3M Composite Conductor 477-kcmil

Stress-Strain Polynomial Coefficients for Design Software

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Reviewed by: Mr. Douglas Johnson

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477-kcmil 3M^{TM} Composite Conductor: Stress-Strain Polynomial Coefficients for Design Software

Summary

An analysis of the Stress-Strain and Creep raw data generated at Neetrac for 477 ACCR generated the coefficients for transmission design that may be incorporated into Alcoa Sag10^{TM} design software. The Sag10^{TM} coefficients are summarized in Table 1.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	58960	-70248	50188	-26201	75865	71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	30028	-23104	-14150	7376	0.00128		
C0	C1	C2	C3	C4	CF		Core
0	47546	-11777	14150	-7376	46093		
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	47546	-11777	14150	-7376	0.000353		

Table 1. Complete Sag10^{TM} design coefficients for 477 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 four references:
"477 kcmil, 3M Brand Composite Conductor, Mechanical Properties, Volume 1 Tensile and Stress-Strain Tests", NEETRAC Project Number: 01-121, March 2002.
"477 kcmil, 3M Brand Composite Conductor, Stress-Strain Tests on Oak Ridge Test Line Sample", NEETRAC Project Number: 02-097, December 2003.
"477 kcmil, 3M Brand Composite Conductor, Mechanical Properties, Volume 2, Room-temperature Creep", NEETRAC Project Number: 01-121, March 2002.
"477-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 477-kcmil ACCR Conductor (both core and aluminum layers). There are two sets of data and each are treated independently at first. 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 477-kcmil ACCR Conductor is provided in Appendix A.

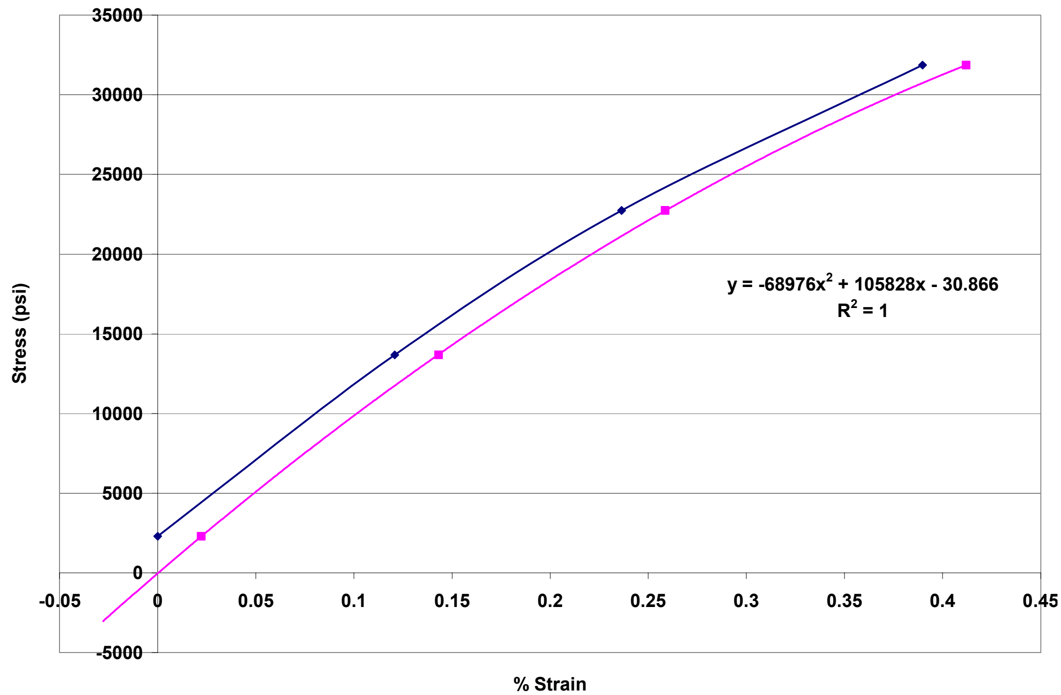
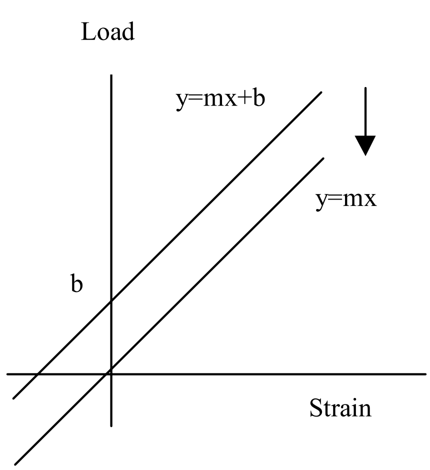


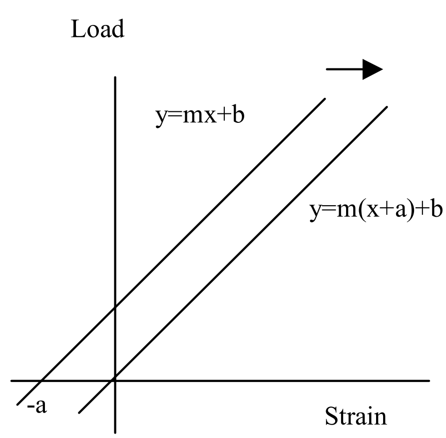
Figure 1. As measured data (blue), and translated data (red) for 477 ACCR Conductor.

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 in Figure 1 above shows the correct translation, with the experimental data points moved horizontally. The 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.

The 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.



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.

If there are more than one set of data, then the experimental points are combined as shown below. The experimental points are at 4 stress levels – 2000lbs, 30%, 50%, 70% RBS.

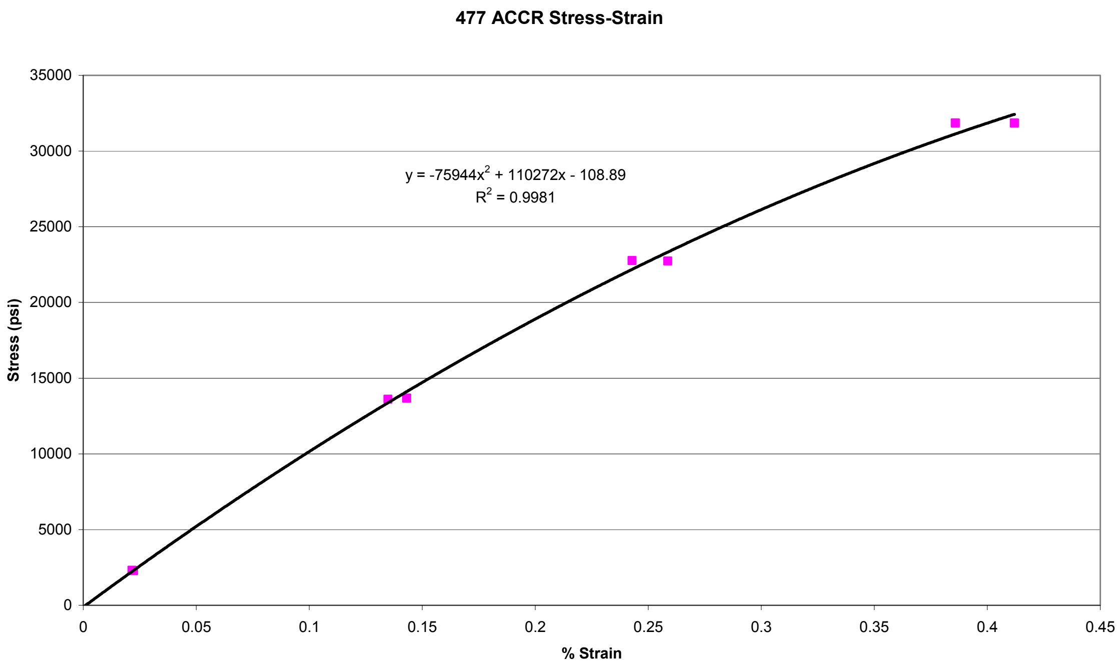


Figure 2. Second order polynomial curve fit through data sets.

The curve fit through the data is a nice second order fit (Figure 2). The curve is extrapolated to reach the approximate failure strain of the conductor at 100% RBS which is ~0.6% (Figure 3).

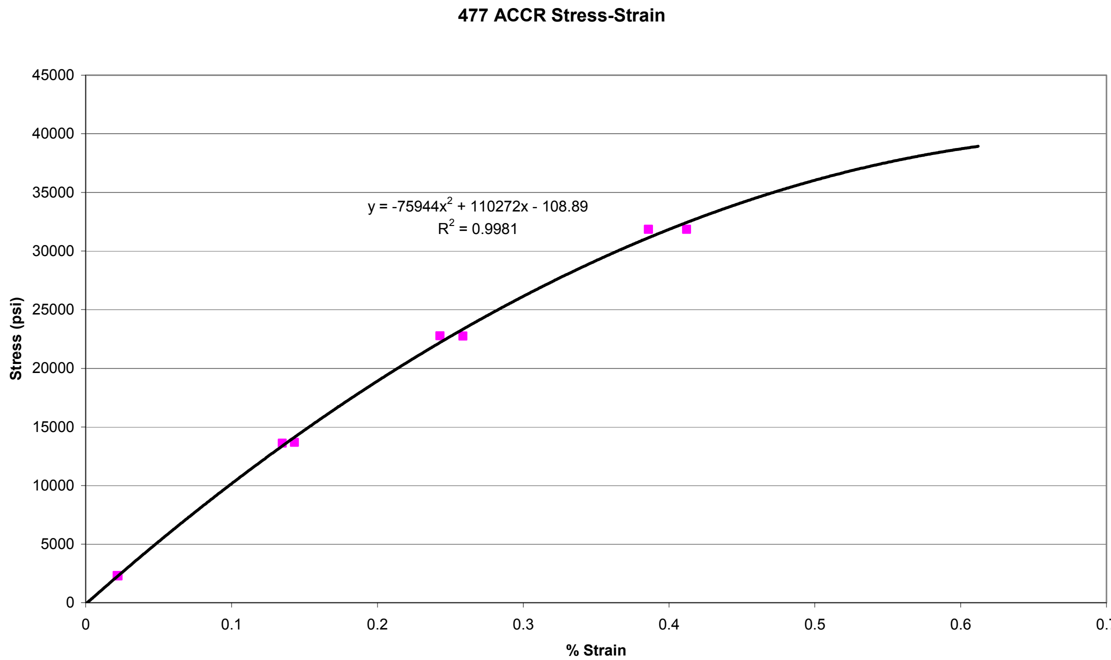


Figure 3. Second-order polynomial extrapolated to failure strain

At ~0.6%, the stress is ~39,000 psi, whereas the 100% RBS value is 44,700 psi. Thus the extrapolation is poor at higher strains. The 100% RBS value is inserted as a data point (0.6, 44700) and the curve fit shifts. The fit still is within the range of the experimental data (Figure 4).

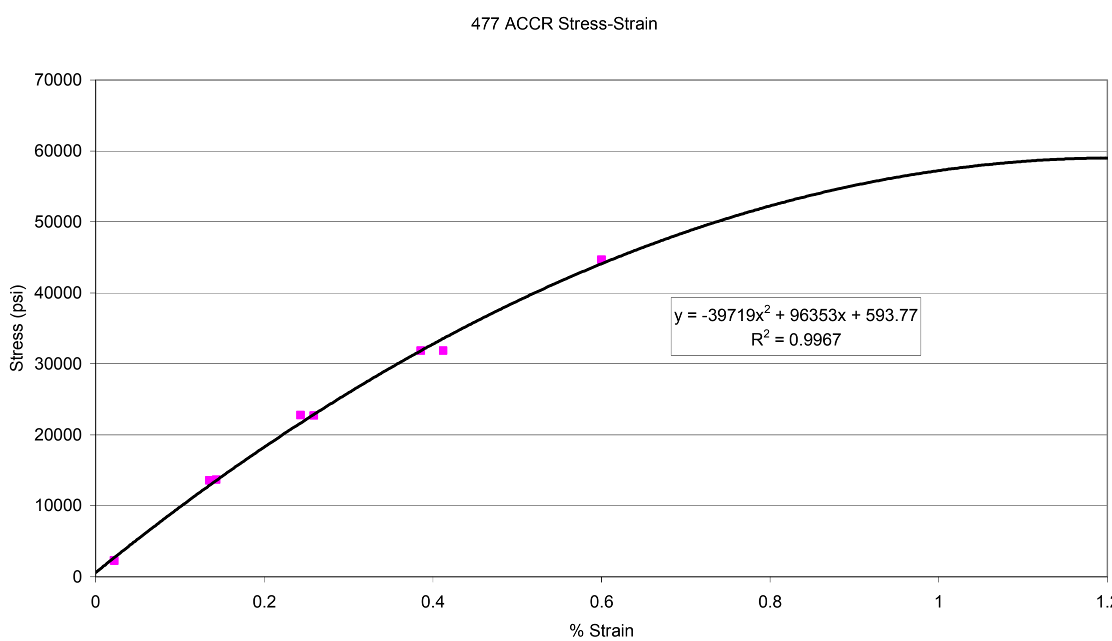


Figure 4. Conductor curve corrected for breaking stress and strain

Additionally, the curve is extrapolated beyond the breaking strain to check for a good extrapolation behavior. In Figure 4 the polynomial is reaching an inflection point at approximately 1.2% 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 ™) or to the breaking strain (PLS-CAD).

Next the intercept is forced to go through zero, as shown below, in Figure 5.

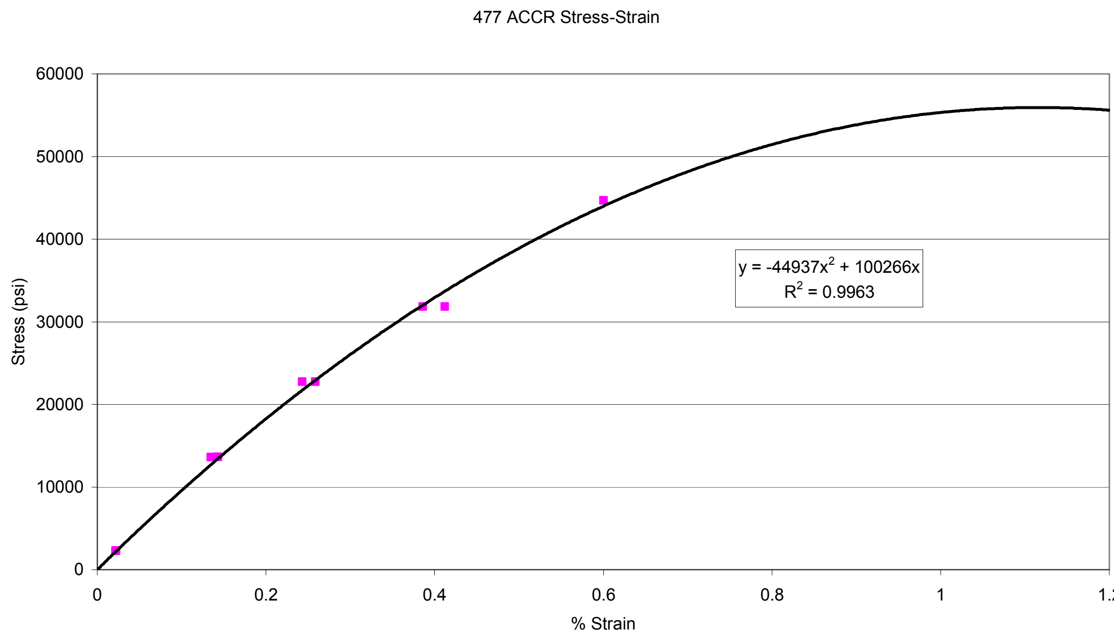


Figure 5. Second-order fit with forced zero intercept.

Now to fit a fourth order polynomial to this data, the fit is poor due to inflection points which are a poor representation of the true behavior. Thus the second order fit and the equation thereby generated is used to calculate extra points to smooth the curve. In this case an ten points were generated at strains of 0.05, 0.1, 0.2, 0.3, 0.35, 0.45, 0.5, 0.55, 0.8, 1.0% using the second order polynomial. This creates a smoother curve for a reasonable 4th order curve fit, as shown below in Figure 6, and maintains a high degree of fit to the real data points within the critical design strain range.

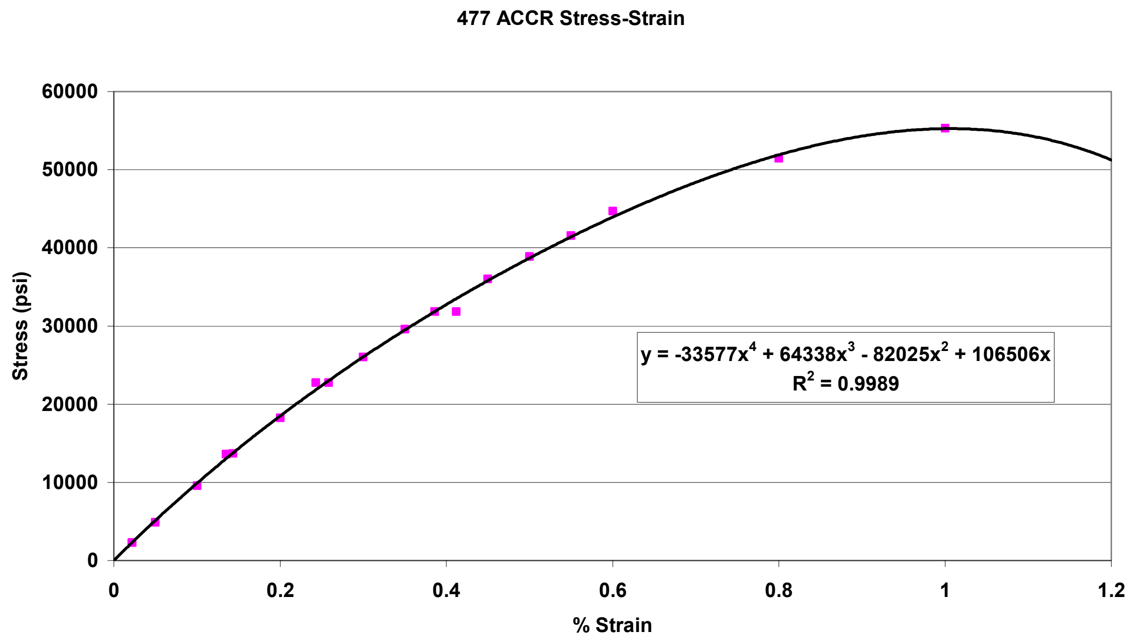


Figure 6. Fourth order polynomial fit to Conductor Stress-strain behavior

From this the 4th order polynomial relating stress (psi) to % strain is
y = -33577x4 + 64338x3 - 82025x2 + 106506x
R2 = 0.9989

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 7. Additional data sets for core are treated independently and in the same way, before combining.

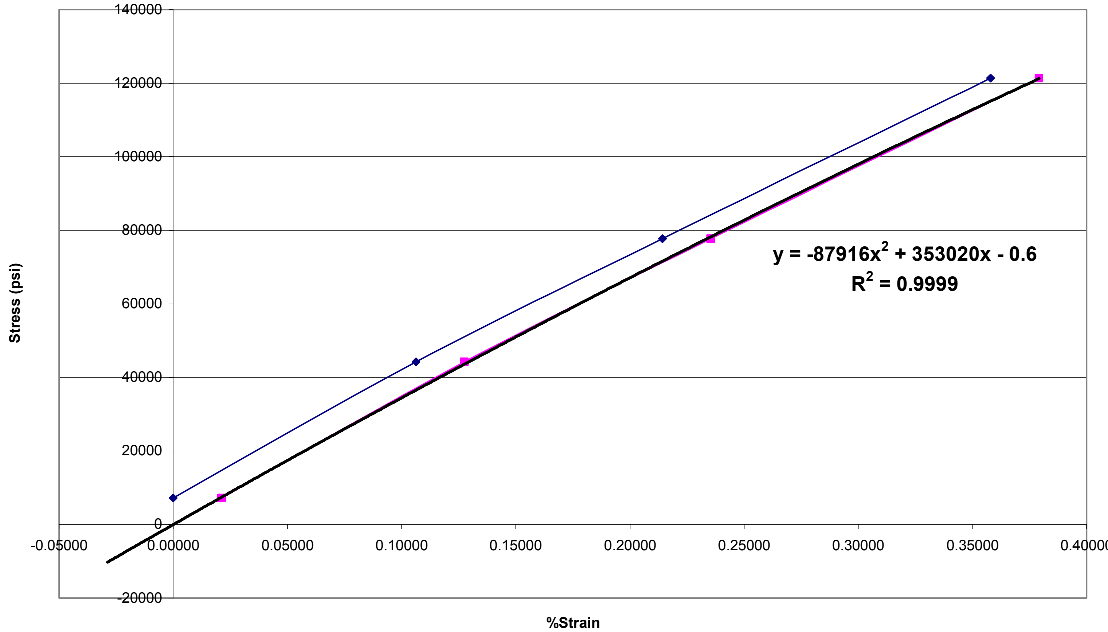


Figure 7. Raw Data and translated curves for 477ACCR core.

Combined data sets have one additional point 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 8, which is extrapolated to 1% strain.

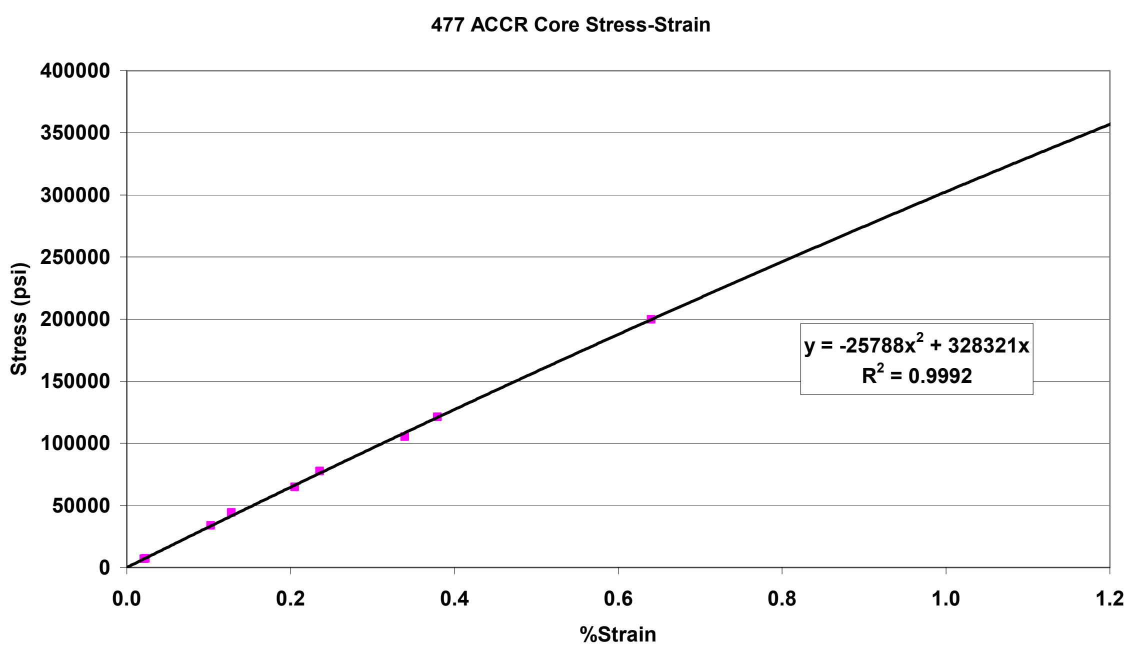


Figure 8. Core Stress-strain behavior corrected for breaking stress

The extrapolation in Figure 8 looks very reasonable, and so this equation is used to create extra data points up to 0.64% strain in order to fit a 4^{th} order polynomial. This is shown in Figure 9.

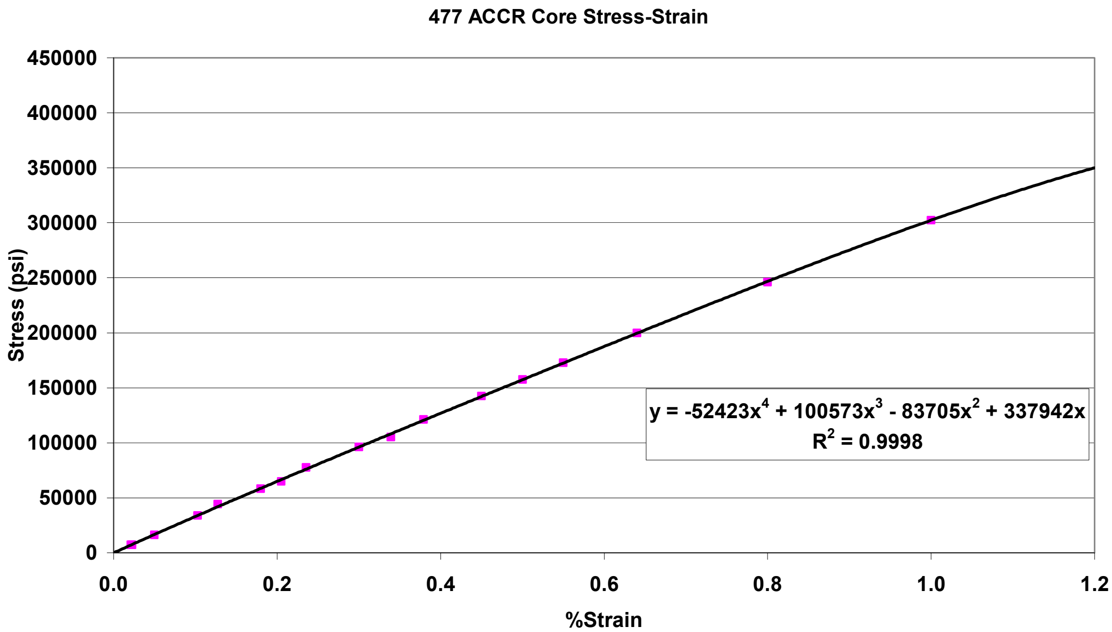


Figure 9. Fourth-order polynomial fit for 477 ACCR core.

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

y = -52423x4 + 100573x3 - 83705x2 + 337942x
R2 = 0.9998

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 10). The fit is good but the slope of the extrapolation becomes negative at ~0.7% strain. However, this is sufficient for the design software.

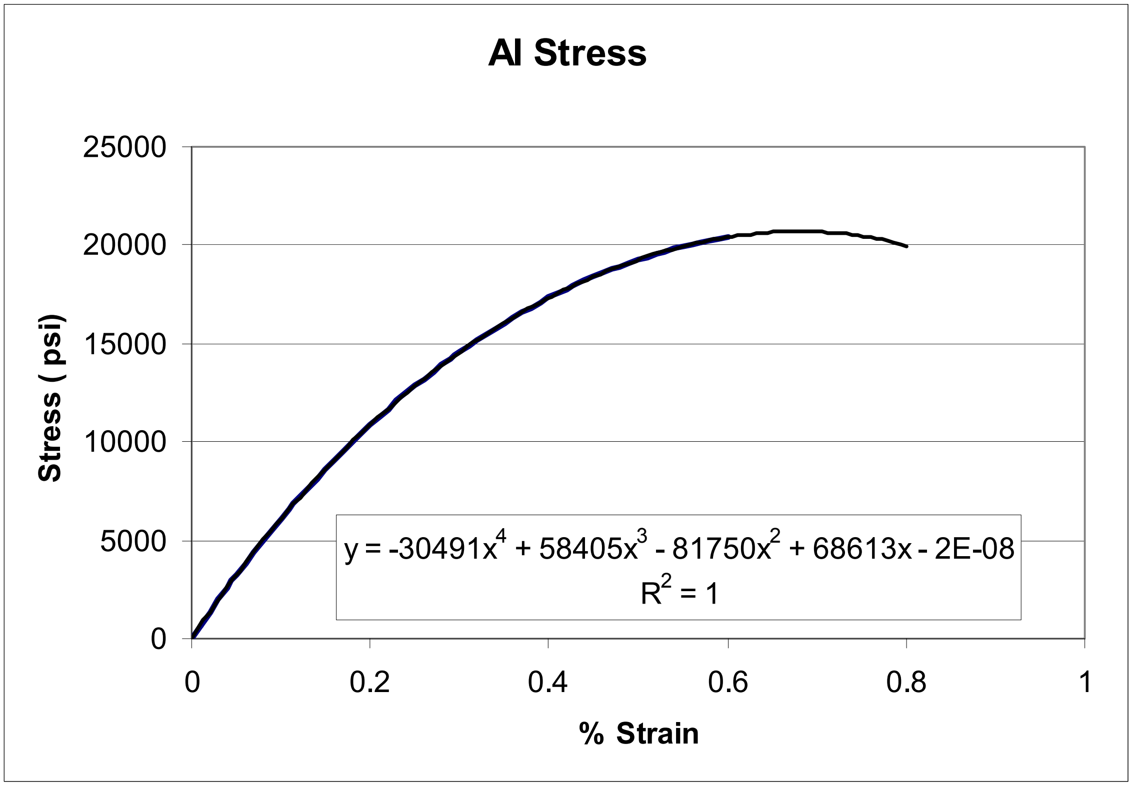


Figure 10. Stress-strain curve for the aluminum layers of 477 ACCR

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

y = -30491x4 + 58405x3 - 81750x2 + 68613x - 2E-08
R2 = 1

To generate the "Initial" stress-strain curves, the data sets are plotted together on 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 477 ACCR)
aluminum stress * Af = aluminum stress * Al area fraction (is 86% for 477 ACCR)

The graph is shown below in Figure 11.

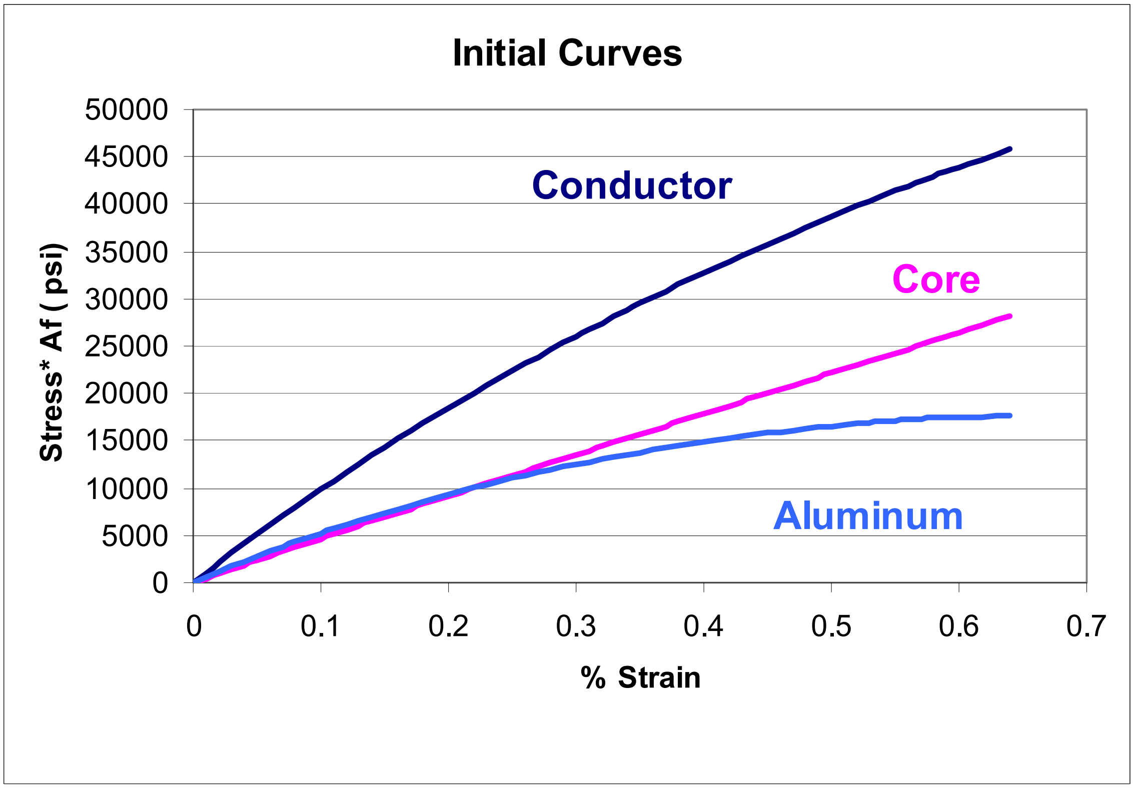


Figure 11. Stress*area fraction vs strain curves for 795 ACCR.

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

The 4th order polynomials are:

Core: y = -7375.6x4 + 14150x3 - 11777x2 + 47546x + 9E-09
R2 = 1

Aluminum: y = -26201x4 + 50188x3 - 70248x2 + 58960x + 7E-09
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	58960	-70248	50188	-26201		71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
					0.00128		
C0	C1	C2	C3	C4	CF		Core
0	47546	-11777	14150	-7376			
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	47546	-11777	14150	-7376	0.000353		

Table 2. Sag10 TM coefficients for "initial" curves of 477 ACCR

The core creep is approximated 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 in Figure 12.

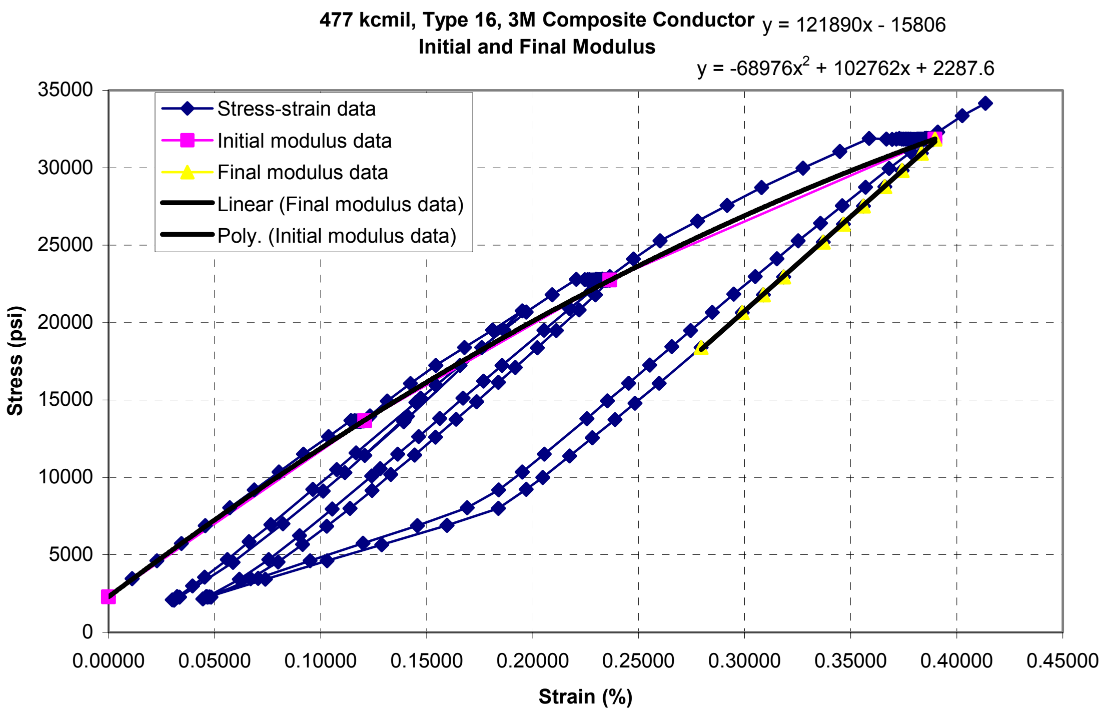


Figure 12. Experimental Stress-strain curves, showing the load-unload sequence for the conductor

The final modulus is derived from the unload curve on 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. Since two sets of conductors were measured, there are two equations derived which relate stress (psi) to % Strain. These are:

Conductor:
y = 121890x – 15806
y = 122361.49x - 12902.15

Core:
y = 326311x + 2020

y = 332160x - 1623.4

Thus for the core, the average final modulus coefficient is (326311+332160)/2 = 329235
CF is normalized by the area fraction
Thus CF = 329235*0.14 = 46093

For each 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 in Figure 13.

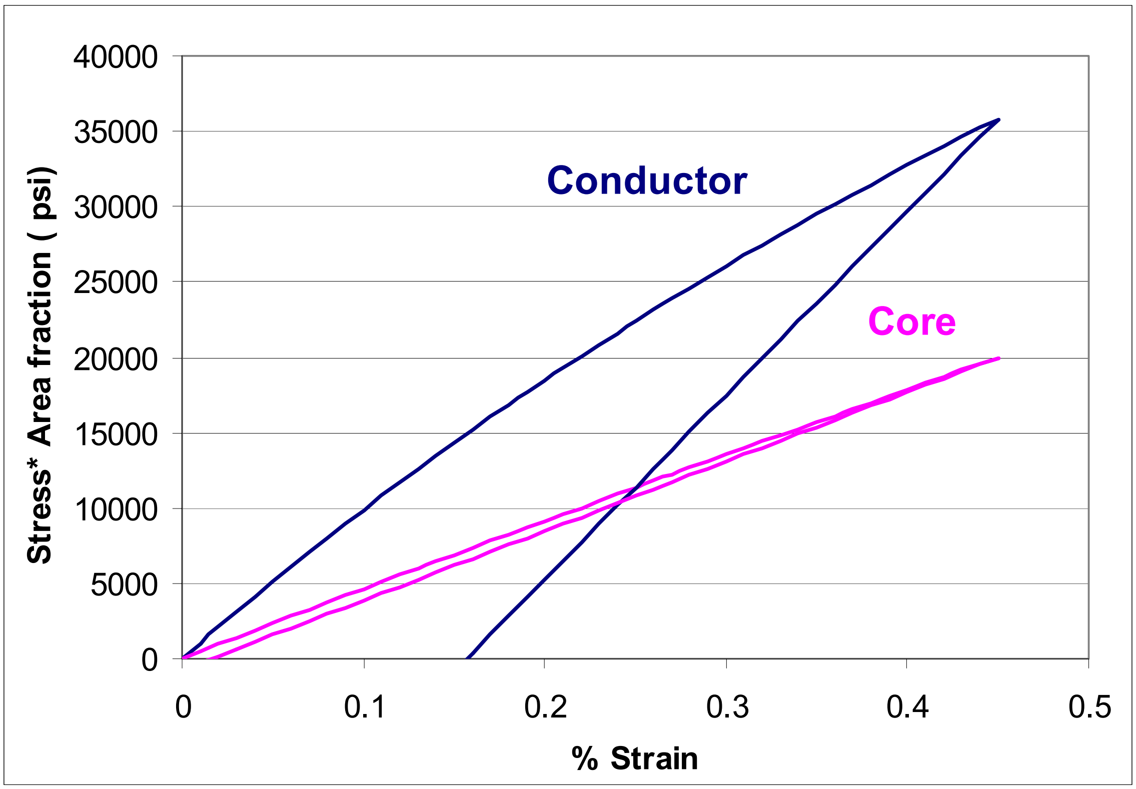


Figure 13. Initial and final curves for Conductor and core

These 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

Fitting the resulting aluminum curve yields the following graph in Figure 14 for one of the conductor-core pairs and the subsequent equation.

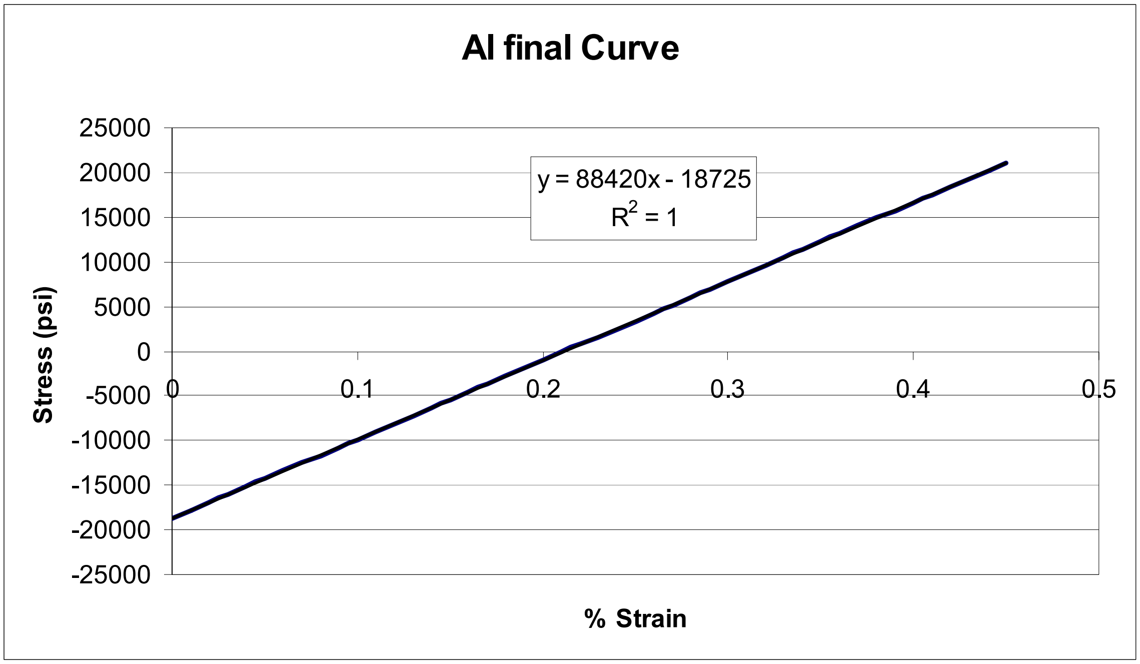


Figure 14. Aluminum “final” stress-strain curve

Aluminum:
y = 88420x – 18725

Likewise for the second conductor-core pairing:
y = 88011x – 21223

Thus the average final modulus is (88011+88420)/2 = 88215

Normalizing by the area fraction (86%)

AF = 75865

Final presentation format of the curves yields a graph as shown in Figure 15 below.

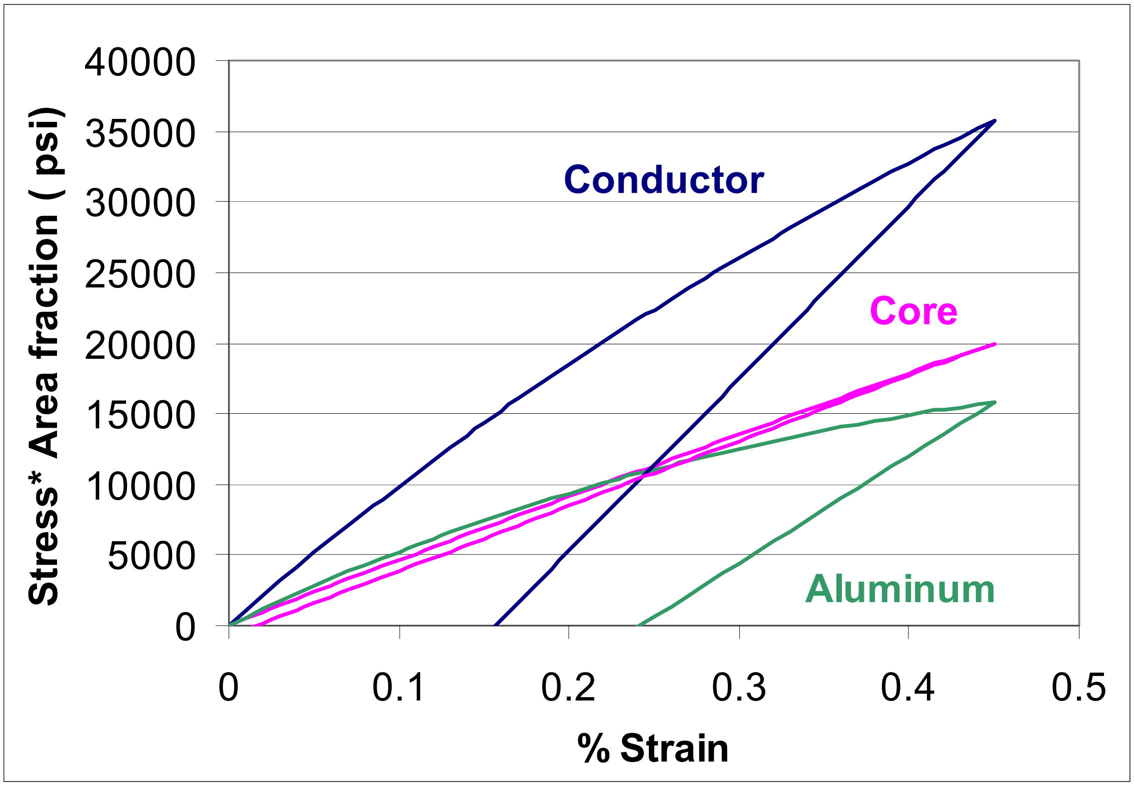


Figure 15. Initial and final curves for all constituents

The coefficients are updated in Table 3.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	58960	-70248	50188	-26201	75865	71	
B0	B1	B2	B3	B4	α (Al)		10 yr creep
					0.00128		
C0	C1	C2	C3	C4	CF		Core
0	47546	-11777	14150	-7376	46093		
D0	D1	D2	D3	D4	α (core)		10 yr creep
0	47546	-11777	14150	-7376	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 477 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%	0.0012	0.242343	6705
20%	0.003328	0.197528	8940
25%	0.003748	0.212924	11175
30%	0.004006	0.224918	13410

Table 4. Creep parameters for 477 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%	0.0012	0.242343	6705	0.0189
20%	0.003328	0.197528	8940	0.0315
25%	0.003748	0.212924	11175	0.0423
30%	0.004006	0.224918	13410	0.0518

Table 5. 10-year creep strain for 477 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
6705	0.066152	0.085074
8940	0.08972	0.121231
11175	0.11411	0.156394
13410	0.13935	0.191155

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

The initial + creep strain data points are plotted compared to the initial curve in Figure 16.

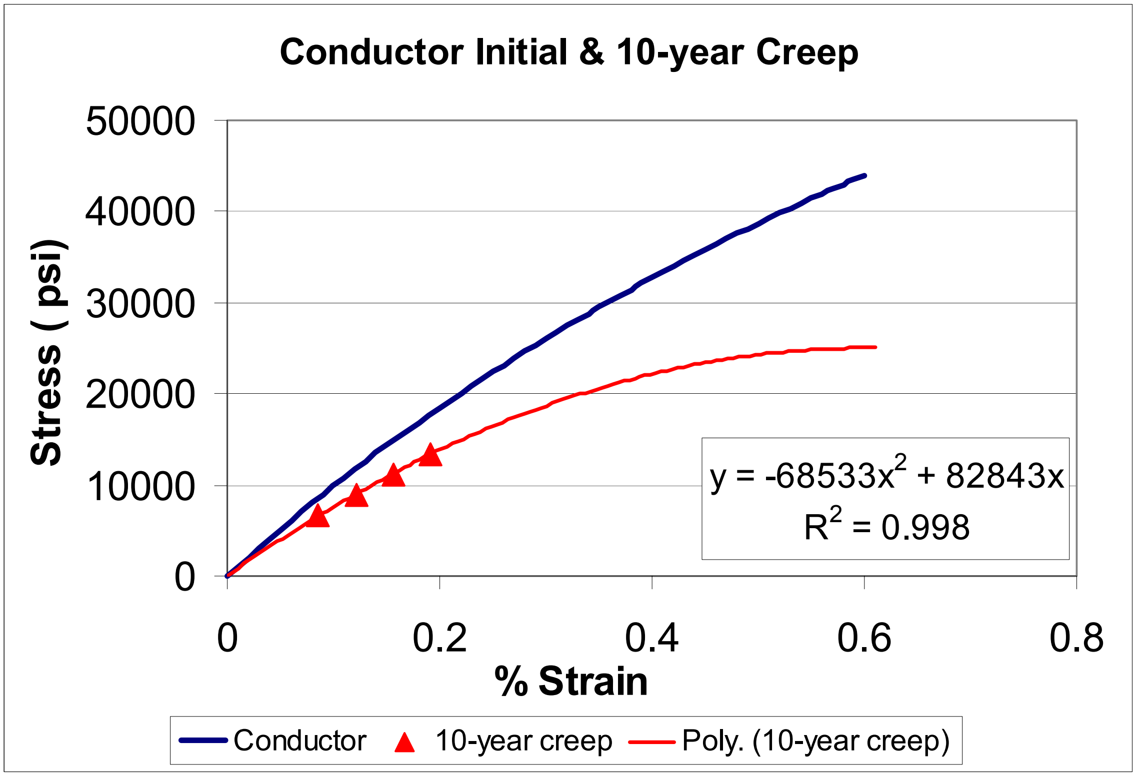


Figure 16. Conductor stress-strain plot reflecting initial and 10-year creep strains

A 2^{nd}-order fit is made through the 10-year creep data points and through the zero point. However the extrapolation at higher strains is poor, and when this is used to derive the aluminum creep, it gives negative aluminum stresses at higher strains. Thus a single artificial point is introduced to pin the 10-year creep curve to higher strains, to make the extrapolated derivations below more self-consistent. This new "pinned" curve is shown in Figure 17.

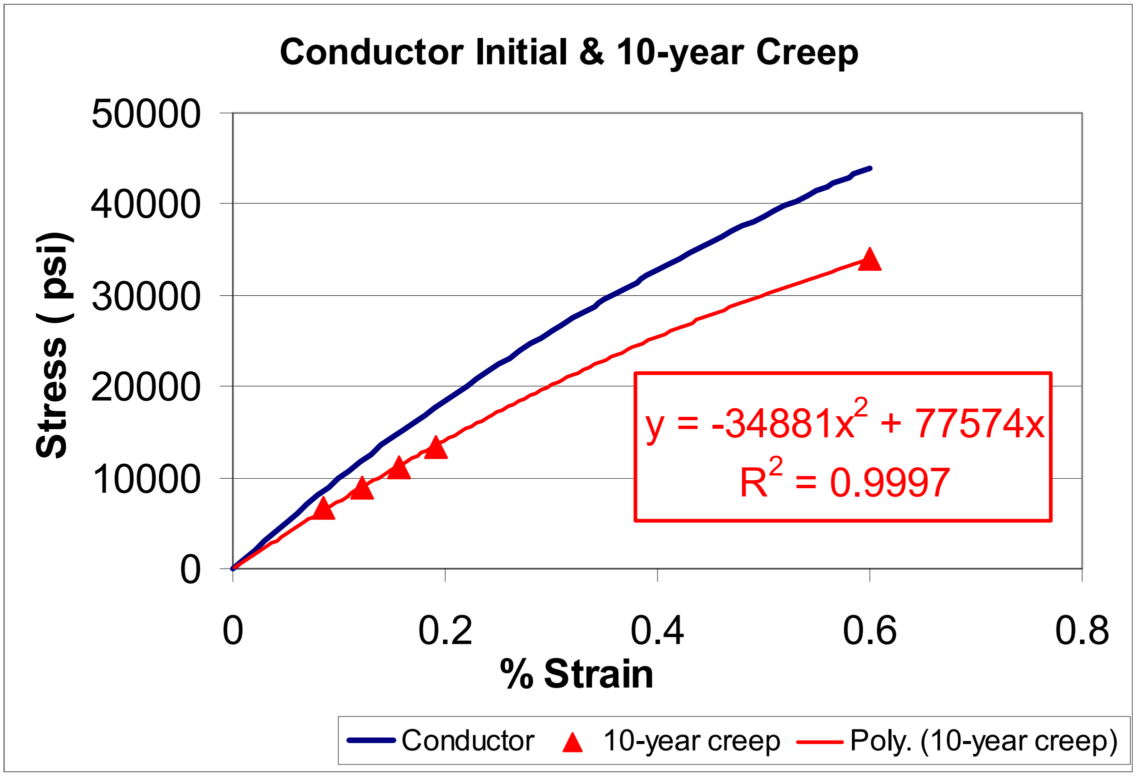


Figure 17. Conductor stress-strain plot reflecting initial and 10-year creep strains with an artificial point at (0.6, 34,000) to assist the self-consistency of the extrapolation

The 10 year conductor creep curve is thus y = -34881x2 + 77574x   R2 = 0.9997

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 – 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 18.

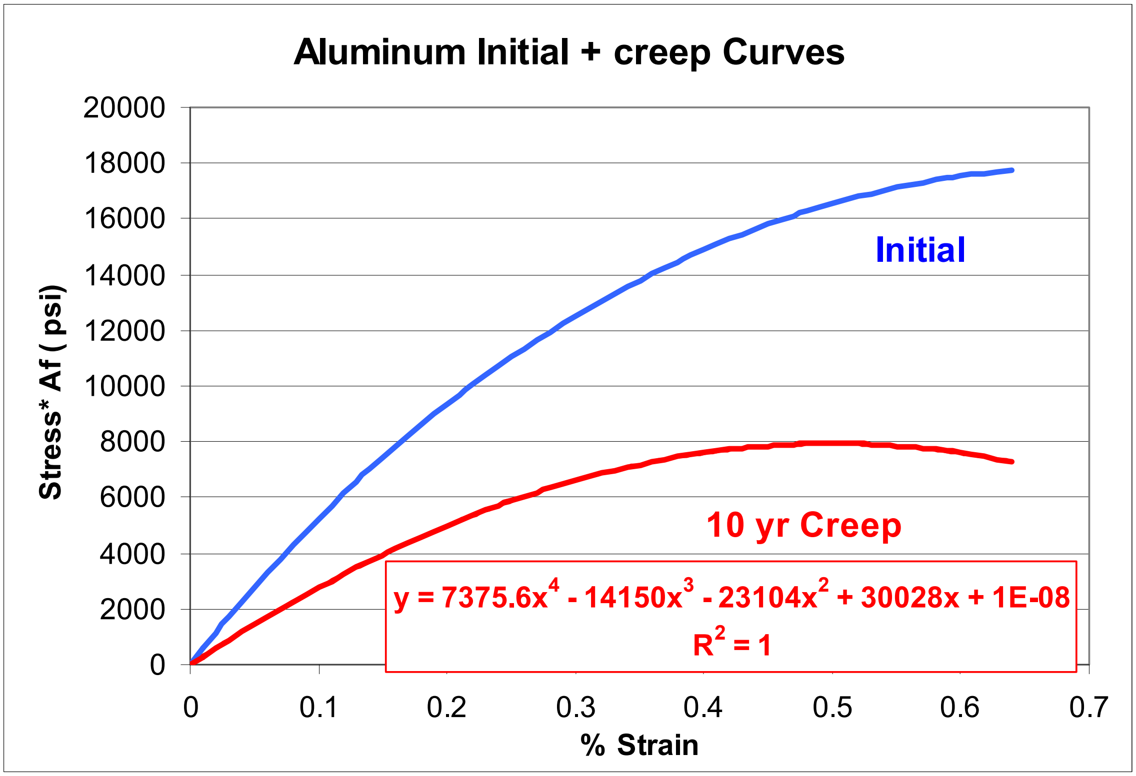


Figure 18. Aluminum initial and 10-year stress-strain curves

The 4th order polynomial fit is:

y = 7375.6x4 - 14150x3 - 23104x2 + 30028x + 1E-08
R2 = 1

The slope begins to turn negative at about of 0.50% reflecting the difficulties in trying to extrapolate accurately outside of the measured data range. However, for reasonable tension ranges, the extrapolations appear to be good.
These coefficients fit the "B" row in the Sag10 TM table, thus completing the Table 7.

A0	A1	A2	A3	A4	AF	TREF	Aluminum
0	58960	-70248	50188	-26201	75865	71	
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D0	D1	D2	D3	D4	α (core)		10 yr creep
0	47546	-11777	14150	-7376	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 477 ACCR generated the coefficients for transmission design that may be incorporated into Alcoa Sag10 TM design software. The coefficients are summarized in Tables 8.

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B0	B1	B2	B3	B4	α (Al)		10 yr creep
0	30028	-23104	-14150	7376	0.00128		
C0	C1	C2	C3	C4	CF		Core
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D0	D1	D2	D3	D4	α (core)		10 yr creep
0	47546	-11777	14150	-7376	0.000353		

Table 8. Complete Sag10 TM design coefficients for 477 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: 477-kcmil, 3M™ Composite Conductor Specification

Conductor Physical Properties		
Designation		477-T16
Stranding		26/7
kcmils	kcmil	477
Diameter		
indiv Core	in	0.105
indiv Al	in	0.135
Core	in	0.32
Total Diameter	in	0.86
Area		
Al	in^2	0.374
Total Area	in^2	0.435
Weight	lbs/linear ft	0.539
Breaking Load		
Core	lbs	11,632
Aluminum	lbs	7,844
Complete Cable	lbs	19,476
Modulus		
Core	Msi	31.4
Aluminum	Msi	8.0
Complete Cable	Msi	11.2
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	13
Aluminum	W-sec/ft-C	194

Conductor Electrical Properties		
Resistance		
DC @ 20C	ohms/mile	0.1832
AC @ 25C	ohms/mile	0.1875
AC @ 50C	ohms/mile	0.2061
AC @ 75C	ohms/mile	0.2247
Geometric Mean Radius	ft	0.0290
Reactance (1 ft Spacing, 60hz)		
Inductive Xa	ohms/mile	0.4296
Capacitive X'a	ohms/mile	0.0988