3M Composite Conductor
795-kcmil

Stress-Strain Polynomial Coefficients for Design Software

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795-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 795 ACCR generated the coefficients for transmission design that may be incorporated into Alcoa Sag10 ™ and PLS-CAD design software. The Sag10™ coefficients are summarized in Table 1.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	51891	-48684	19136	-5256	74602	71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	23443	-20533	-527	793	0.00128		
C0	C1	C2	C3	C4	CF		Core
0	50132	-10898	527	-793	48119		
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	50132	-10898	527	-793	0.000353		

Table 1. Complete Sag10 ™ design coefficients for 795 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:
"795-kcmil, 3M Brand Composite Conductor Room Temperature Stress-Strain Tests", NEETRAC Project Number: 02-133, December 2003.
"795-kcmil, 3M Brand Composite Conductor Room-temperature Creep", NEETRAC Project Number: 02-241, May 2005.
"795-kcmil 3M Brand Composite Conductor: Derivation of Power-Law Creep Parameters", 3M Technical Report, June 2005.

Initial Loading Curves

Derivations start with the raw data from Neetrac for 795-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 795-kcmil ACCR Conductor is provided in Appendix A.

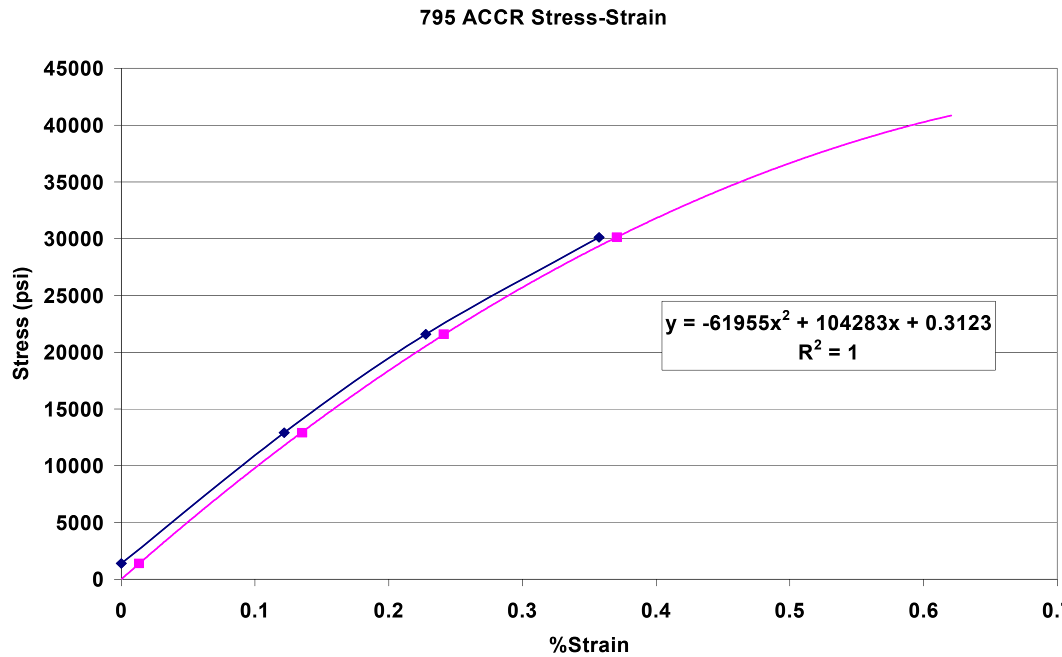

Figure 1. As measured data (blue), and translated data (red) for 795 ACCR Conductor.

The Neetrac test begins strain measurement at 2000 lbs, 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 above (Figure 1) shows the correct translation, with the experimental data points moved horizontally. The curve fit is not forced through zero by interpolation. 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%. The translation is adjusted so the fitted line has a y-axis intercept of less than 1.0.

An important issue is one of correctly translating through zero, the raw data generated at Neetrac (y=mx+b type curve), and then fitting with 4th order equations in order to derive the desired coefficients.

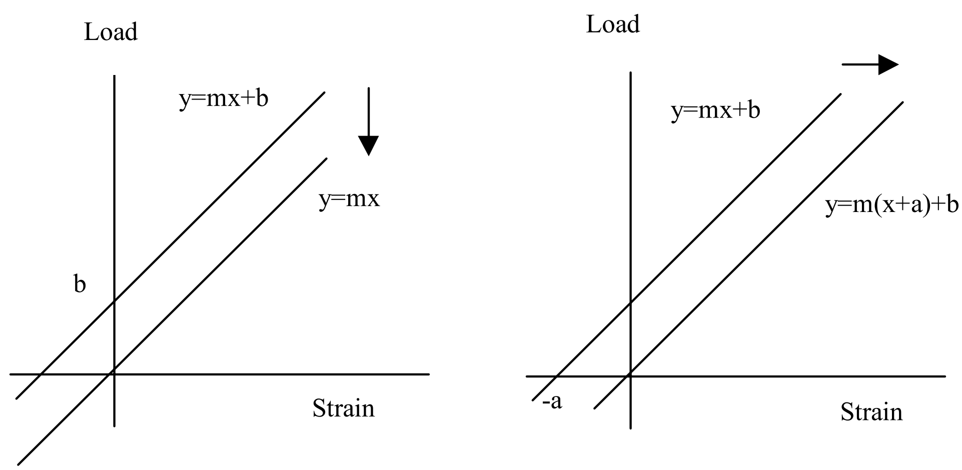

Figure 2. Incorrect translation Correct translation

The incorrect translation is easily made and results in lower loads (& hence stresses) at the higher strains. The correct translation preserves the correct load at higher strains as shown in Figure 2.

At ~0.6%, the stress is ~40,000 psi. The 100% RBS value is 43,003 psi at 0.595%. Thus the extrapolation is poor at higher strains. The RBS value is inserted as a data point (0.595, 43003) and the curve fit shifts. The fit still is good within the range of the experimental data. The intercept is also forced to go through zero – as shown below (Figure 3).

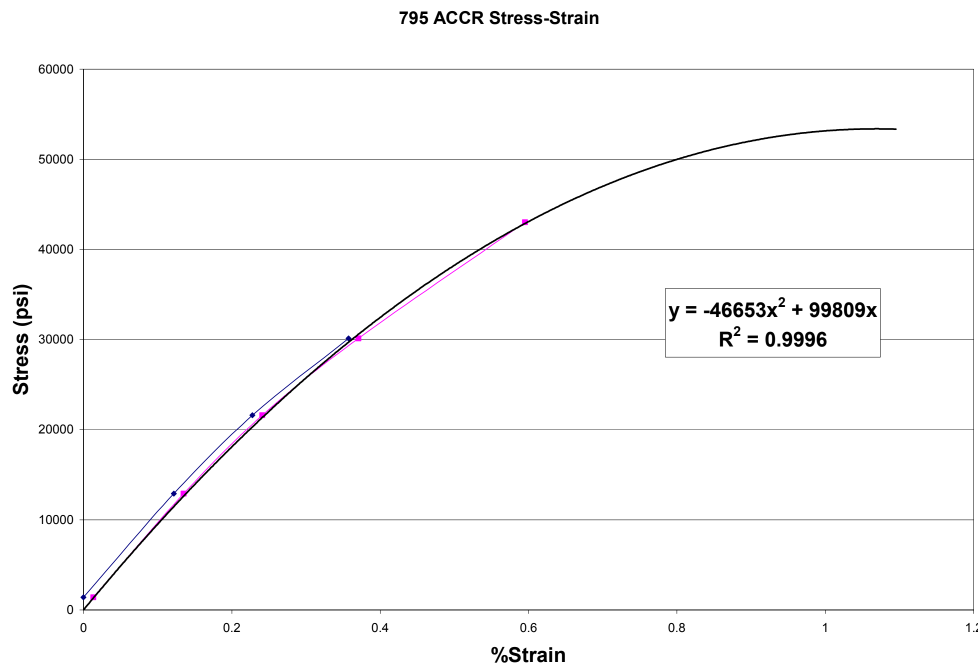

Figure 3. Conductor curve corrected for breaking stress and strain

Additionally, the curve is extrapolated beyond the breaking strain to check for a good extrapolation behavior. In Figure 3, the polynomial is reaching an inflection point at 1% strain where the slope turns negative which shows the extrapolation is failing. For compatibility with transmission design software programs, the polynomial just needs to behave well (maintain positive slope) to 0.5% strain (Alcoa Sag10 TM) or to the breaking strain (PLS-CAD). Thus Figure 3 satisfies both of these criteria. Also additional data points are added between 0.04-0.6% strain using the 2nd order polynomial curve fit of Figure 3, to maintain a high degree of fit to the real data points and to the critical design strain range. Additionally the requirement for a zero intercept is enforced. This creates the graph for a reasonable 4th order curve fit, as shown below (Figure 4).

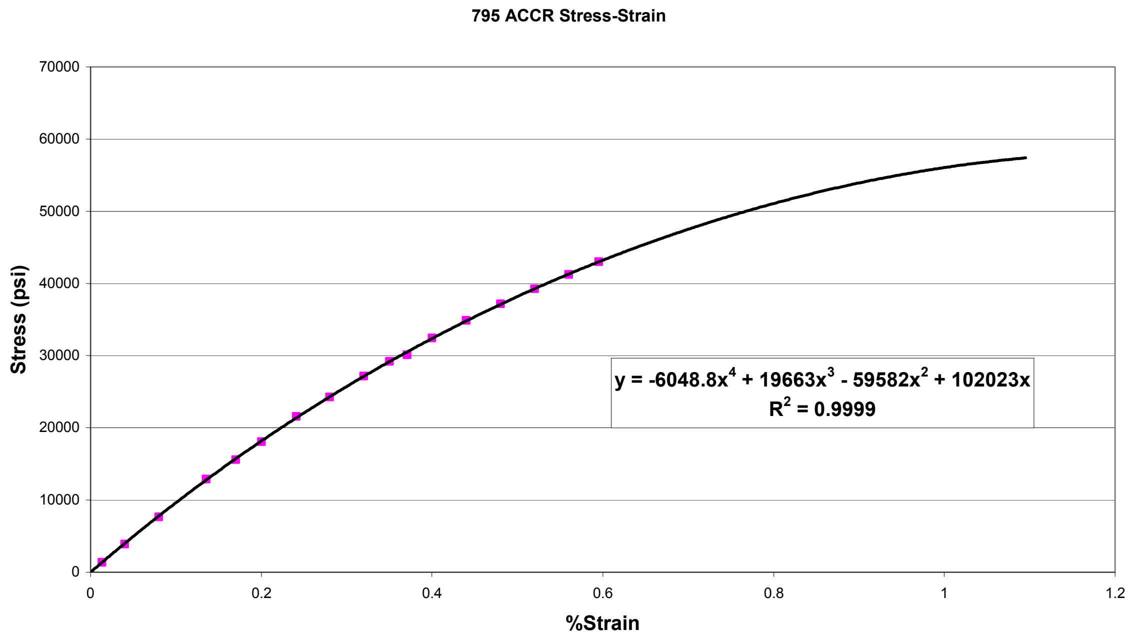

Figure 4. Fourth order polynomial fit to Conductor Stress-strain behavior.

From this the 4th order polynomial relating stress (psi) to % strain is
y = -6048.8x4 + 19663x3 - 59582x2 + 102023x
R2 = 0.999

A similar procedure is now used to process the raw data generated at Neetrac for the AMC Core, but with some differences.

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.

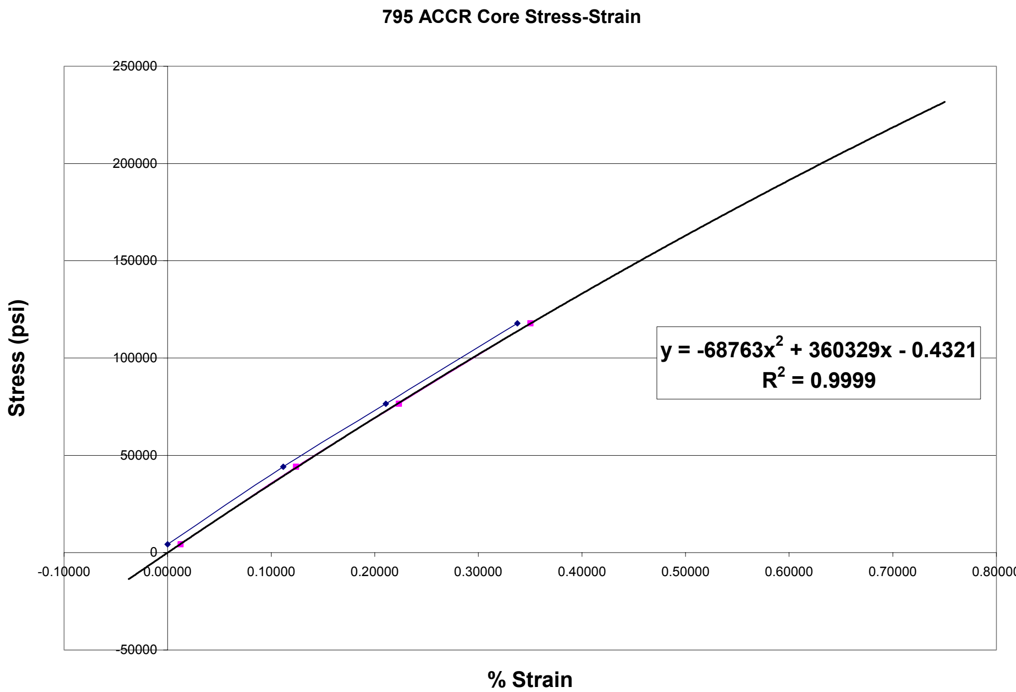

Figure 5. Raw Data and translated curves for 795 ACCR core.

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

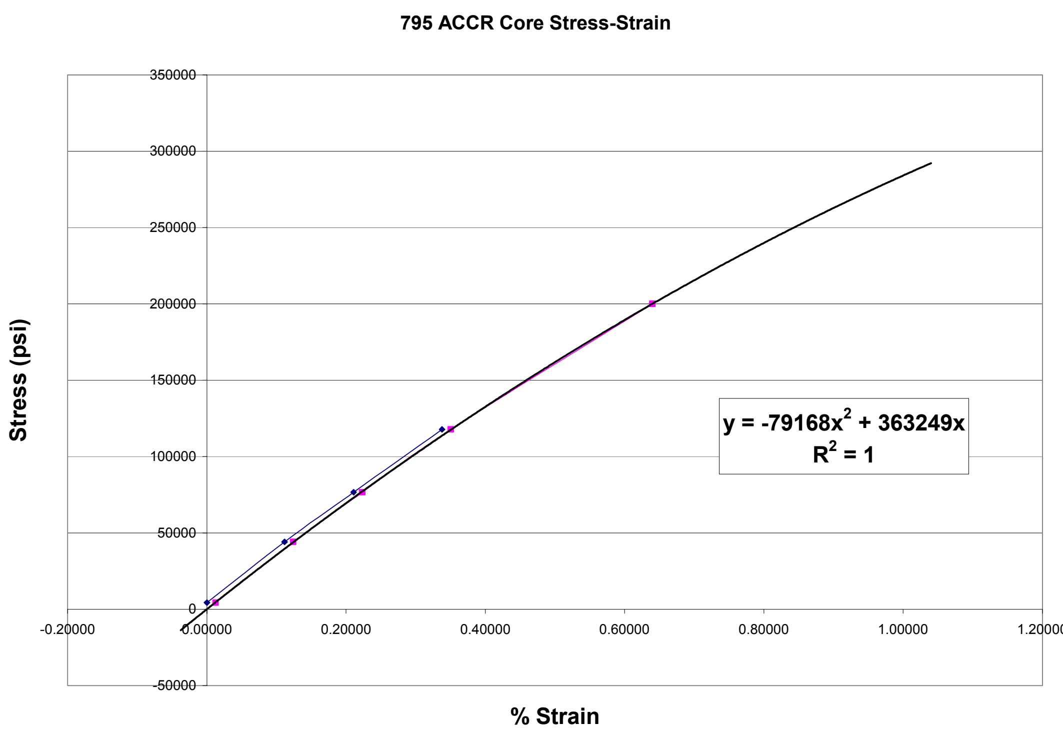

Figure 6. Core Stress-strain behavior corrected for breaking stress.

The extrapolation in Figure 6 looks very reasonable, and so this equation is used to create extra data points up to 0.64% strain in order to fit a 4th order polynomial. This is shown in Figure 7.

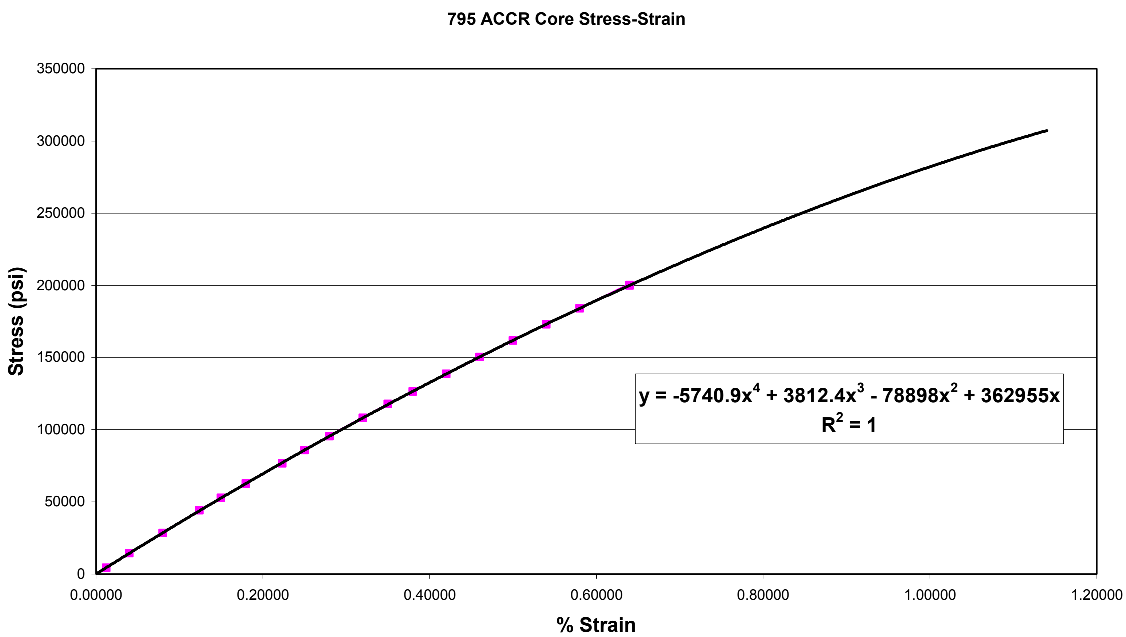

Figure 7. Fourth-order polynomial fit for 795 ACCR core.

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

y = -5740.9x4 + 3812.4x3 - 78898x2 + 362955x
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 * conductor area
Core load = core stress * core area
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 fit is good but the slope of the extrapolation becomes negative at ~0.8% strain. However, this is sufficient for the design software.

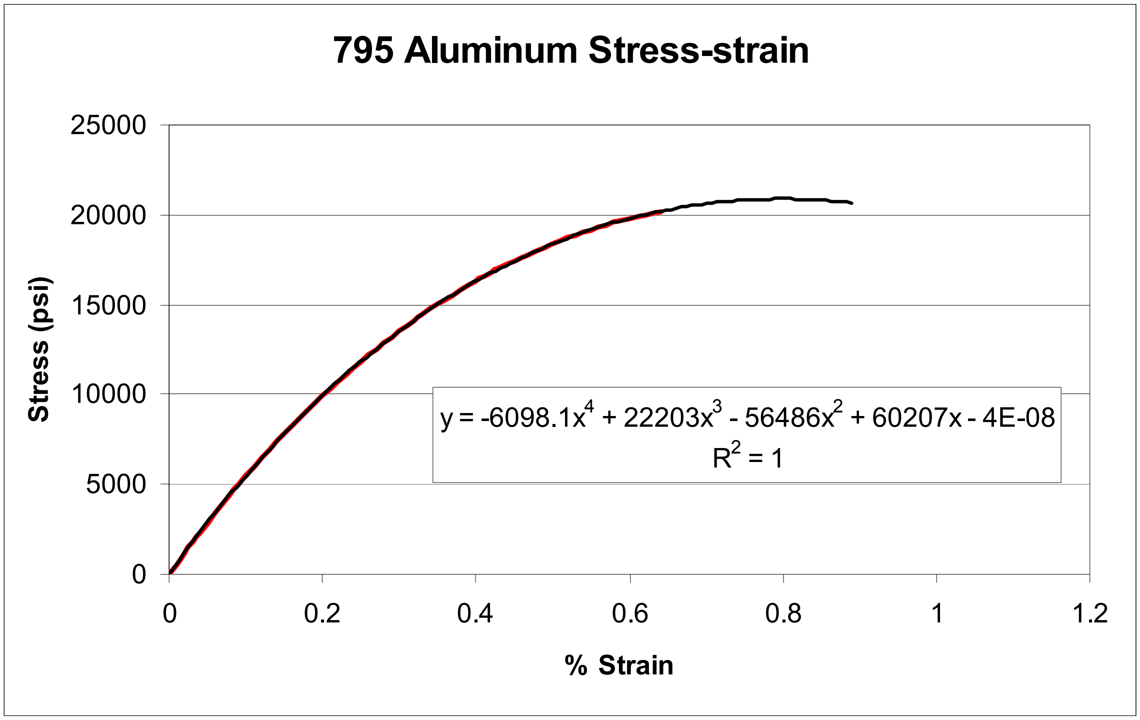

Figure 8. Stress-strain curve for the aluminum layers of 795 ACCR

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

y = -6098.1x4 + 22203x3 - 56486x2 + 60207x - 4E-08
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 14% for 795 ACCR)
aluminum stress * Af = aluminum stress * Al area fraction (is 86% for 795 ACCR)

The graph is shown below in Figure 9.

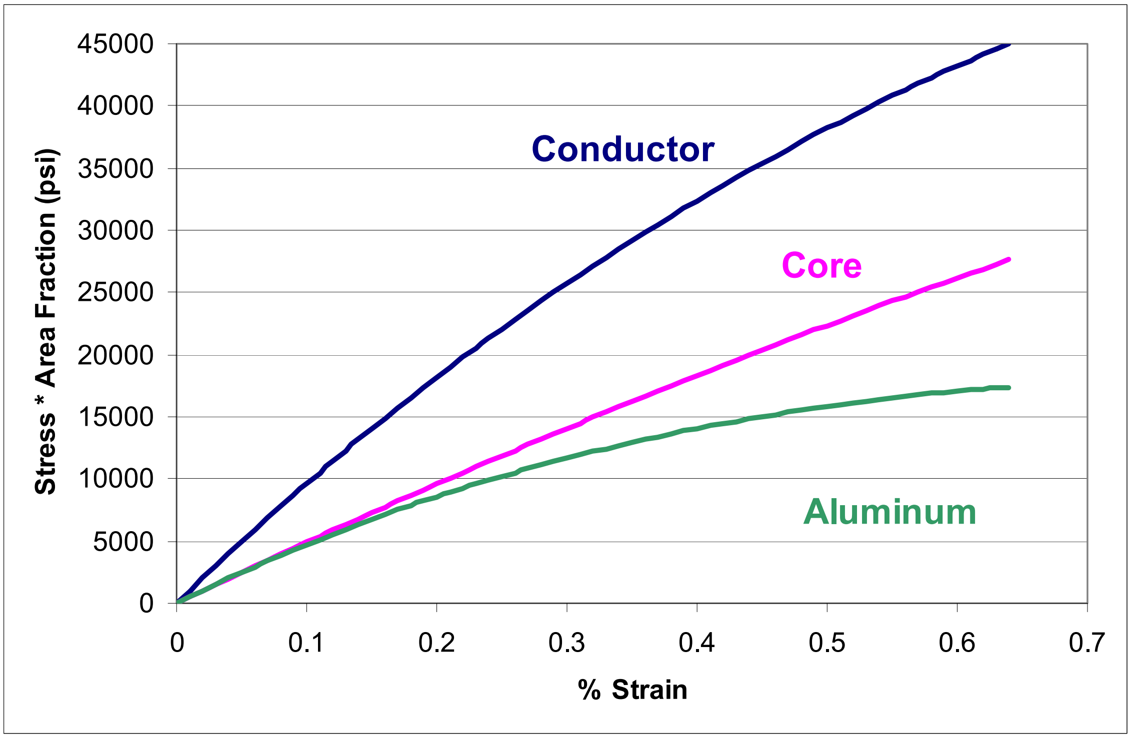

Figure 9. Stress*area fraction vs strain curves for 795 ACCR.

Curve fits to the core*area fraction and aluminum* area fraction curves are required to yield the coefficients for Sag10 TM design software. The full data set to 0.64% is used for the fits.

The 4th order polynomials are:

Core: y = -792.94x4 + 526.57x3 - 10898x2 + 50132x - 6E-08
R2 = 1
Aluminum: y = -5255.9x4 + 19136x3 - 48684x2 + 51891x - 4E-08
R2 = 1

Sag10 TM 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	51891	-48684	19136	-5256		71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
					0.00128		
C0	C1	C2	C3	C4	CF		Core
0	50132	-10898	527	-793			
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	50132	-10898	527	-793	0.000353		

Table 2. Sag10 TM coefficients for "initial" curves of 795 ACCR

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

α is the thermal expansion coefficients (in units of $1\text{x}10^{-4}$/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.

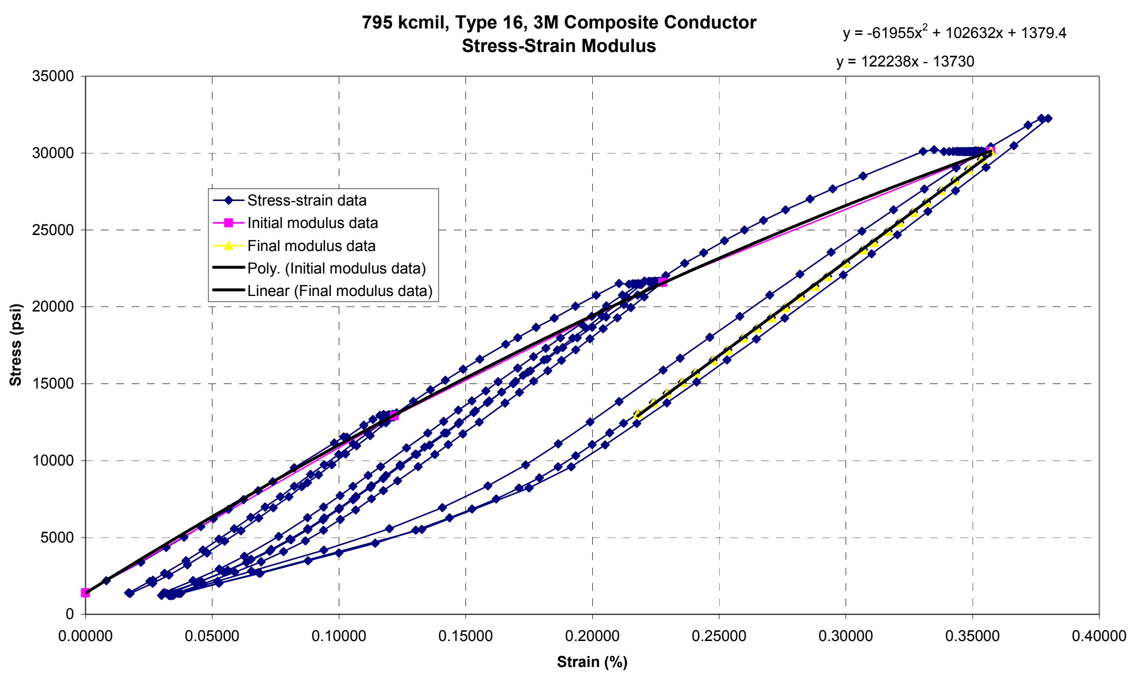

Figure 10. Experimental Stress-strain curves, showing the load-unload sequence for the conductor

The final modulus is derived from the unload curve from the 70% RBS hold. The modulus value is simply 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:

Conductor:
y = 122238x - 13730

Core:
y = 343705x + 253.57

In the sag10 ™ coefficient Table, CF, the conductor final modulus is normalized by the area fraction
Thus CF = 343705*0.14 = 48119

For the conductor-core pairing, the aluminum final curve is derived numerically just as with the initial aluminum curve. Since the only interest is in the slope of the final lines and these are treated as linear, then the offsets or translations become an arbitrary selection. However for conventional display purposes, the final curves are presented as dropping from the initial curve at 0.45% strain. This is achieved by changing the constant for the y-axis intercept to translate the line until the initial curve is intercepted at 0.45% strain. An example for the conductor and core presentation is shown below in Figure 11.

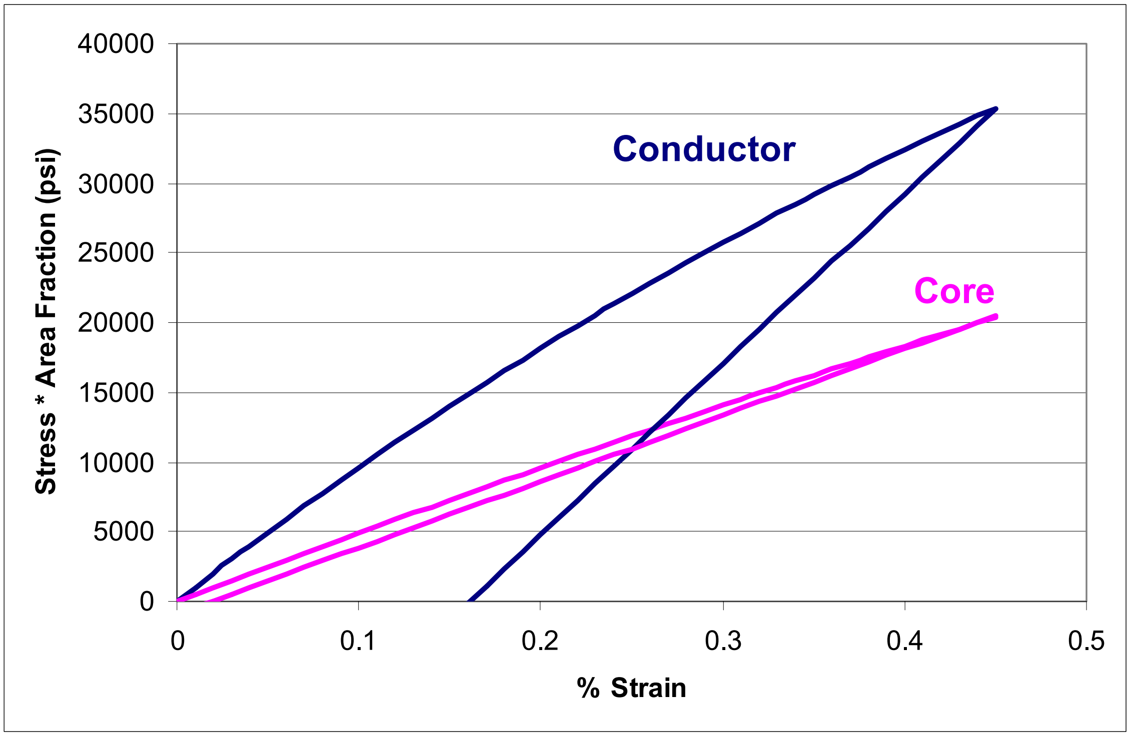

Figure 11. Initial and final curves for Conductor and core.

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 * conductor area
Core load = core stress * conductor area
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

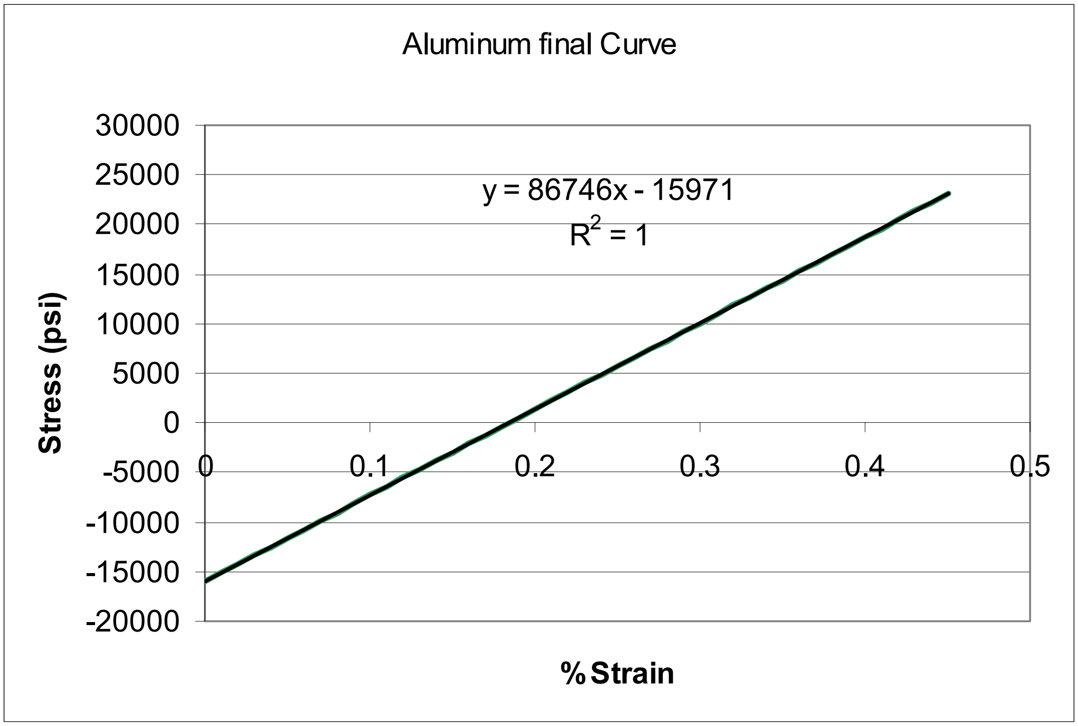

Figure 12. Aluminum "final" stress-strain curve.

Fitting the resulting aluminum curve yields the following graph in Figure 12 and equation

Aluminum:
y = 86,746x – 15,961

Thus the aluminum final modulus is = 86746

Normalizing by the area fraction (86%)

AF = 74602

Final presentation format of the curves yields a graph as shown in Figure 13 below.

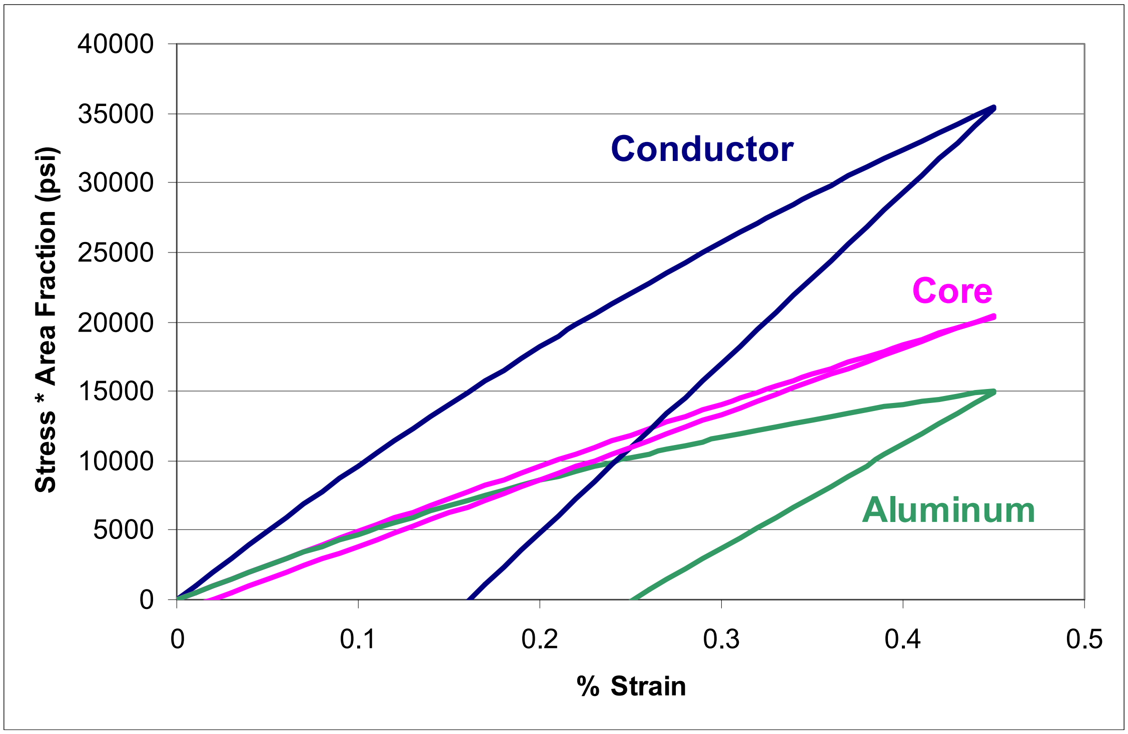

Figure 13. Initial and final curves for all constituents.

The coefficients are updated in Table 3.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	51891	-48684	19136	-5256	74602	71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
					0.00128		
C0	C1	C2	C3	C4	CF		Core
0	50132	-10898	527	-793	48119		
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	50132	-10898	527	-793	0.000353		

Table 3. Sag10 TM 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 795 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/psi
15%	0.003879	0.167249	6450
20%	0.003066	0.212206	8601
25%	0.004123	0.207521	10751
30%	0.006367	0.188254	12901

Table 4. Creep parameters for 795 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/psi	%strain 10 yr creep
15%	0.003879	0.167249	6450	0.0260
20%	0.003066	0.212206	8601	0.0343
25%	0.004123	0.207521	10751	0.0437
30%	0.006367	0.188254	12901	0.0542

Table 5. 10-year creep strain for 795 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
6450	0.06569	0.0917
8601	0.08878	0.1231
10751	0.1125	0.1562
12901	0.13693	0.1912

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 14.

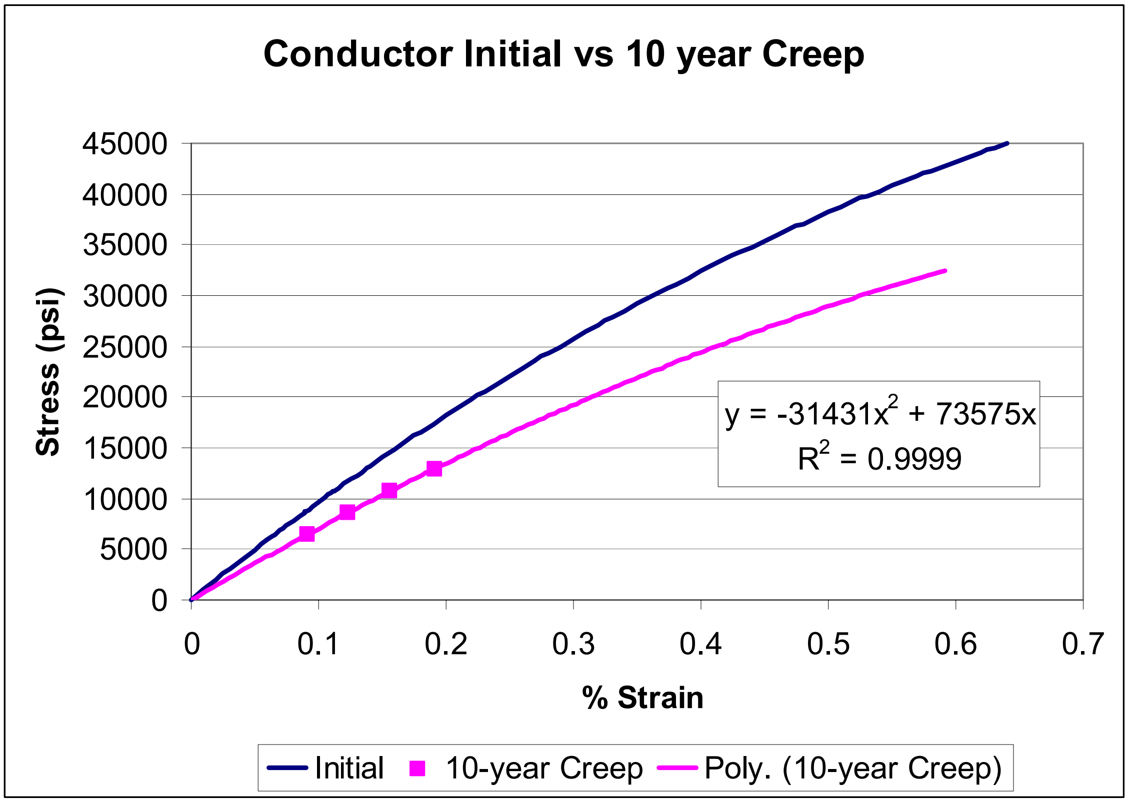

Figure 14. Conductor stress-strain plot reflecting initial and 10-year creep strains.

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 = -31431x2 + 73575x   R2 = 0.9999

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 2nd-order polynomial equation
Core stress is the "initial" 4th order polynomial equation
Conductor load = conductor stress * %strain

Core load = core stress * %strain
Aluminum load = conductor load – core 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 15:

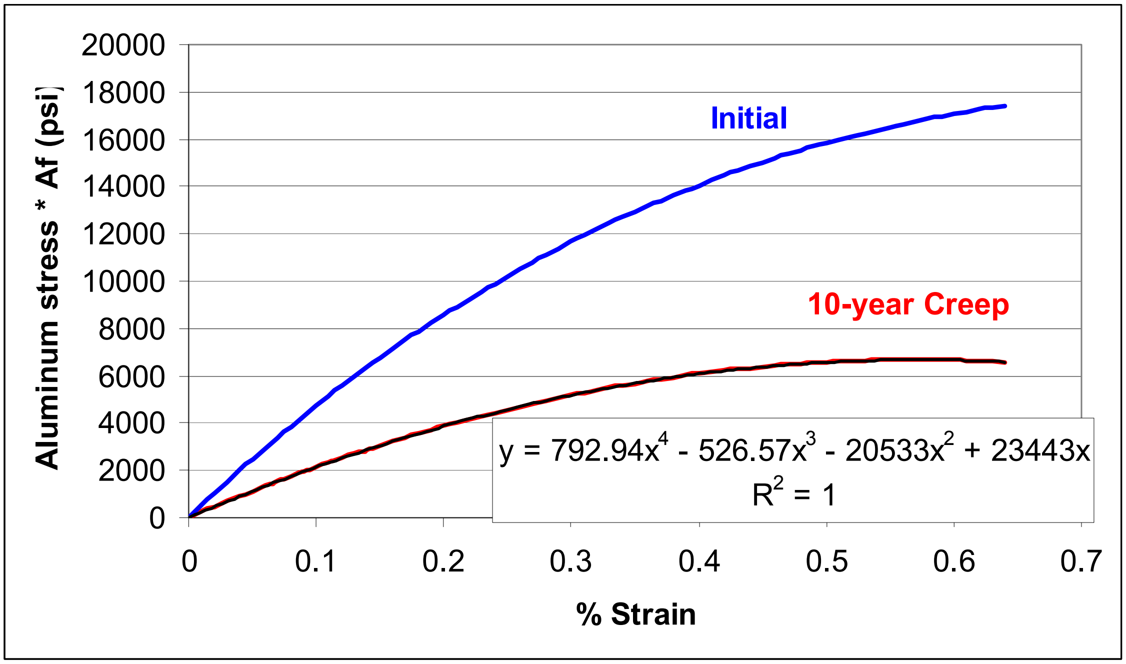

Figure 15. Aluminum initial and 10-year stress-strain curves.

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

y = 792.94x4 - 526.57x3 - 20533x2 + 23443x
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 TM table, thus completing the Table 7.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	51891	-48684	19136	-5256	74602	71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	23443	-20533	-527	793	0.00128		
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D0	D1	D2	D3	D4	α (core)		10 yr creep
0	50132	-10898	527	-793	0.000353		

Table 7. Complete coefficient Table for Sag10 TM design software

Summary

An analysis of the Stress-Strain and Creep raw data generated at Neetrac for 795 ACCR generated the coefficients for transmission design that may be incorporated into Alcoa Sag10 TM and PLS-CAD design software. The coefficients are summarized in Tables 8.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	51891	-48684	19136	-5256	74602	71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	23443	-20533	-527	793	0.00128		
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D0	D1	D2	D3	D4	α (core)		10 yr creep
0	50132	-10898	527	-793	0.000353		

Table 8. Complete Sag10 TM design coefficients for 795 ACCR.

Acknowledgement

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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: 795-kcmil, 3M™ Composite Conductor Specification

Conductor Physical Properties		
Designation		795-T16
Stranding		26/19
kcmils	kcmil	795
Diameter		
indiv Core	in	0.082
indiv Al	in	0.175
Core	in	0.41
Total Diameter	in	1.11
Area		
Al	in^2	0.624
Total Area	in^2	0.724
Weight	lbs/linear ft	0.896
Breaking Load		
Core	lbs	18,556
Aluminum	lbs	12,578
Complete Cable	lbs	31,134
Modulus		
Core	Msi	31.4
Aluminum	Msi	7.4
Complete Cable	Msi	10.7
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	22
Aluminum	W-sec/ft-C	324

Conductor Electrical Properties		
Resistance		
DC @ 20C	ohms/mile	0.1100
AC @ 25C	ohms/mile	0.1126
AC @ 50C	ohms/mile	0.1237
AC @ 75C	ohms/mile	0.1349
Geometric Mean Radius	ft	0.0375
Reactance (1 ft Spacing, 60hz)		
Inductive Xa	ohms/mile	0.3986
Capacitive X'a	ohms/mile	0.0912