3M Composite Conductor
477-kcmil

Derivation of Power-Law Creep Parameters

Principal Investigator: Dr. Colin McCullough

Reviewed by: Mr. Douglas Johnson

Date of Report: June 1, 2005

<u>477-kcmil, 3M^{TM} Composite Conductor: Derivation of Power-Law Creep Parameters</u>

Summary
Creep Testing was performed at room temperature on 477-kcmil, 3M^{TM} Composite Conductor (also known as ACCR – Aluminum Conductor Composite Reinforced). The work was carried out by NEETRAC and is summarized in a report entitled, "477-kcmil, 3M Brand Composite Conductor, Mechanical Properties, Volume 2, Room-temperature Creep", NEETRAC Project Number: 01-121, March 2002. The data from that study is used here to generate the creep equations governing the creep behavior of the conductor.

Creep Data:
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, 3M^{TM} Composite Conductor is provided in Appendix A. Data from each testing load was plotted in a graph of Creep Strain vs. Time (Figure 1-4), using creep strains that have been corrected for load and temperature drift (see orginal test report noted above). This data was selected from one hour onwards since the first hour of creep can often be influenced by a variety of effects (time to load, conductor sample preparation, etc.). The target time for the creep test was 1000 hours, although often this time was exceeded depending on the availability of the test equipment. Power-law curve fits are made to the data and the resulting equations are compiled in Table 1, which relate creep strain (y) to time (x) for each loading (%RBS) condition.

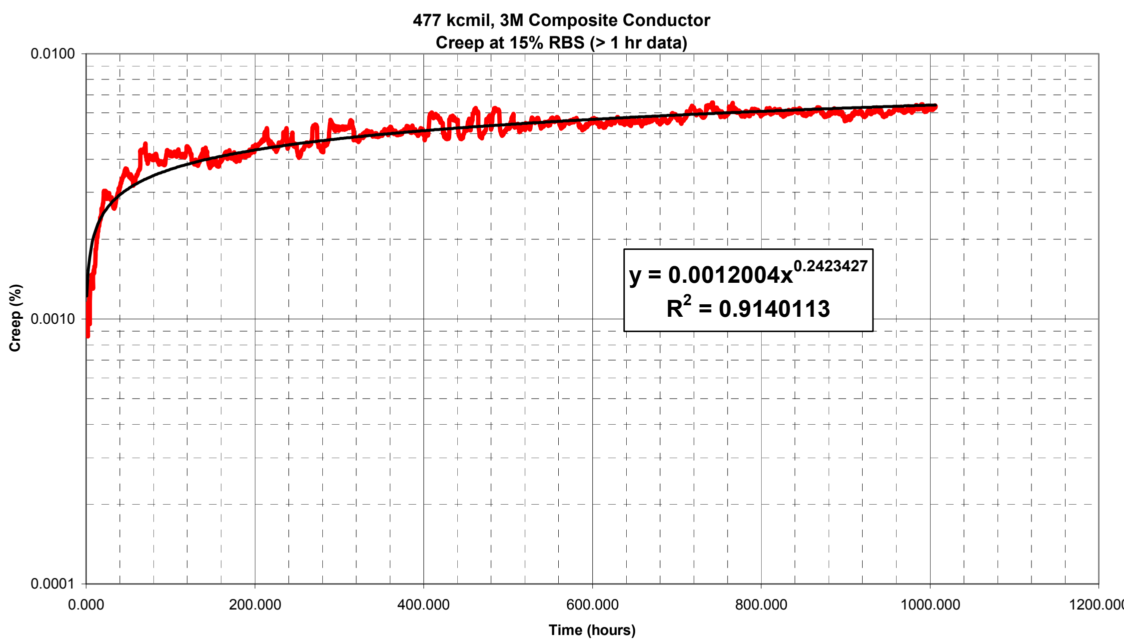

Figure 1. Creep strain vs. time for 477-kcmil conductor at 15% RBS load.

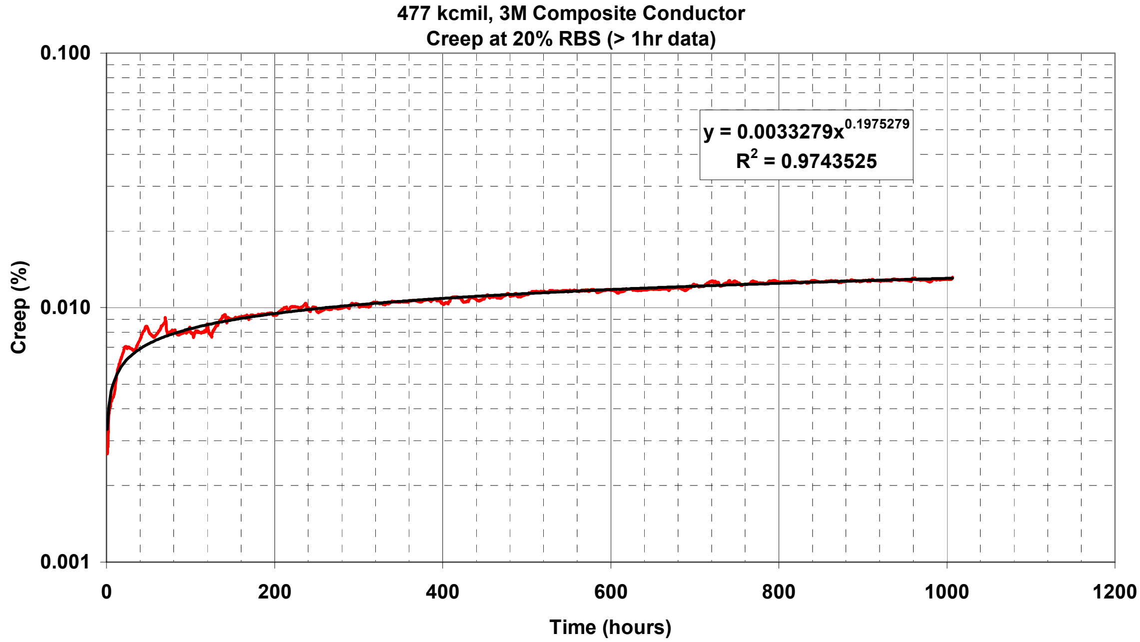

Figure 2. Creep strain vs. time for 477-kcmil conductor at 20% RBS load.

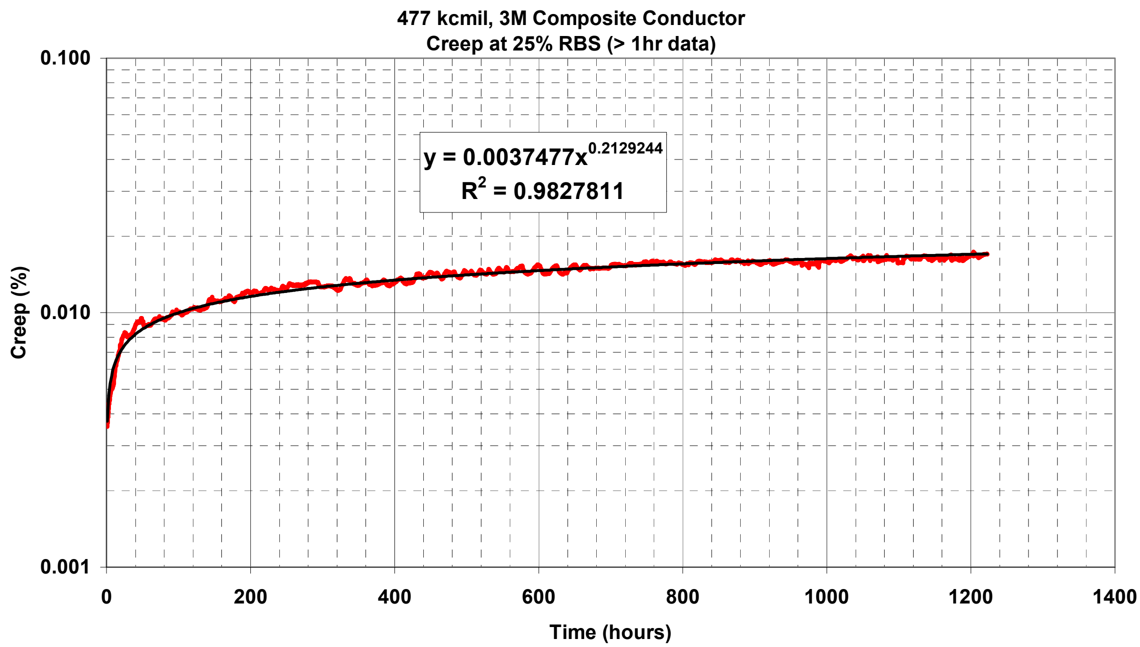

Figure 3. Creep strain vs. time for 477-kcmil conductor at 25% RBS load.

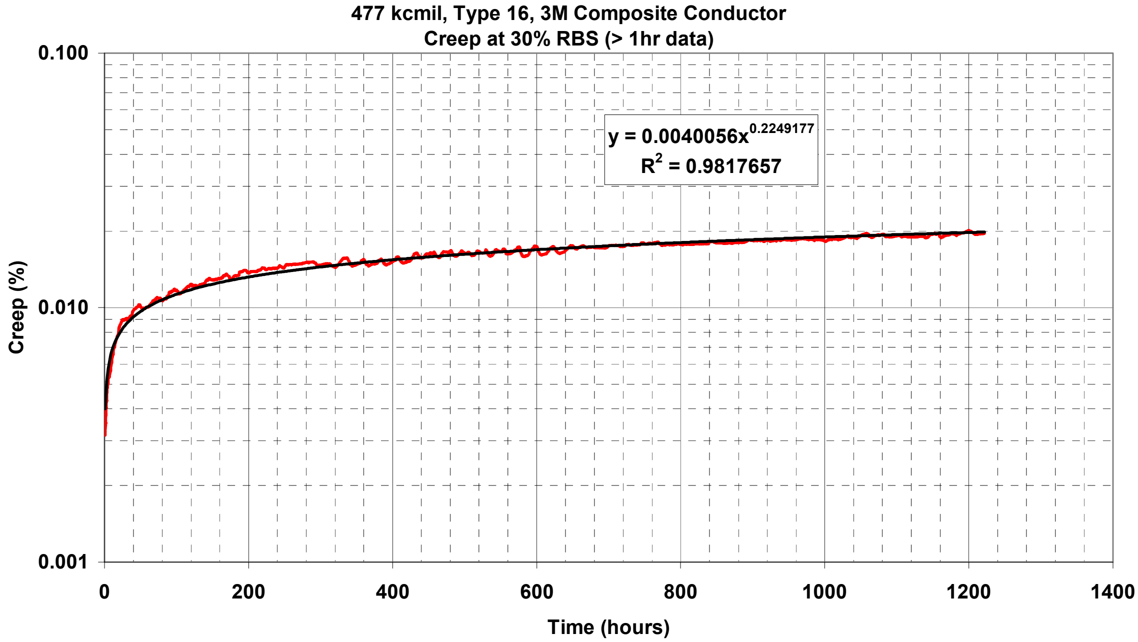

Figure 4. Creep strain vs. time for 477-kcmil conductor at 30% RBS load.

Load (%RBS)	Fitting Equation	Correlation Coefficient
15%	$y = 0.0012004\ x^{0.2423427}$	$R^2 = 0.9140113$
20%	$y = 0.0033279\ x^{0.1975279}$	$R^2 = 0.9743525$
25%	$y = 0.0037477\ x^{0.2129244}$	$R^2 = 0.9827811$
30%	$y = 0.0040056\ x^{0.2249177}$	$R^2 = 0.9817657$

Table 1. Summary of Fitting Equations (in the form y (%) = b*[(x in hrs)^c])

Examining the data in Table 1, the coefficients of the fitting equations seem reasonably well behaved. The power term varies from 0.197-0.242 with the term at 20% RBS perhaps lower than the others, since this term does not usually vary with stress. The first term before the abscissa increases with stress, and this seems normal, as this term should increase with stress.

Self-Consistency of Creep Data:

Creep data is notoriously difficult to generate experimentally due to small variations in both samples and test procedure. Plotting the fitting equations on a single graph, yields Figures 5 and 6, which are extrapolated out to 100,000 hours to check for sensible behavior in the extrapolation. This data is used to predict the 10-year (87,600 hours) creep behavior of the conductor. In Figure 5, the curves are uniformly spaced suggesting the relative long-term creep behavior is well captured. However, in Figure 6 the short-term behavior is not as consist. Although the lines do not cross, the bottom line (15% RBS) seems to be relatively low, suggesting an under estimation of creep at this load for short times. At longer times (the more critical region), this discrepancy appears to reduce. Overall, this data seems to be suitable for predicting long-term creep.

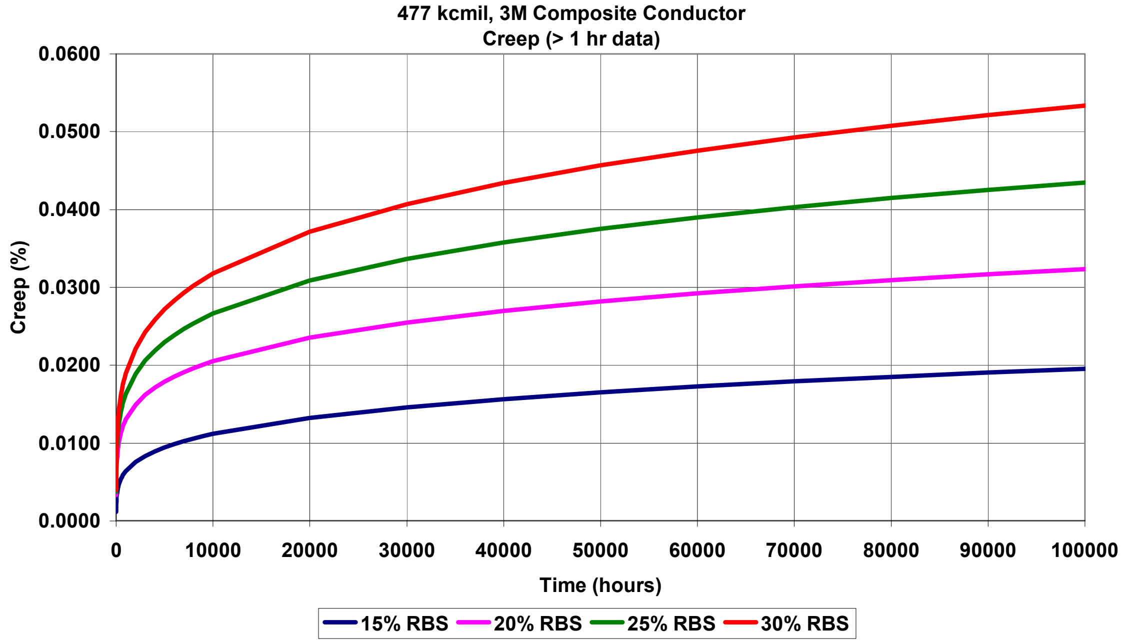

Figure 5. Creep strain vs. time for 477-kcmil conductor at all test loads.

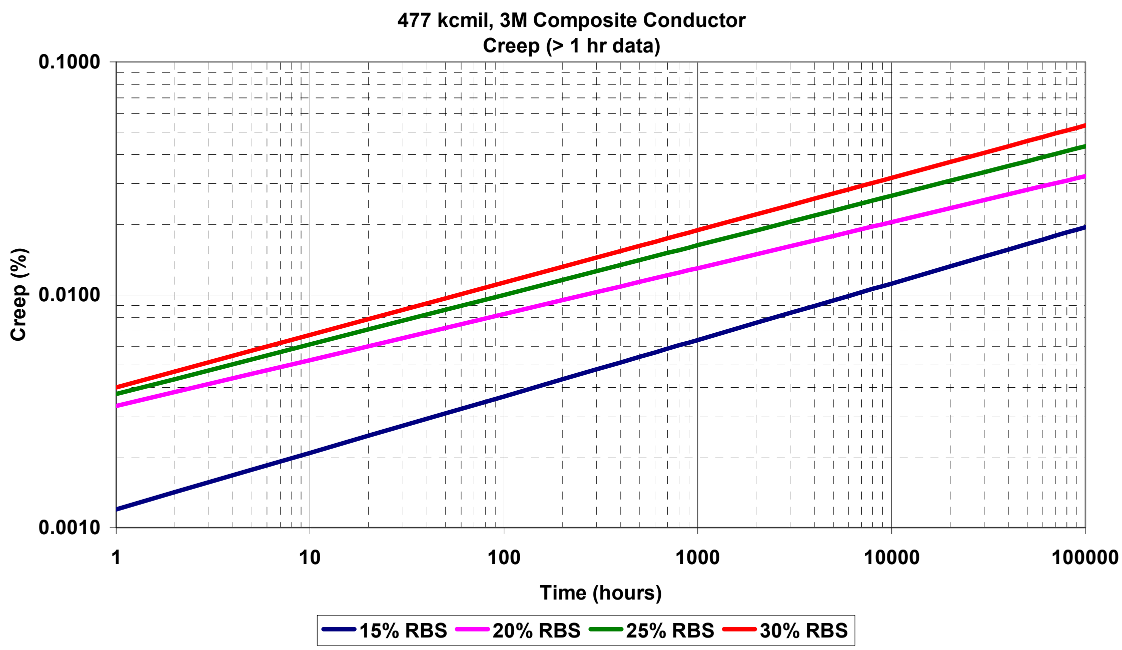

Figure 6. Log. Creep strain vs. Log. time for 477-kcmil conductor at all test loads.

Initial Loading Condition:

One cause for discrepancies in creep data can be during the initial loading phase. Data from this phase is presented for each loading condition in Figures 7-10 for comparison.

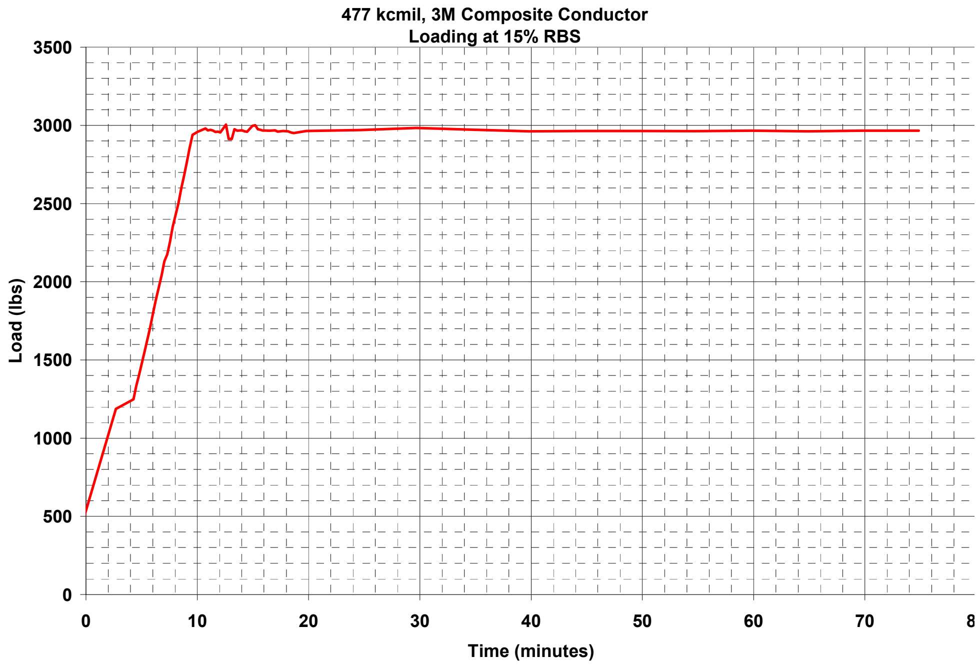

Figure 7. 15% RBS initial loading. Load was held at approx. 500 lbs for 12 hours and then increased to target load in 10 minutes.

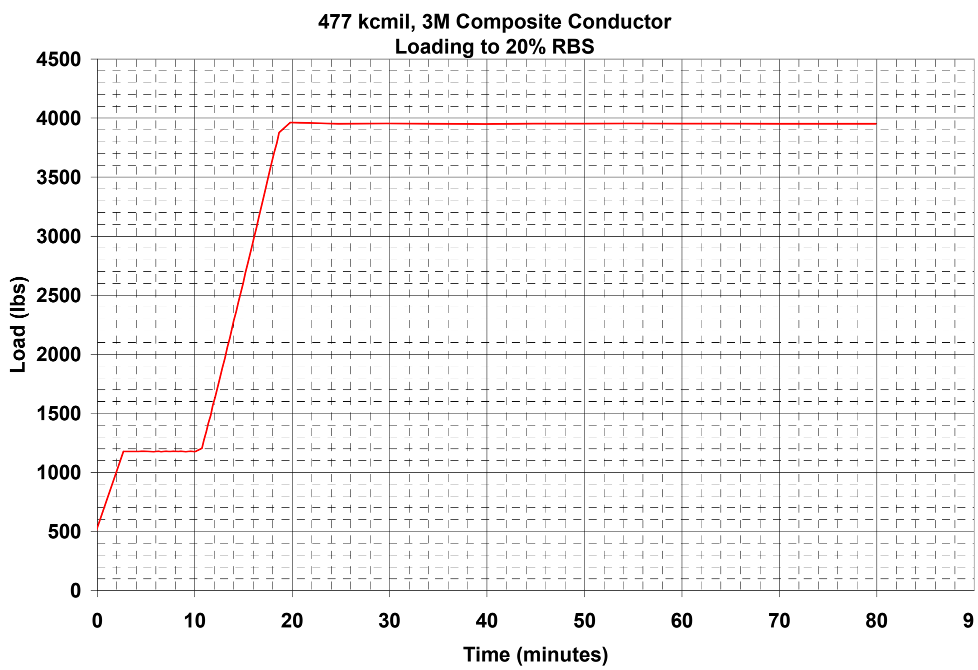

Figure 8. 20% RBS initial loading. Load was held at approx. 500 lbs for 12 hours and then increased to target load in 20 minutes, with a rest at 1200 lbs.

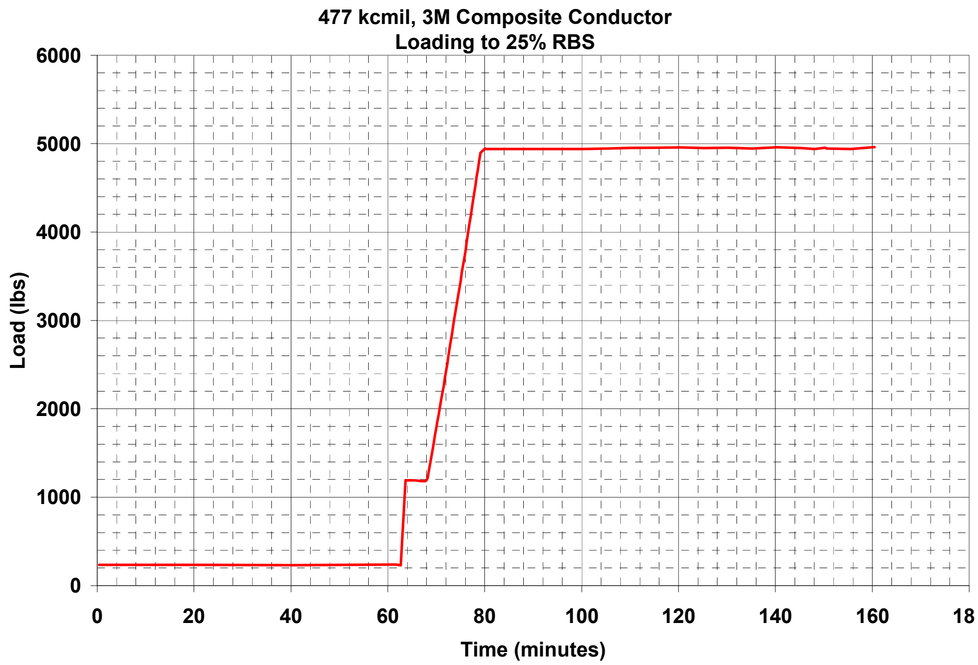

Figure 9. 25% RBS initial loading. Load was held at approx. 200 lbs for 36 hours and then increased to target load in 18 minutes.

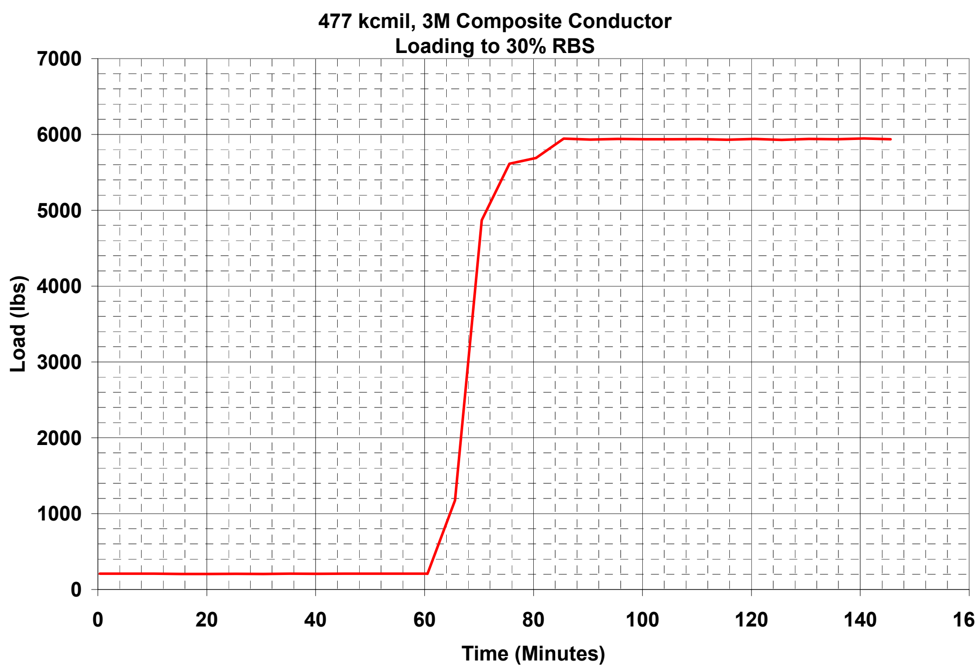

Figure 10. 30% RBS initial loading. Load was held at approx. 200 lbs for 36 hours and then increased to target load in 23 minutes.

Overall, while there are small differences in pre-load holding time, target pre-load, and also in load ramp time, there is not sufficient to suggest any significant effects of the test procedure.

Creep Stress-Strain Curves

The creep behavior is used to generate stress-strain curves for the conductor after 6 months, 1-year and 10-years of creep. Using the creep equations in Table 1, the creep strain at each stress level is generated for each of the time intervals. These creep strains are then added to the strain from the inherent stress-strain behavior for each stress level. The latter strain is derived in a 3M Technical Report entitled, "477-kcmil, 3M™ Composite Conductor: Stress-Strain Polynomial Coefficients for Design Software", August 2005. The conductor stress-strain behavior is given by the following 4th order polynomial equation relating stress (y) in psi to % strain (x);

y = -33577x4 + 64338x3 - 82025x2 + 106506x

The creep strains and total conductor strains are given in Table 2.

Stress (psi)	Initial Strain (%)	6-mo creep strain	1-yr creep strain	10-yr creep strain	Total 6-mo strain	Total 1-yr strain	Total 10-yr strain
6705	0.06615	0.0092	0.0108	0.0189	0.0753	0.0770	0.0851
8940	0.08972	0.0174	0.0200	0.0315	0.1072	0.1097	0.1212
11175	0.11411	0.0223	0.0259	0.0423	0.1365	0.1400	0.1564
13410	0.13935	0.0264	0.0309	0.0518	0.1658	0.1702	0.1912

Table 2. Creep strains with time and total strains for stresses used in creep tests

For each creep time, the total strain is plotted and then curve-fit using a 2nd-order polynomial equation with a zero intercept. However some further consideration of the curve fit is needed. For example, for the 10-year creep is given in Figure 11 using two different curve fits. A cluster of four points is shown between 0.0-0.2% strain, which are the total strains computed using the 10-year creep extrapolation at each creep stress. One potential curve fit (red line) to these four data points is shown. In computing the aluminum creep strains in the 3M Report, "477-kcmil 3M™ Composite Conductor: Stress-Strain Polynomial Coefficients for Design Software", this extrapolation causes the aluminum stress to drop (it should not), thus it overestimates the creep relaxation. An artificial point is added at 0.6% strain, noted in Figure 11. This keeps the aluminum stress-strain response to a rational behavior. Note this does not significantly change the fit to the cluster of four data points between 0.0-0.2% strain, thus the "experimental" data is still well represented. The notion of an artificial point at 0.6% strain is also used for the creep at 6-months and 1-year.

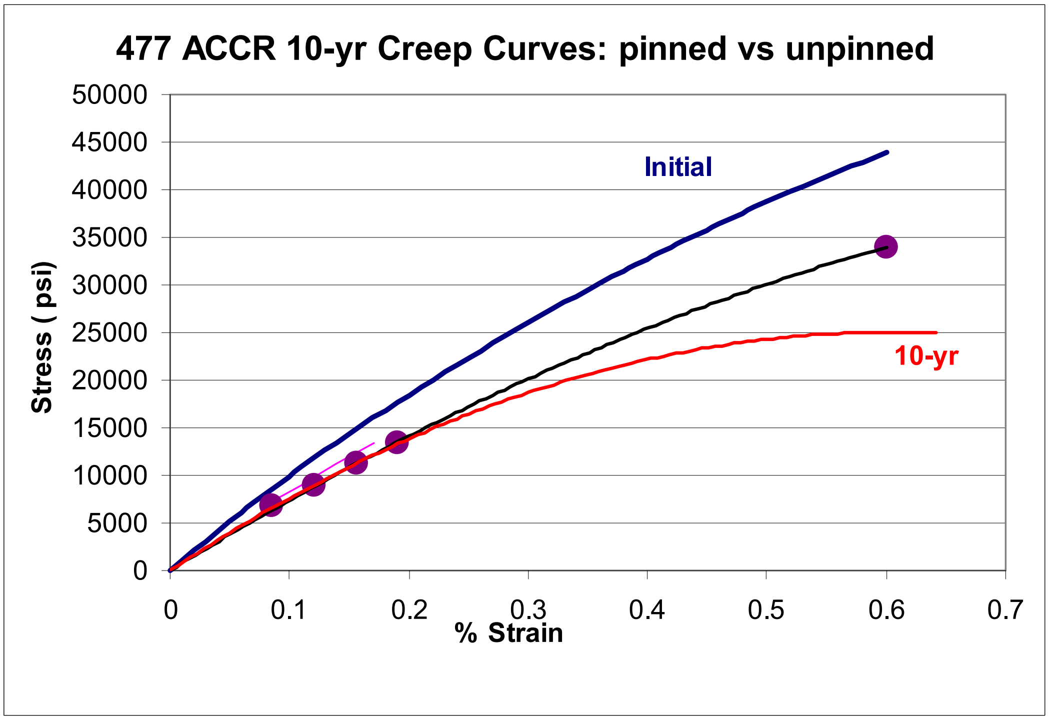

Figure 11. 10-year creep curves for 477-kcmil, 3M™ Composite Conductor with and without the artificial point at 0.6% strain

The stress-strain equations for different creep times are summarized in Table 3.

Creep Time	Creep Stress-Strain Equation
0	y = -33577x4 + 64338x3 - 82025x2 + 106506x
6 months	y = -41405x2 + 88167x
1 year	y = -44502x2 + 86692x
10-years	y = -34881x2 + 77574x

Table 3. Creep Stress-strain equations for 477-kcmil, 3M™ Composite Conductor

These equations are plotted in a summary form in Figure 12.

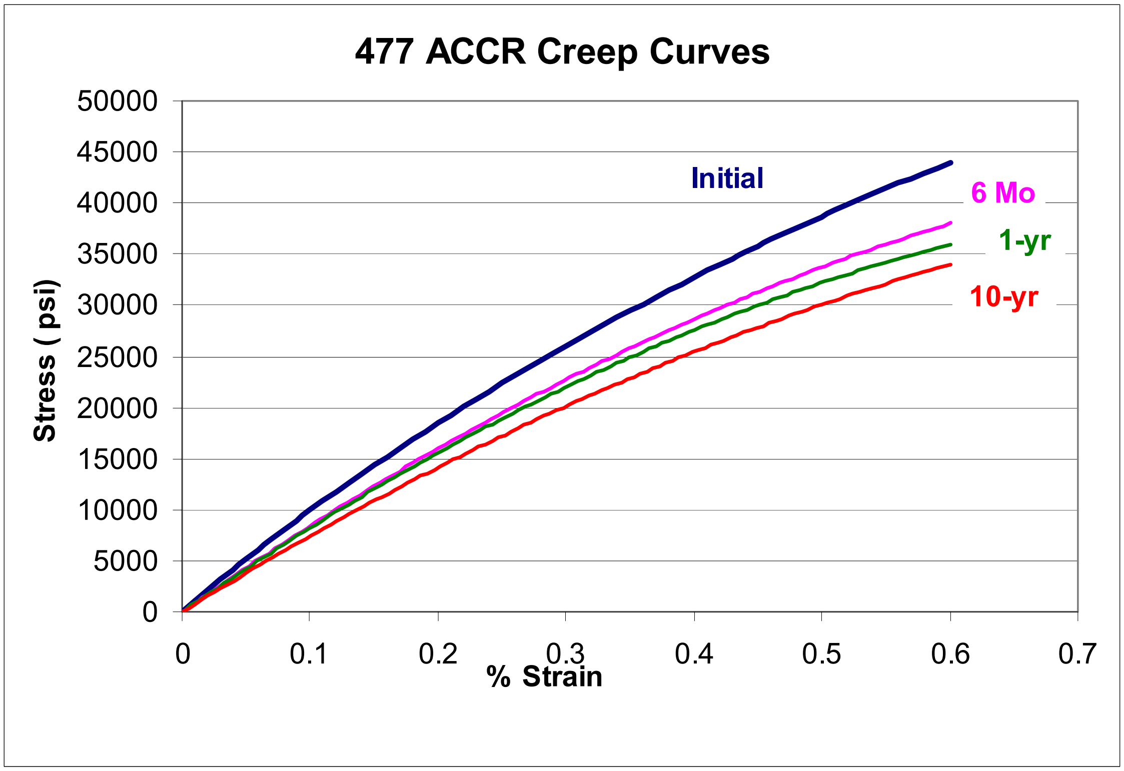

Figure 12. Creep Stress-Strain Curves for 477-kcmil, 3M™ Composite Conductor

Conclusion:

Creep data from 477-kcmil, 3M™ Composite Conductor reported was re-analyzed using a standard methodology and checked for consistency. The resulting power-law creep equations fit a form of:

a (%) = b*[(hrs)^c]   where b and c are constants and a is the creep strain

The creep parameters are summarized in Table 4.

Load (%RBS)	Stress (psi)	b	c
15	6705	0.0012	0.242343
20	8940	0.003328	0.197528
25	11175	0.003748	0.212924
30	13410	0.004006	0.224918

Table 4. Summary of Creep Parameters for 477-kcmil, 3M™ Composite Conductor

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: 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