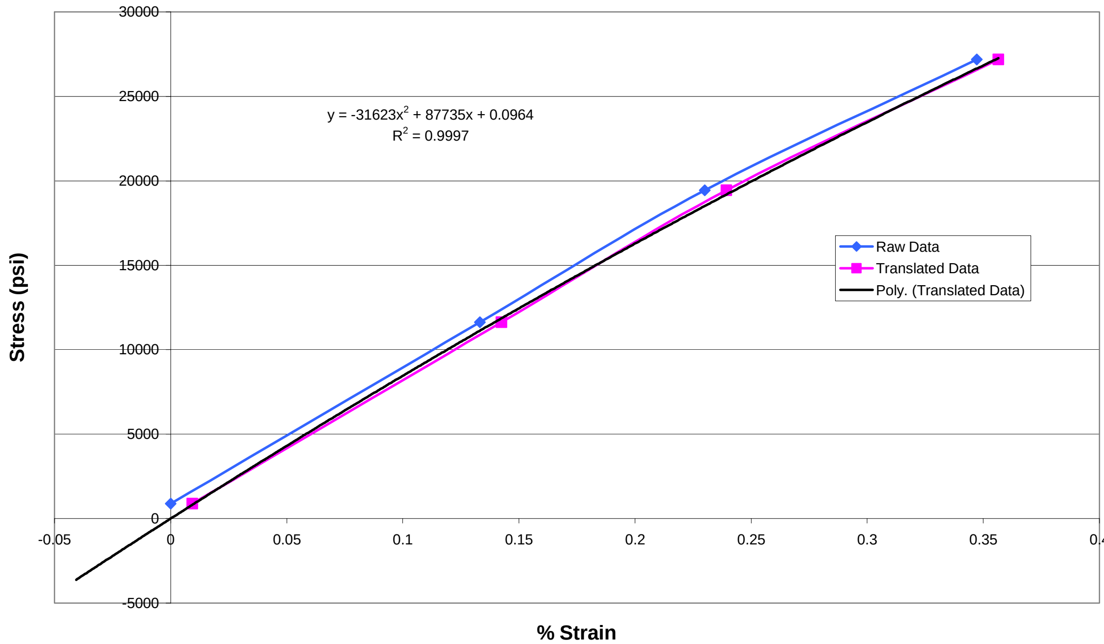

Figure 1. Measured data (blue), and translated data (red) for 1272 ACCR Conductor.

The Neetrac test begins strain measurement at 990 lbs (880 psi), so the resulting "initial" curve needs to be translated to zero. An easy mistake is to translate vertically whereas the curve must be translated horizontally to be accurate. The graph in Figure 1 shows the correct translation, with the experimental data points moved horizontally. The 2nd order curve fit is not forced through zero by interpolation. The curve is translated until the constant representing the y axis intercept is less than 1. This now sets the translation of the data along the strain axis.

The curve fit through the data is a nice second order fit. The curve is extrapolated to reach the approximate failure strain of the conductor at 100% RBS which is ~0.6% Figure 2). At ~0.6%, the stress extrapolation is ~41,000 psi. The 100% RBS specification value is 43,677 lbs (38,805 psi). Thus the extrapolation is poor at higher strains.

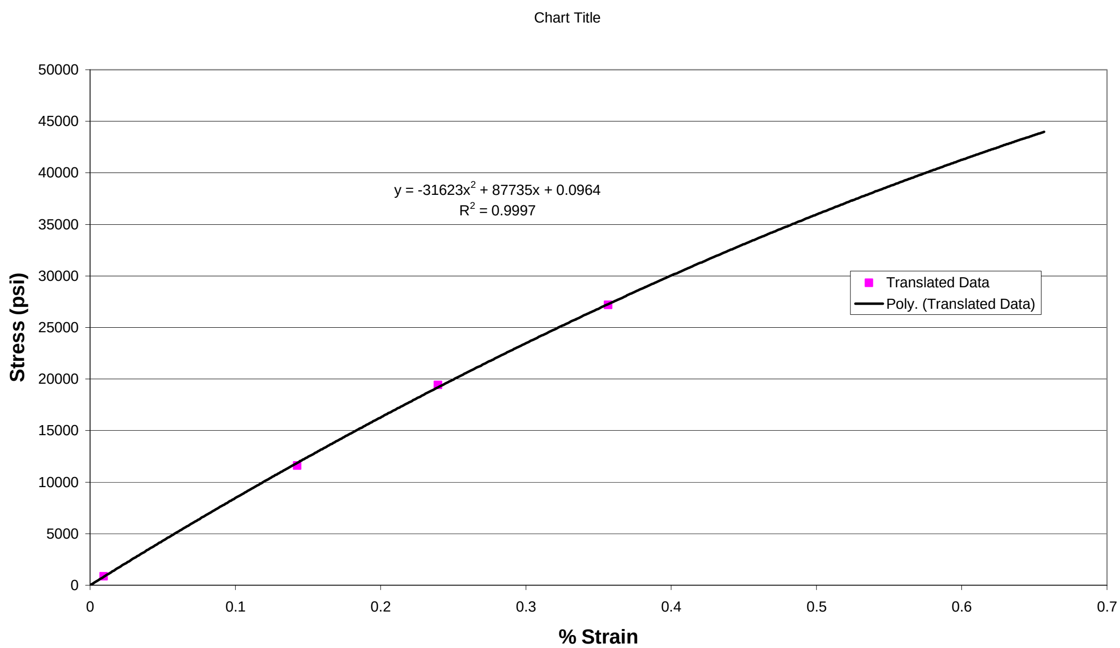

Figure 2. Translated Conductor curve extrapolated above the breaking strain

The RBS value is inserted as a data point (0.6, 38805) and the curve fit shifts. The fit still is good within the range of the experimental data. The intercept is fixed to go through zero – as shown in Figure 3.

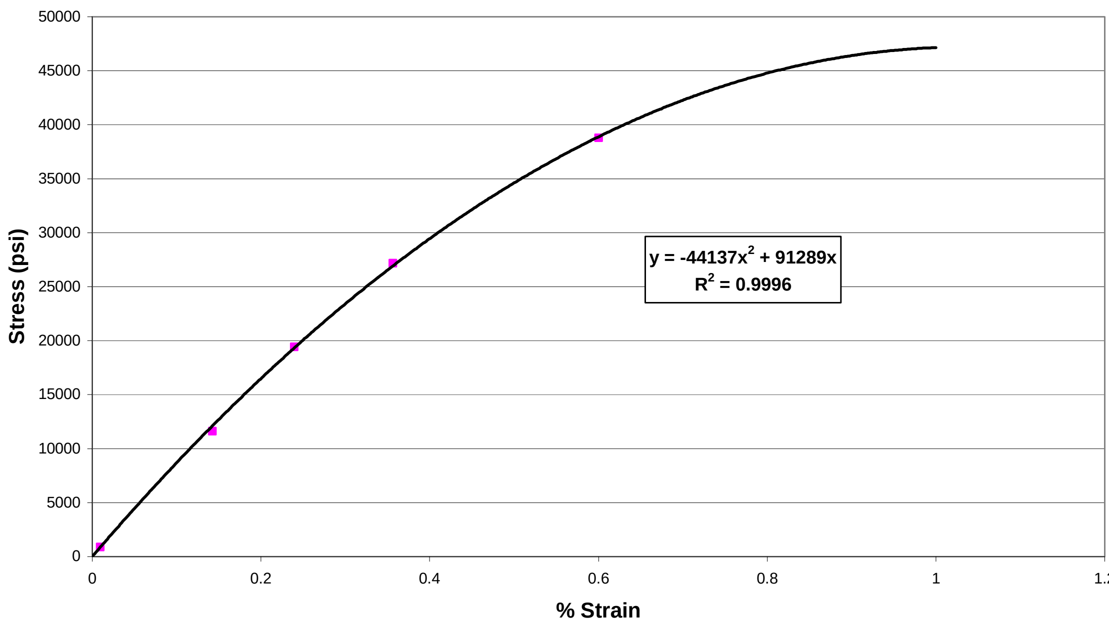

Figure 3. Conductor curve corrected for breaking stress and strain

The fit of a fourth order polynomial to this data is not good due to inflection points which are a poor representation of the true behavior. For compatibility with transmission design software programs, the polynomial needs to behave well (maintain positive slope) to

0.5% strain (Alcoa Sag10™) or to the breaking strain (PLS-CAD). Thus, the second order fit and the equation thereby generated is used to calculate extra points to smooth the curve. In this case an extra eight points were generated at strains of 0.05, 0.1, 0.2, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55%, 0.8% and 1% using the second order polynomial. Additionally the requirement for a zero intercept is enforced. This creates a smoother curve for a reasonable 4th order curve fit, as shown in Figure 4. Note the extrapolation begins to break-down at approximately 1.2% where the curve slope turns negative.

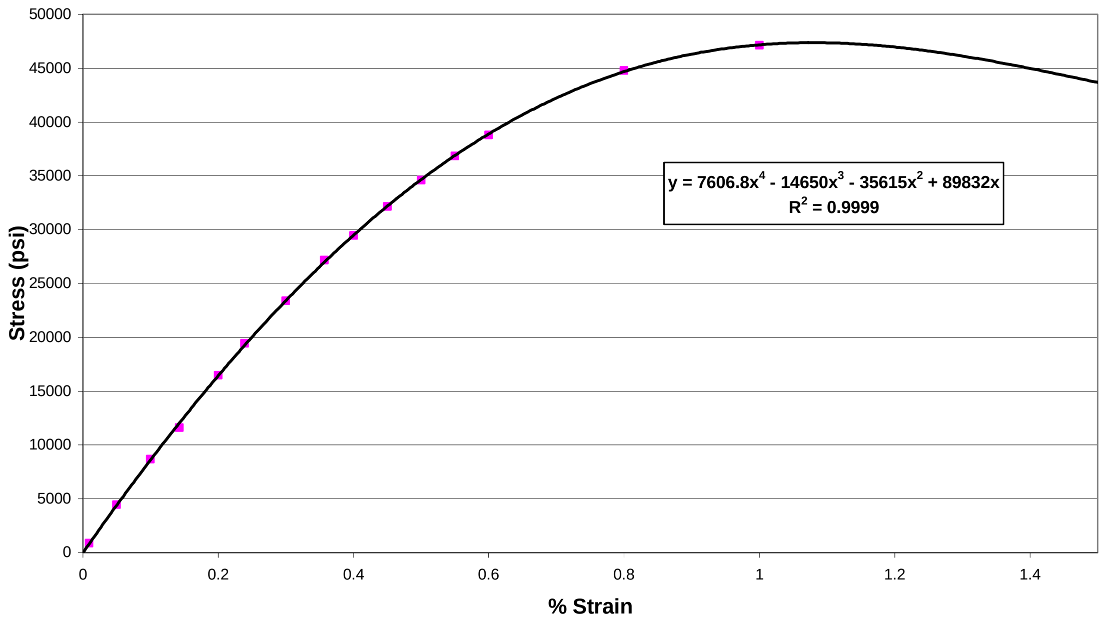

Figure 4. Fourth order polynomial fit to Conductor Stress-strain behavior.

From this the 4th order polynomial relating stress (psi) to % strain is
y = 7606.8x4 - 14650x3 - 35615x2 + 89832x
R2 = 0.9999

The same procedure is now used to process the raw data generated at Neetrac for the AMC Core.

The Neetrac test begins strain measurement at a pre-load, so the resulting “initial” curve needs to be translated to zero. The translation is adjusted so the fitted 2nd order polynomial line has a y-axis intercept of less than 1.0. This is shown in Figure 5.

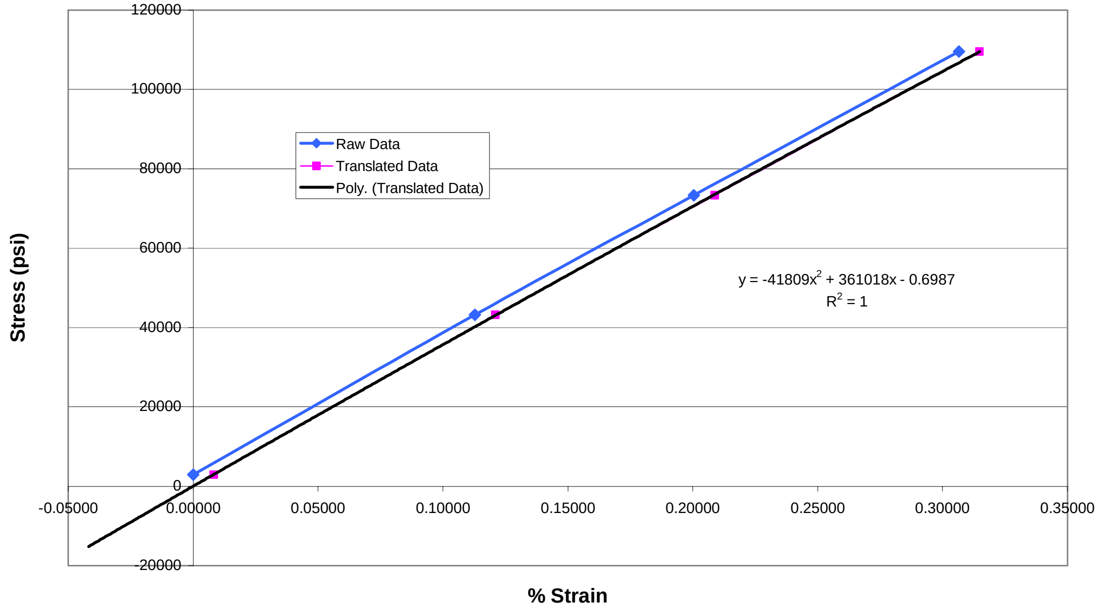

Figure 5. Raw Data and translated curves for 1272 ACCR core.

One additional point is added to calibrate the minimum breaking point at (0.64, 200000), and the fit fixed to go through zero. This gives the graph in Figure 6, which is extrapolated above 1% strain.

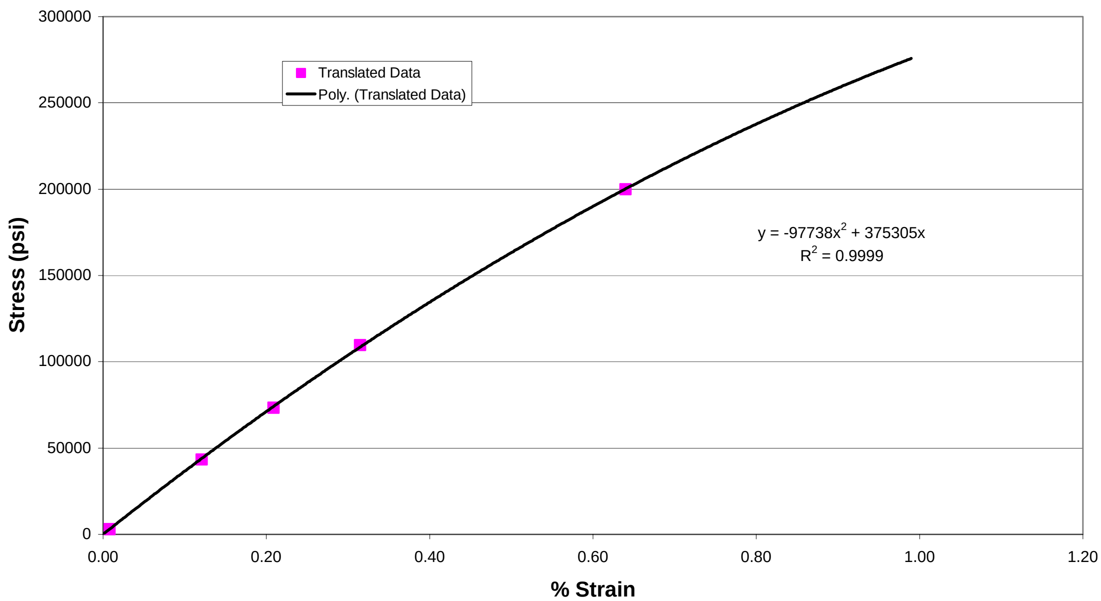

Figure 6. Core Stress-strain behavior corrected for breaking stress.

The extrapolation in Figure 6 looks reasonable. This equation is used to create extra data points up to 1% strain in order to fit a 4th order polynomial. This is shown in Figure 7. Note the extrapolation is good to 1.5% strain.

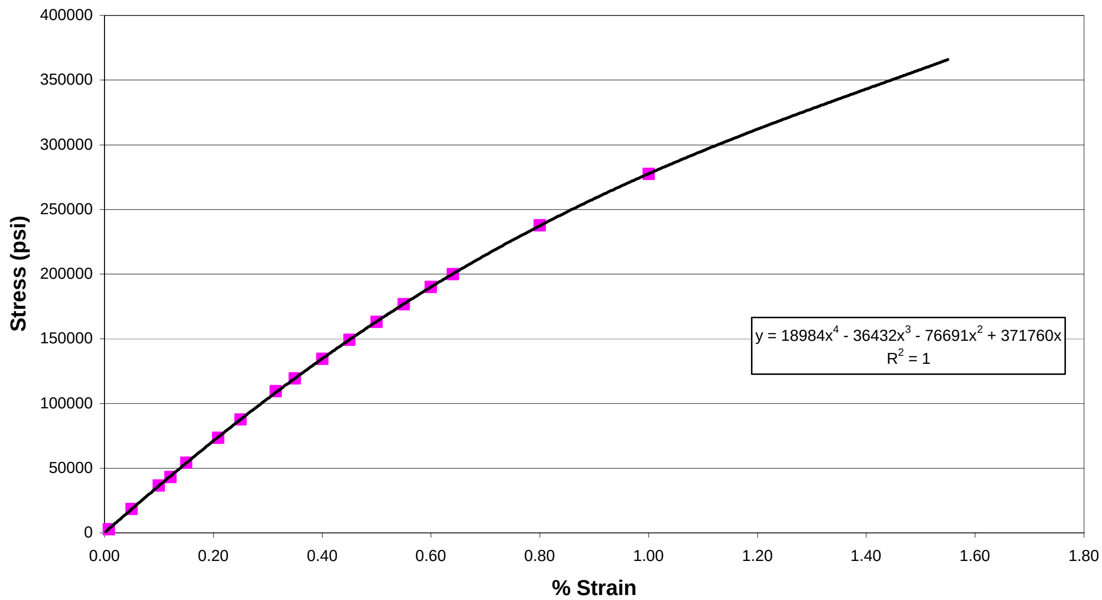

Figure 7. Fourth-order polynomial fit for 795 ACCR core.

From this the 4th order polynomial relating stress (psi) to % strain is

y = 18984x4 - 36432x3 - 76691x2 + 371760x
R2 = 1

These equations are used to numerically derive the aluminum stress-strain curve. 0.01% strain increments were used from 0 to 0.64% using an Excel® software spreadsheet with the following column headings.

%Strain	Conductor Stress/psi	Core Stress/psi	Conductor Load/lbs	Core Load/lbs	Al Load/lbs	Al Stress/psi	Core Stress * Af core	Al Stress * Af Al

The spreadsheet columns are defined as follows:
Conductor stress is the first 4th order polynomial
Core stress is the second 4th order polynomial
Conductor load = conductor stress * %strain
Core load = core stress * %strain
Aluminum load = conductor load – conductor load
Aluminum stress = aluminum load / aluminum area
Core stress* Af core = core stress * core area fraction
Al stress * Af Al = aluminum stress * aluminum area fraction

Plotting the aluminum stress-strain curve gives the graph below (Figure 8). The slope becomes negative at ~0.7% strain, however, this is sufficient for the design software.

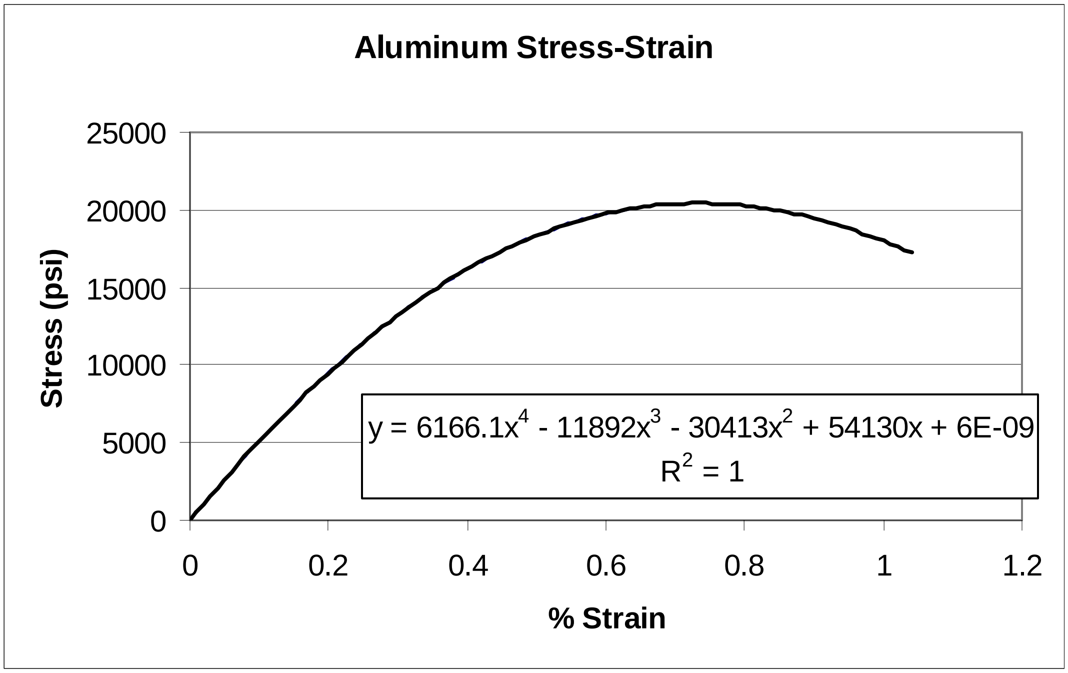

Figure 8. Stress-strain curve for the aluminum layers of 1272 ACCR

From this the 4th order polynomial relating stress (psi) to % strain is

y = 6166.1x4 - 11892x3 - 30413x2 + 54130x + 6E-09
R2 = 1

To generate the "Initial" stress-strain curves, the data sets are plotted together using a normalized stress axis, i.e. stress * constituent area fraction.

Thus,
conductor stress* Af = conductor stress * 1 (the conductor is the whole area)
core stress * Af = core stress * core area fraction (is 11% for 1272 ACCR)
aluminum stress * Af = aluminum stress * Al area fraction (is 89% for 1272 ACCR)

The graph is shown below in Figure 9.

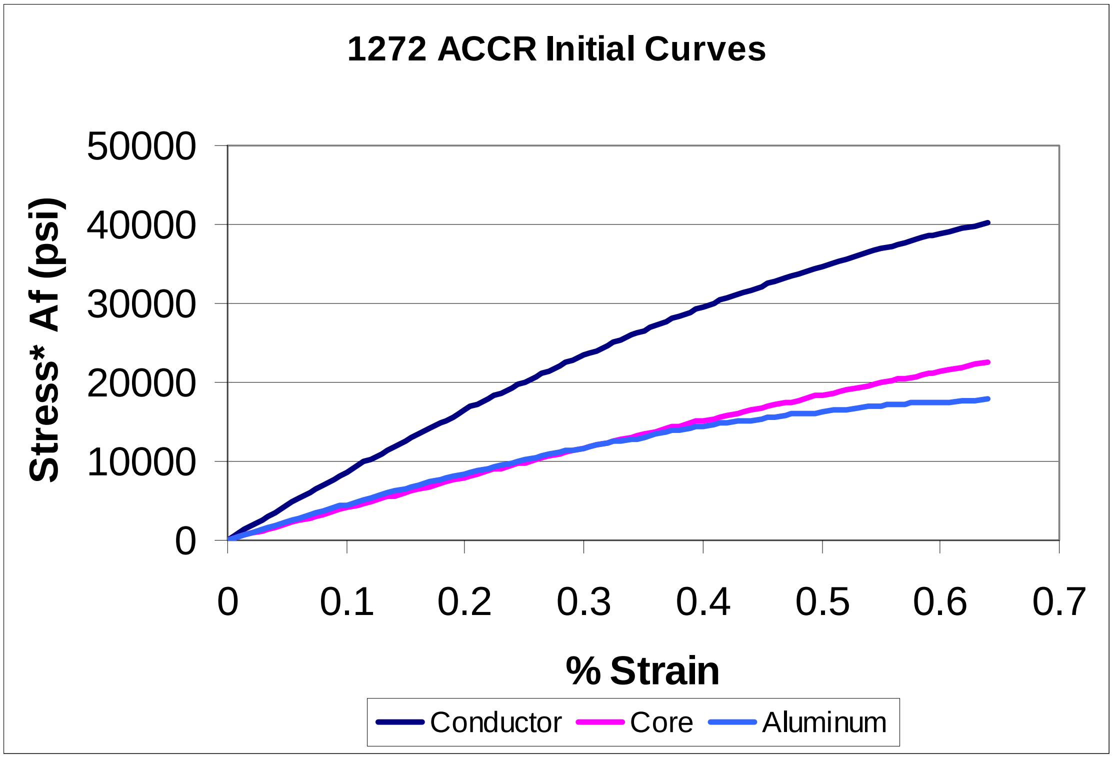

Figure 9. Stress*area fraction vs strain curves for 1272 ACCR.

Curve fits to the core*area fraction and aluminum* area fraction curves are required to yield the coefficients for Sag10™. The 4th order polynomials are:

Core:
y = 2133.8x4 - 4095x3 - 8620.1x2 + 41786x + 9E-09
R2 = 1

Aluminum:
y = 5473x4 - 10555x3 - 26995x2 + 48046x + 6E-09
R2 = 1

Sag10 ™ has a table of coefficients, for which these equations provide some values as shown in Table 2 below.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	48046	-26995	-10555	5473		70.5	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
					0.00128		
C0	C1	C2	C3	C4	CF		Core
0	41786	-8620	-4095	2134			
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	41786	-8620	-4095	2134	0.000353		

Table 2. Sag10™ coefficients for "initial" curves of 1272 ACCR

The core creep is set to zero, so the 10-year creep coefficients (Row D) replicate the initial curve (Row C).

α is the thermal expansion coefficients (in units of $1x10^{-4}$/Fahrenheit) of the constituents. TREF is the temperature at which the stress-strain testing was performed (in Fahrenheit).

Final Modulus

The final modulus can be derived from the raw data. The experimental stress-strain curve is shown below in Figure 10.

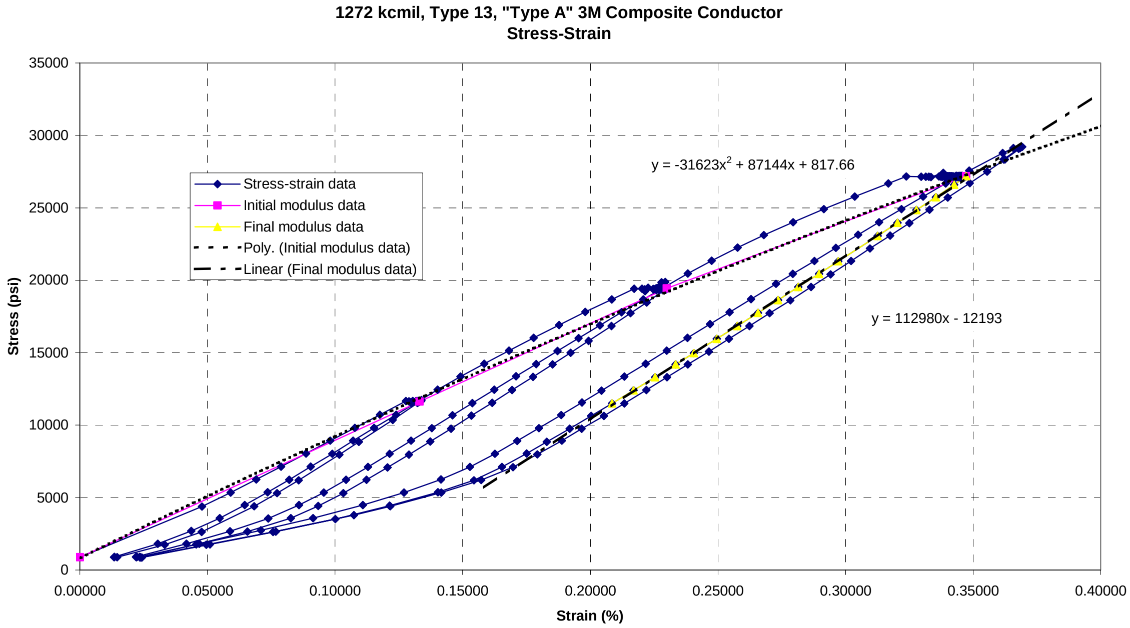

Figure 10. Experimental Stress-strain curves, showing the load-unload sequence for the conductor

The final modulus is derived from the unload curve from the 70% RBS hold. The modulus value is the slope of the linear fit to the unload line. The value is independent of any load offsets or translations.
The equations derived relate stress (psi) to % Strain. These are:

Conductor:
y = 112980x - 12193
R2 = 0.9998

Core:
y = 353362x + 145.21
R2 = 0.9995

In the sag10™ coefficient Table, CF, the conductor final modulus is normalized by the area fraction
Thus CF = 353362*0.1124 = 39718

The equations are used to numerically derive the aluminum stress-strain curve. 0.01% strain increments were used from 0 to 0.45% using an Excel® software spreadsheet with the following column headings.

%Strain	Conductor Stress/psi	Core Stress/psi	Conductor Load/lbs	Core Load/lbs	Al Load/lbs	Al Stress/psi	Core Stress * Af core	Al Stress * Af Al

The spreadsheet columns are defined as follows:
Conductor stress is the linear equation
Core stress is the linear equation
Conductor load = conductor stress * %strain
Core load = core stress * %strain
Aluminum load = conductor load – conductor load
Aluminum stress = aluminum load / aluminum area
Core stress* Af core = core stress * core area fraction
Al stress * Af Al = aluminum stress * aluminum area fraction

From this, it was determined:

Aluminum: (psi units)
y = 82540x - 13755
R2 = 1

Normalizing by the area fraction (88.76%)
AF = 73263
Final presentation format of the curves yields a graph as shown below.

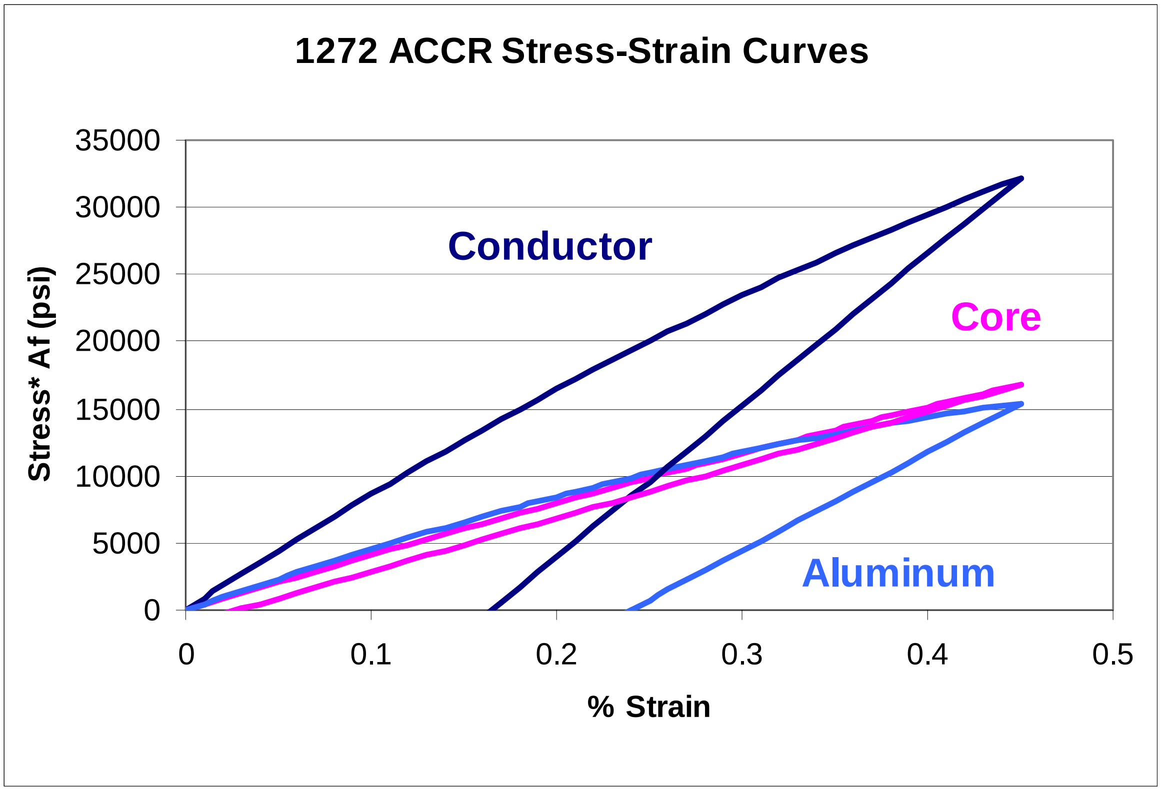

Figure 11. Initial and final curves for all constituents

The coefficients are updated in Table 3.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	48046	-26995	-10555	5473	73263	70.5	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
					0.00128		
C0	C1	C2	C3	C4	CF		Core
0	41786	-8620	-4095	2134	39718		
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	41786	-8620	-4095	2134	0.000353		

Table 3. Sag 10™ coefficients summarizing initial and final curves

Ten –year Creep Curves

From the Neetrac Data, the creep rates are derived and extrapolations are made to deduce the creep for 10 years.

For the 1272 ACCR, the creep strain over time at different tension levels were:

a (%) = b*[(hrs)^c]

The derivation of these equations is summarized in a separate document.

Thus, Table 4 summarizes the creep coefficients for different stress levels.

% RBS	b	c	Stress/ksi
15	0.00303	0.175643	5819
20	0.003165	0.215123	7758
25	0.004363	0.21274	9697
30	0.00804	0.169828	11638

Table 4. Creep parameters for 1272 ACCR

From these, the creep strain accumulated over 10 years (87600 hours) can be calculated and is summarized in Table 5.

% RBS	b	c	Stress/ksi	%Strain 10 yr creep
15	0.00303	0.175643	5819	0.0224
20	0.003165	0.215123	7758	0.0366
25	0.004363	0.21274	9697	0.0491
30	0.00804	0.169828	11638	0.0555

Table 5. 10-year creep strain for 1272 ACCR

The creep strain is added to the “initial” strain for each of these stress levels (Table 6).

stress/psi	initial % strain at creep stress	% strain creep+initial
5819	0.06658	0.088945
7758	0.08966	0.126273
9697	0.11325	0.162365
11638	0.13744	0.1930

Table 6. Initial strain and added creep strain at stresses used in creep testing.

The initial + creep strain data are plotted and compared to the initial curve in Figure 12. A 2nd-order fit is made through the 10-year creep data points and through the zero point, which gives an excellent fit and a smooth and reasonable extrapolation to higher strains.

The 10-year conductor creep curve is thus y = -36759x2 + 66760x, R2 = 0.9956

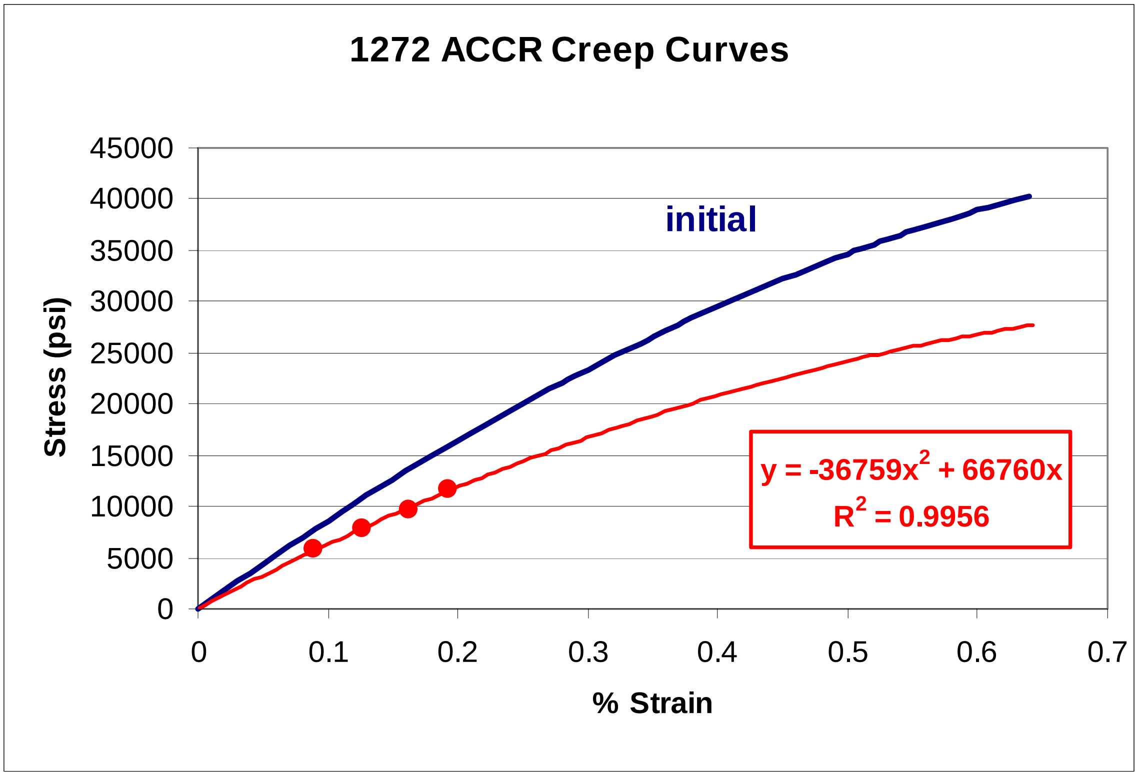

Figure 12. Conductor stress-strain plot reflecting initial and 10-year creep strains.

The goal is to derive the aluminum curve after 10-year creep. An assumption is made that the core exhibits zero creep (not measured but compared to the aluminum creep this is not unreasonable). Thus the core "initial" curve is also the core 10-year creep curve. Thus we numerically subtract the core initial curve from the conductor 10-year creep to deduce the aluminum 10-year creep.

These equations are used to numerically derive the aluminum stress-strain curve. 0.01% strain increments were used from 0 to 0.64% using an Excel® software spreadsheet with the following column headings.

%Strain	10-yr conductor stress/psi	core stress/psi	conductor load/lbs	core load lbs	Al load lbs	10 yr Al creep Stress/psi	Core Stress * Af core	10 yr Al Stress * Af Al

The spreadsheet columns are defined as follows:
10-yr Conductor stress is the linear equation
Core stress is the "initial" 4^{th} order polynomial
Conductor load = conductor stress * %strain
Core load = core stress * %strain
Aluminum load = conductor load – conductor load
10 yr aluminum creep stress = aluminum load / aluminum area
Core stress* Af core = core stress * core area fraction
Al stress * Af Al = aluminum stress * aluminum area fraction

This gives the graph for aluminum in Figure 13.

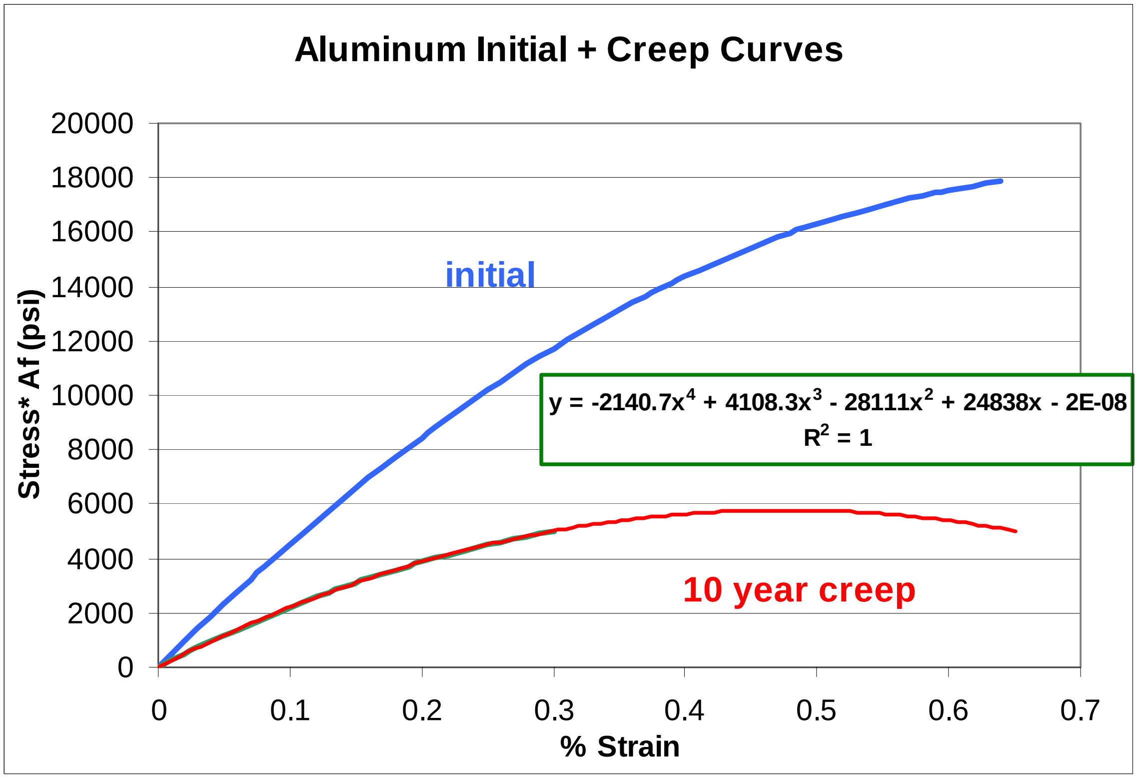

Figure 13. Aluminum initial and 10-year stress-strain curves.

The 4th order polynomial fit, forced to go through a zero intercept is:

y = -2140.7x4 + 4108.3x3 - 28111x2 + 24838x - 2E-08
R2 = 1

The slope begins to turn negative in the range of 0.55-0.60% reflecting the difficulties in trying to extrapolate accurately outside of the measured data range.

These coefficients then fit the "B" row in the Sag10™ table, thus completing the Table 7.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	48046	-26995	-10555	5473	73263	70.5	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	24838	-28111	4108	-2141	0.00128		
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D0	D1	D2	D3	D4	α (core)		10 yr creep
0	41786	-8620	-4095	2134	0.000353		

Table 7. Complete coefficient Table for Sag10™ design software.

Summary

An analysis of the Stress-Strain and Creep raw data generated at Neetrac for 1272 ACCR generated the coefficients for transmission design that may be incorporated into Alcoa Sag10™ design software. The coefficients are summarized in Table 8.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	48046	-26995	-10555	5473	73263	70.5	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	24838	-28111	4108	-2141	0.00128		
C0	C1	C2	C3	C4	CF		Core
0	41786	-8620	-4095	2134	39718		
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	41786	-8620	-4095	2134	0.000353		

Table 8. Complete Sag10 ™ design coefficients for 1272 ACCR.

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 A: 1272-kcmil, 3M™ Composite Conductor Specification

Conductor Physical Properties		
Designation		1272-T13
Stranding		54/19
kcmils	kcmil	1,272
Diameter		
indiv Core	in	0.092
indiv Al	in	0.153
Core	in	0.46
Total Diameter	in	1.38
Area		
Al	in^2	0.999
Total Area	in^2	1.126
Weight	lbs/linear ft	1.392
Breaking Load		
Core	lbs	23,622
Aluminum	lbs	20,055
Complete Cable	lbs	43,677
Modulus		
Core	msi	31.4
Aluminum	msi	8.0
Complete Cable	msi	10.6
Thermal Elongation		
Core	10^-6/F	3.5
Aluminum	10^-6/F	12.8
Complete Cable	10^-6/F	9.2
Heat Capacity		
Core	W-sec/ft-C	28
Aluminum	W-sec/ft-C	520

Conductor Electrical Properties		
Resistance		
DC @ 20C	ohms/mile	0.0700
AC @ 25C	ohms/mile	0.0717
AC @ 50C	ohms/mile	0.0787
AC @ 75C	ohms/mile	0.0858
Geometric Mean Radius	ft	0.0466
Reactance (1 ft Spacing, 60hz)		
Inductive Xa	ohms/mile	0.3720
Capacitive X'a	ohms/mile	0.0847