477-kcmil 3M Brand Composite Conductor
Evaluation of Materials from ORNL Field Test

3M Company

NEETRAC Project Number: 04-114

December, 2004

A Research Center of the
Georgia Institute of Technology

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SUMMARY

A 477-kcmil 3M Brand Composite Conductor (also referred to as ACCR – Aluminum Conductor Composite Reinforced) was evaluated in an outdoor test line at the Oak Ridge National Laboratory. During six months of operation, the conductor experienced significant time at temperatures above 200°C, and also experienced temperature cycling from ambient temperature to temperatures above 200°C. At the conclusion of the outdoor testing, conductor and connectors from the Oak Ridge National Laboratory (ORNL) outdoor test line were sent to NEETRAC and evaluated to determine the effect of exposure to outdoor conditions and in-service temperature cycles. Data from tests on the same materials "as manufactured" were retrieved for baseline property values. Evaluation results show that expected creep has occurred, but mechanical and electrical properties of the conductor are unchanged.

KEY FINDINGS

1) Stress-strain results show the expected effect of creep from in-service tension.
2) Mechanical and electrical properties of the conductor are unchanged from baseline (new) conditions, other than conductor creep.
3) Connector dissection showed everything was done properly except that the conductor surface was not wire-brushed prior to connector installation.

SAMPLES

1) Two (2) AFL (Alcoa-Fujikura Ltd.) compression dead ends (catalogue # B9085-A) with ~10 meters (33 ft) of conductor attached. All conductor tails were clamped at the cut location to preserve the "in-service" position of all conductor components.
2) One (1) AFL compression splice (catalogue # B9095-A) with ~5 meters (16ft) of conductor attached to each end. Both free ends were clamped at the cut location to preserve the "in-service" position of all conductor components.
3) Free span conductor, approximately 40 meters (130 ft) with the free ends clamped at the cut point. The "in-service" position of the conductor components was preserved to measure the "in-service" stress-strain characteristics.

PROCEDURE

The scope of the evaluation included the following tests:

I) Conductor tensile tests (three samples plus "bonus" samples from the stress-strain test): Samples from the "free-span" conductor were terminated using cast-resin terminations.

Clamps were used to preserve the as-received position of the conductor layers until the resin cured. The sample preparation method ensures that the lab tensile test loads each conductor strand in the same manner as a field overload, and thereby measure the in-service conductor strength. Free conductor between the end fittings is 20 feet (6 meters).

II) Connector tensile tests (two dead-ends): Cast-resin fittings were applied to the sample's free end (one per dead-end). The procedure preserves the "as received" position of the conductor components, and thereby assures that the breaking strength is the same as existed when the samples were in service on the test span.

III) Conductor resistance (one sample): Bolted dead end fitting were installed at each end of a 22-foot long sample from the free-span section. The purpose for the dead end fitting was two-fold:

   i. provide a means to put sample under nominal tension sufficient to keep the sample straight, and;
   ii. provide a location to connect the current leads of the 4-wire resistance instrument.

A second set of voltage equalizers in the form of tightly-wrapped solid copper strands are applied 19 feet apart in the test section. The sample is placed on a flat surface, and pulled with sufficient tension to remove any residual curvature in the conductor. Tension was not measured, but is estimated at 200 – 300 lb. A digital low-resistance Ohmmeter was used to make a 4-wire resistance measurement for the conductor section between the two voltage equalizers. A digital multimeter was used to verify the sample was electrically isolated.

IV) Connector resistance (one dead-end, one splice): Connector resistance was measured using the same technique used for measuring conductor resistance. The measurement includes the resistance of the conductor between the connector and the equalizer. The length of exposed conductor is measured, and a resistance value is subtracted from the measured value to obtain a measurement of the resistance of the splice. In accordance with industry conventions, connector resistance is expressed in terms of "resistance ratio", which is the connector resistance divided by the resistance of conductor the same length as the connector.

V) Connector dissection (one dead end): A milling machine was used to split the aluminum sleeve and reveal the internal components. Correct installation is verified by observing proper placement of the core grip, proper conductor preparation, and proper injection of inhibitor compound prior to compression. The core grip was removed. Proper crimping was confirmed. The steel sleeve was longitudinally sectioned (split), and the inner aluminum liner was confirmed to be completely formed around the MMC core strands.

VI) Stress-strain: Two samples from the free-span section were terminated with cast-resin using a process that ensures that each conductor layer and strand is not displaced from its in-service position. One conductor sample was tested with all strands in the finished conductor configuration. The core sample was prepared by cutting the aluminum strands from the second test sample. The 1999 Aluminum Association guide for conductor stress-strain testing was followed with the exception of special values for the elastic properties of the metal matrix composite (MMC) core were used instead of values for steel core used in ACSR conductors. The core strand is tested by preparing a complete conductor sample, and then removing all the aluminum strands.

RESULTS

I) Conductor tensile tests (three samples as-received, plus the stress-strain sample after the stress-strain test):

Sample #	Breaking Load (lb)	% RBS	Failure Mode
04114T1	20,710	106	All strands fractured in the gage section
04114T2	19,860	102	All strands fractured at the resin fitting
04114T3	20,800	107	All strands fractured at the resin fitting
Stress-strain conductor	20,350	104	Mid-span break, all strands
Stress-strain core	12,910	111	Mid-span break, all strands

See appendix I for chart showing test data

II) Connector tensile tests (two dead-ends):

Sample #	Breaking Load (lb)	% RBS	Failure Mode
04114DE1 (dead end)	20,380	105	All strands fractured ~ 5" inside dead end
04114DE2 (dead end)	19,550	100	All strands fractured ~ 5" inside dead end

See appendix II for chart showing test data.

III) Conductor resistance (one sample):

Conductor resistance measures 0.1834 Ω/mile at 20° C. The published value is 0.1832 Ω/mile at 20° C. This is remarkably good agreement between predicted and measured values. See appendix III for a worksheet showing data and calculations. The small discrepancy relative to the nominal value is well within the measurement error.

IV) Connector resistance (one splice, two dead end samples):

Splice resistance measures 49.2 μΩ. The "resistance ratio" is 0.41. See appendix IV for raw measurements and calculations.

Dead end # 1 resistance measures 29.9 μΩ. The "resistance ratio" is 0.39. See appendix IV for raw measurements and calculations.

Dead end # 2 resistance measures 25.5 μΩ. The "resistance ratio" is 0.33. See appendix IV for raw measurements and calculations.

There exists no universal agreement on acceptable values for resistance ratio. However NEETRAC has performed extensive testing and measurements in this field, and from this work it suggests, that there is general agreement that values above 1.0 indicate a serious problem. Values above 1.4 signal imminent failure. Values around 0.8 are normal for connectors with low cross-sections, typically implosion-type connectors. Values around 0.8 would indicate problems with larger compression connectors. All values from the 3M conductor in the field test are low, and typical of newly-installed connectors. There is no evidence of connector degradation during the test line thermal cycling.

V) Connector dissection (one dead end): See appendix V for photographs and discussion documenting the connector dissections. The dissections and inspections showed good workmanship for core and aluminum insertion depth, component placement, and the crimping operation. The center cavity was full of oxide inhibitor, and the distribution pattern shows that the injection was done correctly prior to the start of crimping. One discrepancy was noted: There is no evidence that the conductor was wire-brushed prior to splice installation. AFL instructions require wire-brushing of the conductor Outside D iameter only in cases where the connector is installed on weathered conductor. However, most field and lab experience is that failure to wire-brush new conductor can cause premature connector failure.

VI) Stress-strain: See appendix VI for stress-strain equations and charts illustrating the stress-strain test. The term "initial modulus" is used with the field-aged test data for consistency with the test procedure. "Initial" is in quotes because the conductor is not at initial condition following the field test. Stress-strain results are similar to results from the same conductor prior to the field test. The principal difference is that creep during the 30% load hold phase is less on the field sample, apparently because the field loads caused the initial creep to be removed from the conductor.

CONCLUSION:

Test results show the conductor properties are not changed by the field trial. The only significant difference is the change in the initial modulus coefficients from the stress-strain test. That is expected because the conductor is no longer at "initial" conditions after creep in the field.

EQUIPMENT LISTING

1) MTS Servo-hydraulic tensile machine, Control # CQ 0195 (load and crosshead data)

2) Dynamics Research Corporation (DRC)/NEETRAC cable extensometer, Control # CQ 3002 (strain data).
3) Yokogawa DC100 data acquisition system, Control # CN 3022 (temperature data)
4) HBM linear position indicator for crosshead displacement (for reference only)
5) AVO/Biddle Digital Low Resistance Ohmmeter, Calibration Control #CQ 1097

REFERENCES AND STANDARDS LISTING

1) ASTM E4, (Calibration of Load Testing Machines)
2) ANSI C119.4, (Connector testing)

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 I, Conductor Tensile Data

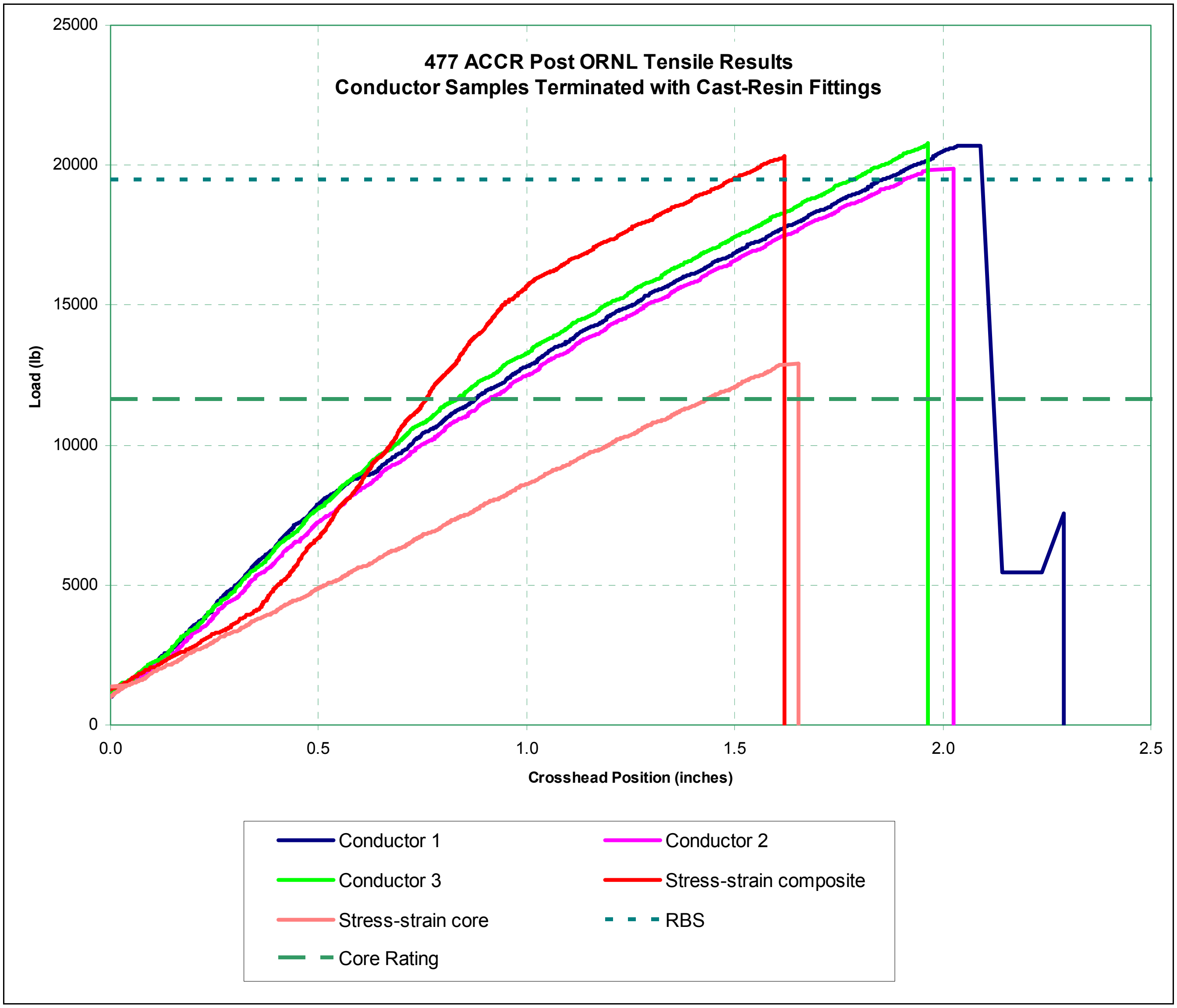


Figure 1, free-span conductor tensile test data

APPENDIX II, Data from Connector Tensile Tests

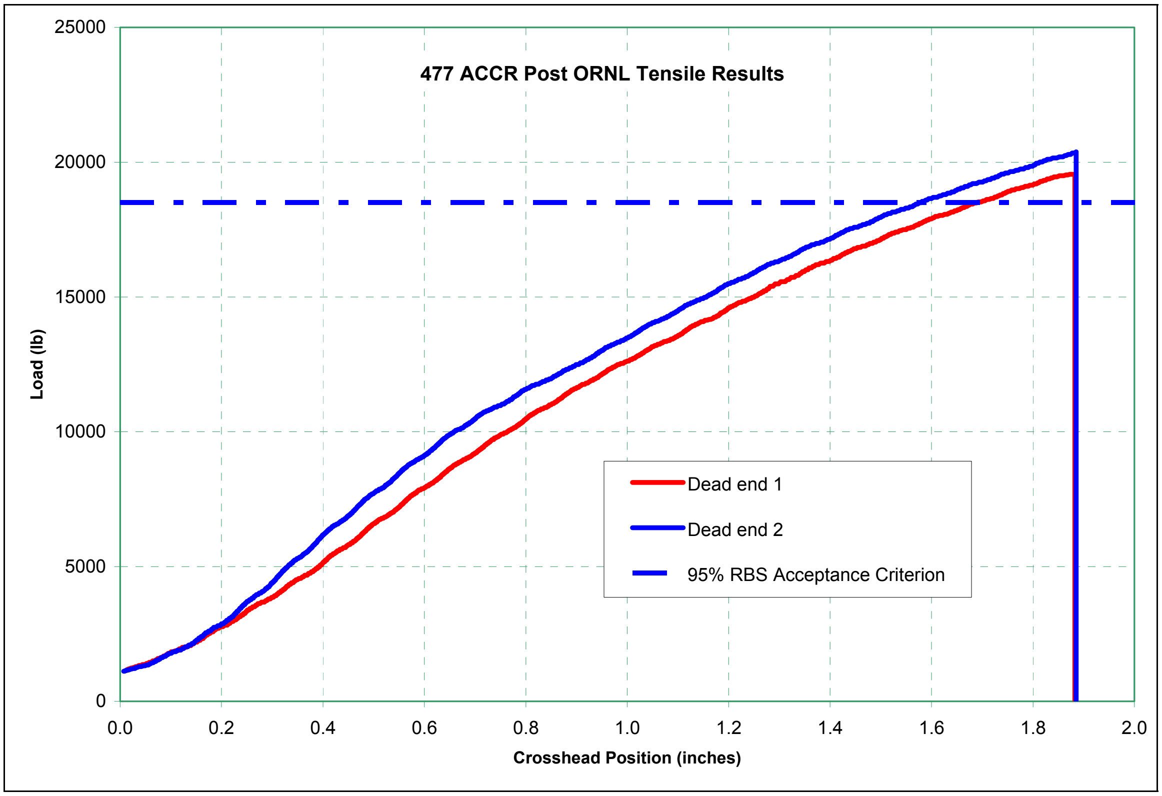
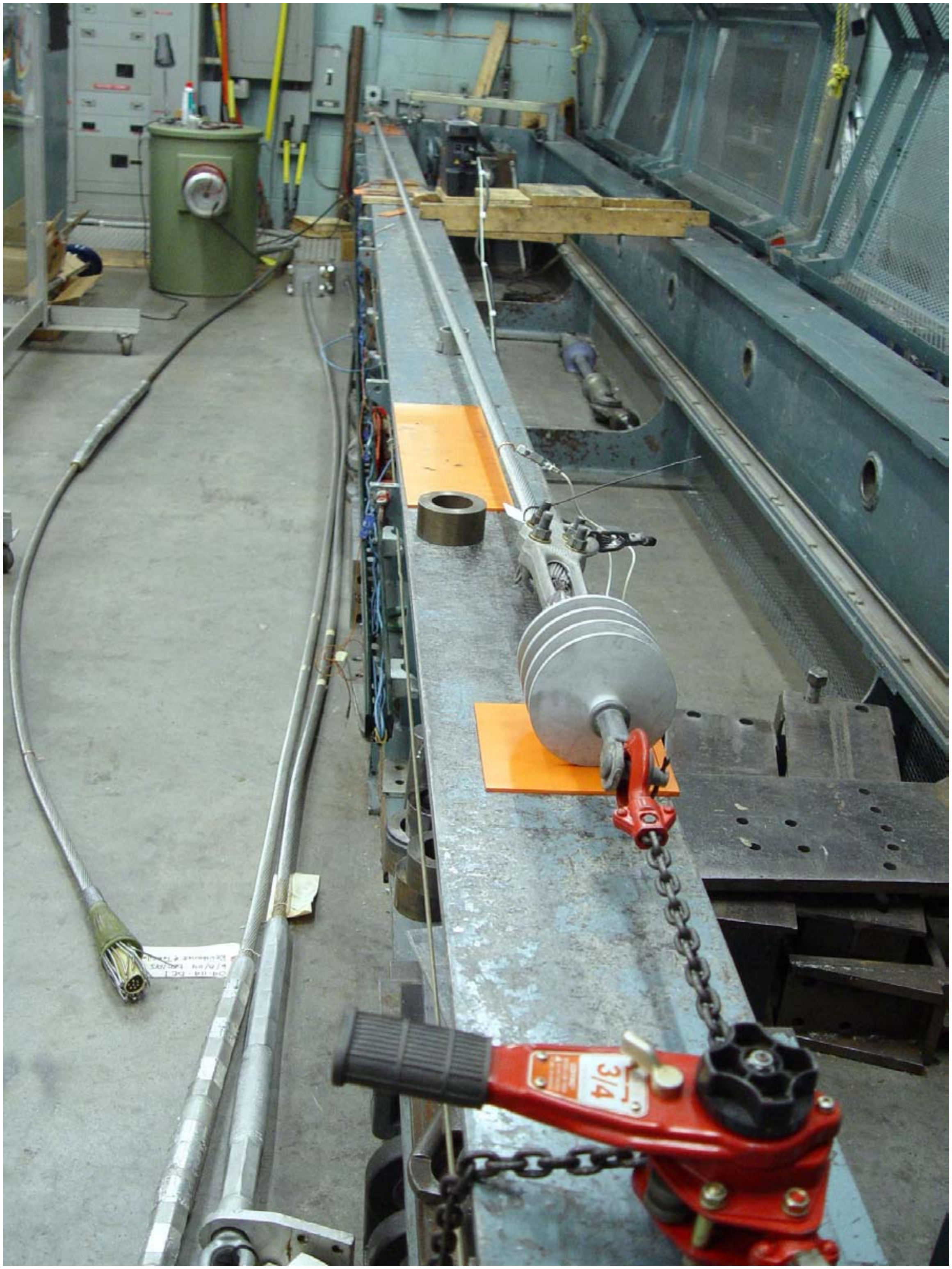


Figure 2, connector tensile test data

Photograph 1, dead end sample after dissection, showing break about 5 inches inside the sleeve. The conductor interstitial spaces are full of inhibitor, showing that inhibitor was injected prior to crimping the outer sleeve.

APPENDIX III, Conductor Resistance



Photograph 2, conductor sample during resistance measurement

Resistance of a 19 ft test section was measured. Readings were repeated later in the day as noted below. The average of all readings is 0.1834 Ω/mile at 20° C. The published value is 0.1832 Ω/mile at 20° C.

Conductor Resistance

NEETRAC Project No.	04-114		= Data Input Cells
AVO (Biddle) DLRO, Calibration Control #	CQ1097		= Calculated Value
Temperature Indicator (Instrument)	CN3022		
Temperature coefficient for resistance:	0.0036		

Resistance measurement on a 477 ACCR sample from the ORNL test line. Bolted end fitting for equalizer (see photos), pulled to ~200 lbs tension w/a come-a-long

These readings taken manually @ 10/25/04 @ 10:19 AM

Conductor Temperature:	21.8	deg C			
Test Section:	19.000	ft			
Resistance Reading 1	665.1	uOhms	At	21.8	deg C
Resistance Reading 2	665.1	uOhms	At	21.8	deg C
Resistance Reading 3	664.9	uOhms	At	21.8	deg C
Average of 3 Readings	665.03	uOhms	At	21.8	deg C
Ohms/ft:	3.5002E-05	Ohm/ft	At	21.8	deg C
Ohms/ft:	3.4775E-05		At	20.0	deg C
Ohms/mi	0.184809	Ohm/mi	At	21.8	deg C
Ohms/mi @ 20C:	0.183612	Ohm/mi	At	20.0	deg C

These readings taken manually @ 10/25/04 @ 1:24 pm

Conductor Temperature:	21.3	deg C			
Test Section:	19.000	ft			
Resistance Reading 1	663.5	uOhms	At	21.30	deg C
Resistance Reading 2	663.5	uOhms	At	21.30	deg C
Resistance Reading 3	663.5	uOhms	At	21.30	deg C
Average of 3 Readings	663.50	uOhms	At	21.30	deg C
Ohms/ft:	3.4921E-05	Ohm/ft	At	21.30	deg C
Ohms/ft:	3.4695E-05		At	20.00	deg C
Ohms/mi	0.184383	Ohm/mi	At	21.30	deg C
Ohms/mi @ 20C:	0.183188		At	20.00	deg C

Average

Ohms/mi @ 20C:	**0.18340**		At	20.0	deg C
3M nominal	0.18317	Ohm/mi	At	20.0	deg C

APPENDIX IV, Connector Resistance Details

Splice Resistance Ratio Worksheet

NEETRAC Project No.	04-114		
AVO (Biddle) DLRO, Calibration Control #	CQ1097		= Data Input Cells
Temperature Indicator (Instrument)	CN3022		= Calculated Value
Temperature coefficient for resistance:	0.0036		

Resistance measurement on a 477 ACCR Dead-End Setup in the tensile room on the MTS frame, Bolted end fitting for equalizer (see photos), pulled to ~100 lbs tension w/a come-a-long

X1 =	72	Inches from end of splice to P1
X2 =	72	Inches from end of splice to P2
L =	41.25	Inches, Length of Splice (end to end)
Current =	10	Amps DC

These readings taken manually @ 10/21/04 @ 3:49 AM

Conductor Temperature:	22.45	deg C					
Test Section:	15.437	ft	P1 to P2				
Resistance Reading 1	470.9	uOhms		At	22.45	deg C	
Resistance Reading 2	470.8	uOhms		At	22.45	deg C	
Resistance Reading 3	470.7	uOhms		At	22.45	deg C	
Average of 3 Readings	470.80	uOhms		At	22.45	deg C	= measured resistance over length X1 + X2 + L
Corrrected to 20C:	466.65	uOhms		At	20.0	deg C	

These readings taken manually @ 10/21/04 @ 4:14 PM

Conductor Temperature:	21.85	deg C					
Test Section:	15.437	ft	P1 to P2				
Resistance Reading 1	468.5	uOhms		At	21.85	deg C	
Resistance Reading 2	468.5	uOhms		At	21.85	deg C	
Resistance Reading 3	468.5	uOhms		At	21.85	deg C	
Average of 3 Readings	468.50	uOhms		At	21.85	deg C	= measured resistance over length X1 + X2 + L
Corrrected to 20C:	465.38	uOhms		At	20.0	deg C	

Average	466.01	uOhms	At	20.0	deg C

Calculated Resistance Ratio:

CR =	2.89	uOhms/Inch	Conductor Resistance
DEC =	466.01	uOhms	Splice Resistance + Conductor Resistance P1 to P2

$$RR = \frac{(DEC) - [(X1 + X2) * (CR)]}{(L) * (CR)} = 0.41$$

Splice Resistance: 49.2 uOhms at 20 C

Dead-End #1 Resistance Ratio Worksheet

NEETRAC Project No.	04-114		
AVO (Biddle) DLRO, Calibration Control #	CQ1097	(green)	= Data Input Cells
Temperature Indicator (Instrument)	CN3022	(yellow)	= Calculated Value
Temperature coefficient for resistance:	0.0036		

Resistance measurement on a 477 ACCR Dead-End Setup in the tensile room on the MTS frame, Bolted end fitting for equalizer (see photos), pulled to ~100 lbs tension w/a come-a-long

X =	195.25	Inches from end of splice to P2, (length of exposed conductor to P2)
L =	26.75	Inches, Length from P1 to Mouth of Dead-End
X + L =	222	Inches from P1 to P2
Current =	10	Amps DC

These readings taken manually @ 10/20/04 @ 8:51 AM

Conductor Temperature:	22.0	deg C					
Test Section:	18.500	ft	P1 to P2				
Resistance Reading 1	599.4	uOhms		At	22.0	deg C	
Resistance Reading 2	599.5	uOhms		At	22.0	deg C	
Resistance Reading 3	599.5	uOhms		At	22.0	deg C	
Average of 3 Readings	599.47	uOhms		At	22.0	deg C	= measured resistance over length X + L
Corrrected to 20C:	595.15	uOhms		At	20.0	deg C	

These readings taken manually @ 10/20/04 @ 9:17 AM

Conductor Temperature:	22.1	deg C					
Test Section:	18.500	ft	P1 to P2				
Resistance Reading 1	599.6	uOhms		At	22.1	deg C	
Resistance Reading 2	599.6	uOhms		At	22.1	deg C	
Resistance Reading 3	599.6	uOhms		At	22.1	deg C	
Average of 3 Readings	599.60	uOhms		At	22.1	deg C	= measured resistance over length X + L
Corrrected to 20C:	595.07	uOhms		At	20.0	deg C	

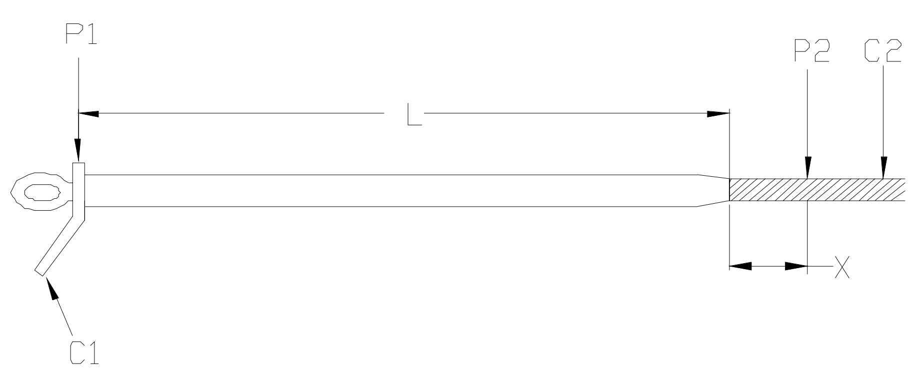
Average	595.11	uOhms	At	20.0	deg C

Calculated Resistance Ratio:

CR =	2.89	uOhms/Inch	Conductor Resistance
DEC =	595.11	uOhms	Splice Resistance + Conductor Resistance P1 to P2

$$RR = \frac{(DEC) - [(X) * (CR)]}{(L) * (CR)} = 0.39$$

Connector Resistance = 29.9 uOhms At 20.0 deg C



Dead-End #2 Resistance Ratio Worksheet

NEETRAC Project No.	04-114
AVO (Biddle) DLRO, Calibration Control #	CQ1097
Temperature Indicator (Instrument)	CN3022
Temperature coefficient for resistance:	0.0040

= Data Input Cells
= Calculated Value

Resistance measurement on a 477 ACCR Dead-End Setup in the tensile room on the MTS frame, Bolted end fitting for equalizer (see photos), pulled to ~100 lbs tension w/a come-a-long

X =	195.252	Inches from end of splice to P2, (length of exposed conductor to P2)
L =	26.625	Inches, Length from P1 to Mouth of Dead-End
X + L =	222	Inches from P1 to P2
Current =	10	Amps DC

These readings taken manually @ 10/20/04 @ 3:30 PM

Conductor Temperature:	21.8	deg C					
Test Section:	18.500	ft	P1 to P2				
Resistance Reading 1	594.2	uOhms		At	21.8	deg C	
Resistance Reading 2	594.2	uOhms		At	21.8	deg C	
Resistance Reading 3	594.2	uOhms		At	21.8	deg C	
Average of 3 Readings	594.20	uOhms		At	21.8	deg C	= measured resistance over length X + L
Corrected to 20C:	589.92	uOhms		At	20.0	deg C	

These readings taken manually @ 10/201/04 @ 4:30 PM

Conductor Temperature:	21.7	deg C					
Test Section:	18.500	ft	P1 to P2				
Resistance Reading 1	595.7	uOhms		At	21.7	deg C	
Resistance Reading 2	595.4	uOhms		At	21.7	deg C	
Resistance Reading 3	595.6	uOhms		At	21.7	deg C	
Average of 3 Readings	595.57	uOhms		At	21.7	deg C	= measured resistance over length X + L
Corrected to 20C:	591.52	uOhms		At	20.0	deg C	

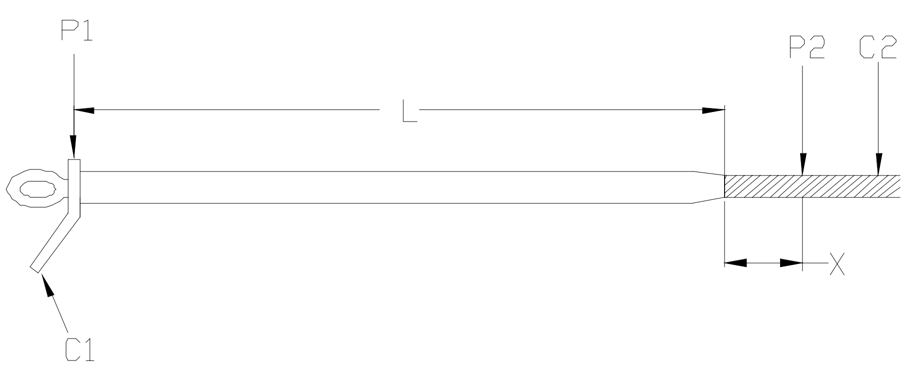
Average	590.72	uOhms	At	20.0	deg C

Calculated Resistance Ratio:

CR =	2.89	uOhms/Inch	Conductor Resistance
DEC =	590.72	uOhms	Splice Resistance + Conductor Resistance P1 to P2

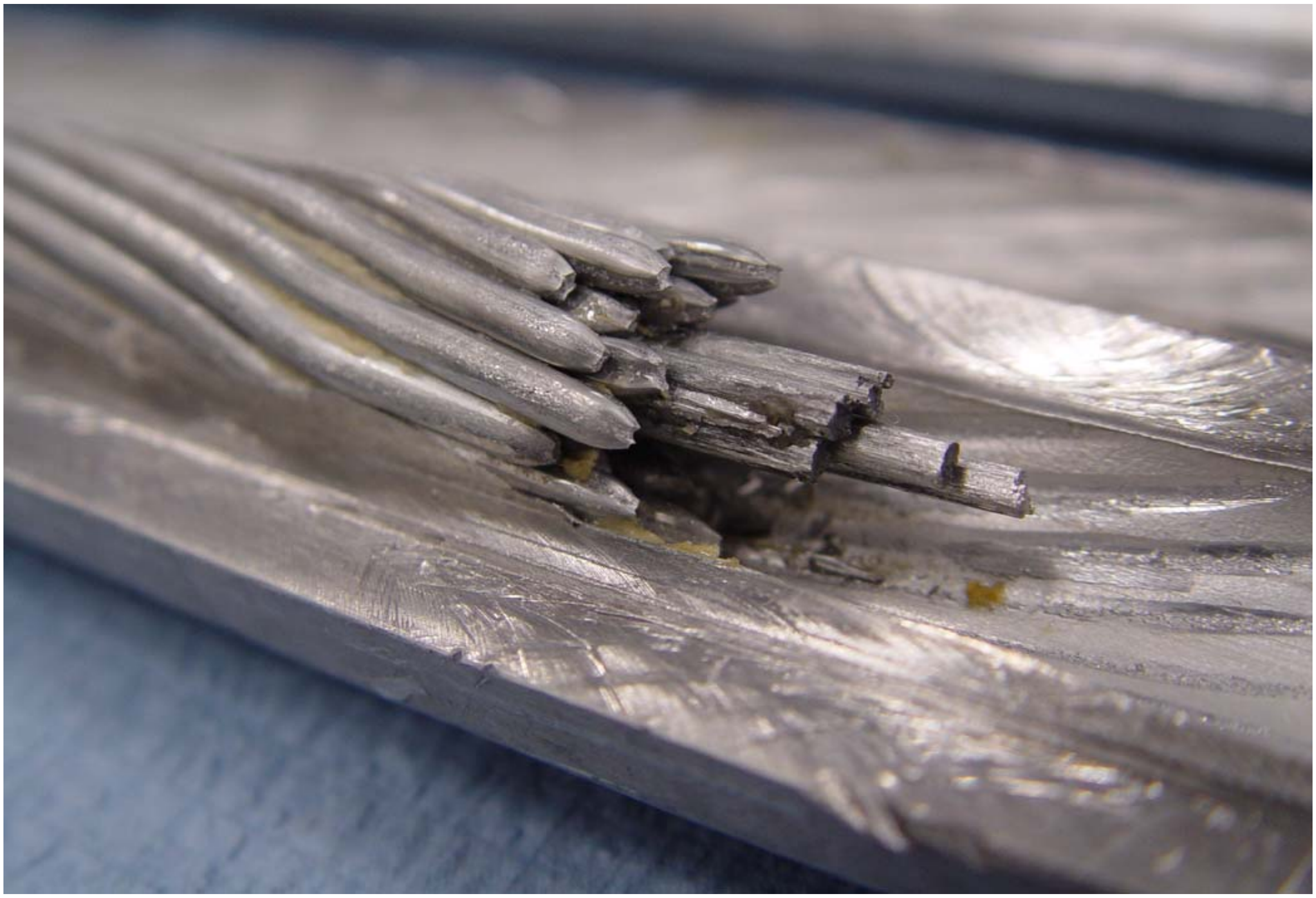
$$RR = \frac{(DEC) - [\,(X) * (CR)\,]}{(L) * (CR)} = 0.33$$

DE Resistance=	25.5	uOhms	At	20.0	deg C



APPENDIX V, Connector Dissection Details

Photograph 3, dead end splice components following dissection



Photograph 4, break location inside sleeve. Note that inhibitor fills interstitial spaces between strands, showing proper injection of inhibitor prior to crimping.

Photograph 5, conductor from crimp zone has no evidence of wire-brush marks

APPENDIX VI, Stress-strain Results

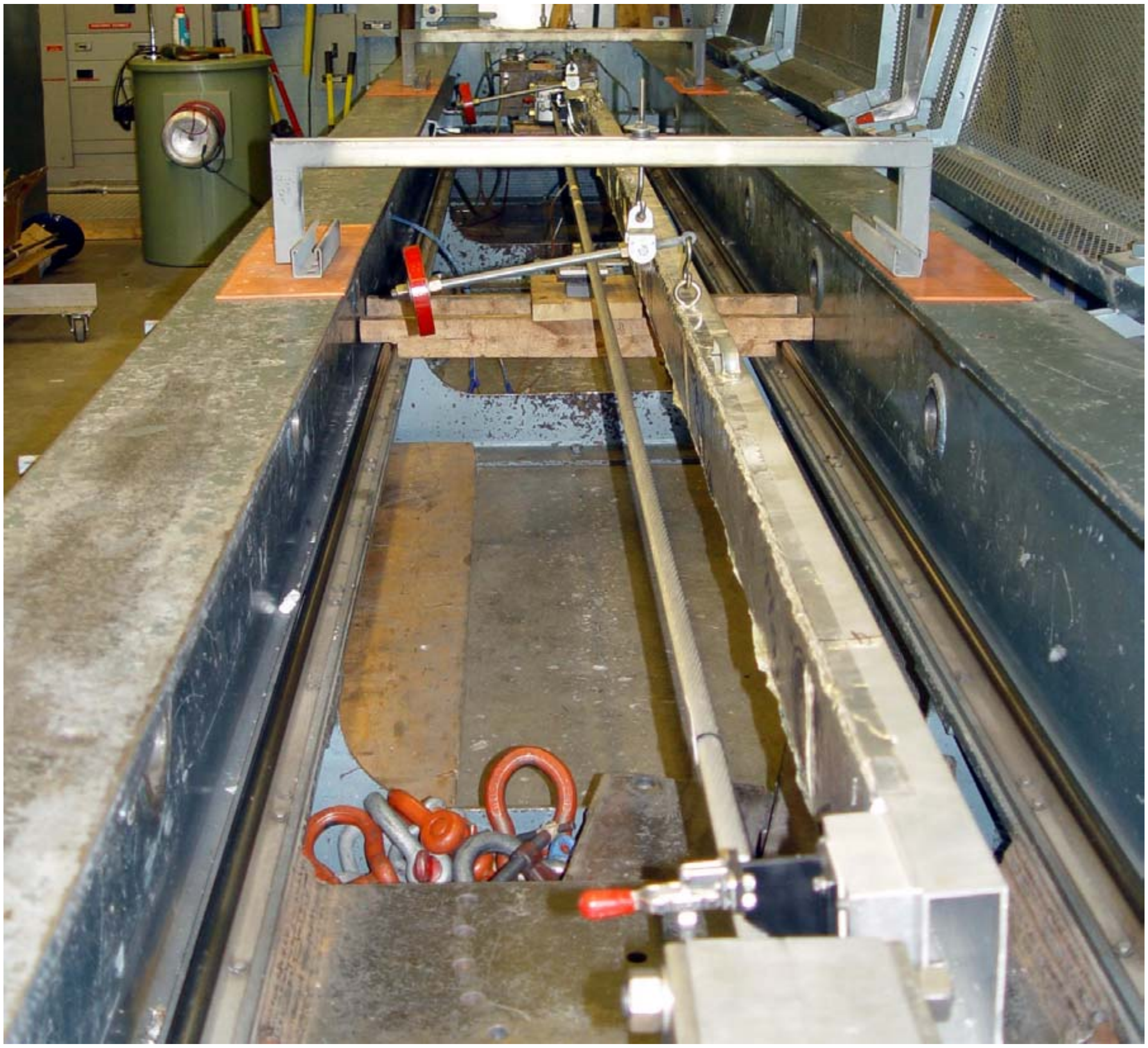
Detailed Procedure:

Composite conductor:

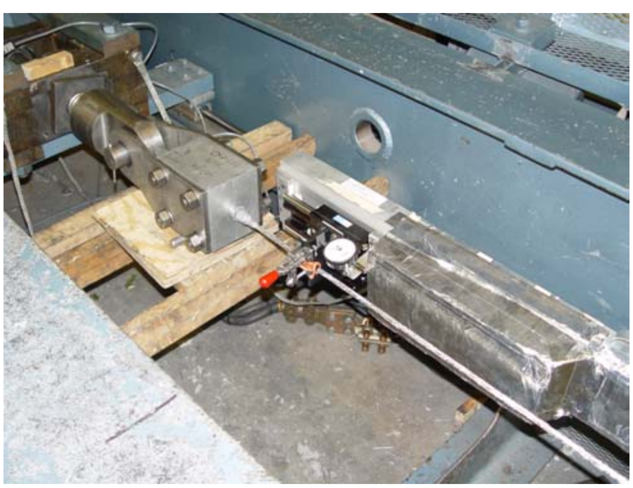
1) Apply load of 1,000 lb. Remove sag with a mid-span support
2) Install extensometer, and set to zero
3) Pull to 30% of RBS (5,840 lb)
4) Hold for 30 minutes
5) Relax load to 1,000 lbs
6) Pull to 50% RBS (9,740 lbs)
7) Hold for one hour
8) Relax load to 1,000 lb
9) Pull to 70% RBS (13,630 lb)
10) Hold for one hour
11) Relax load to 1,000 lb
12) Pull to 75% RBS (14,610 lb)
13) Relax load to 1000 lbs, and remove the extensometer (for its own protection)
14) Pull to destruction (bonus task not required by Aluminum Association)

Core strands:

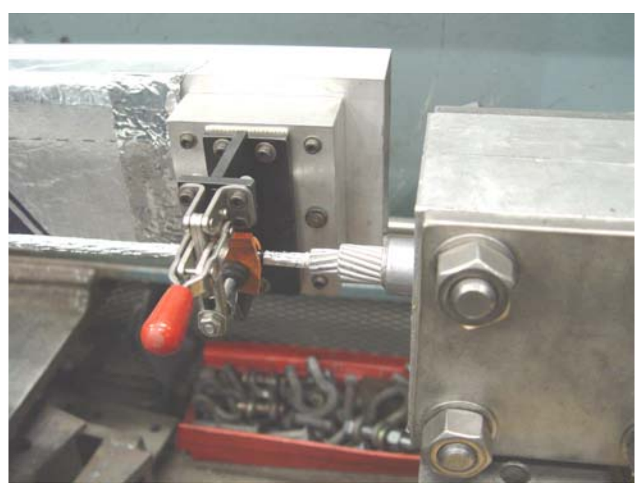
1) Pull to calculated initial tension (in this case, 380 lbs). Remove sag.
2) Pull to same strain as conductor at start of 30% of RBS test (0.09648%). Hold for 30 minutes.
3) Relax load to 380 lbs.
4) Pull to same strain as conductor at start of 50% of RBS test (0.19389%). Hold for one hour.
5) Relax load to 380 lbs.
6) Pull to same strain as conductor at start of 70% of RBS test (0.33167%). Hold for one hour.
7) Relax load to 380 lbs.
8) Pull to 75% RBS.
9) Relax load to 1000 lbs
10) Pull to destruction (bonus task not required by Aluminum Association)



Photograph 6, long view of conductor stress-strain test



Photograph 7
Detail of extensometer and end fitting



Photograph 8
Detail showing core stress-strain sample

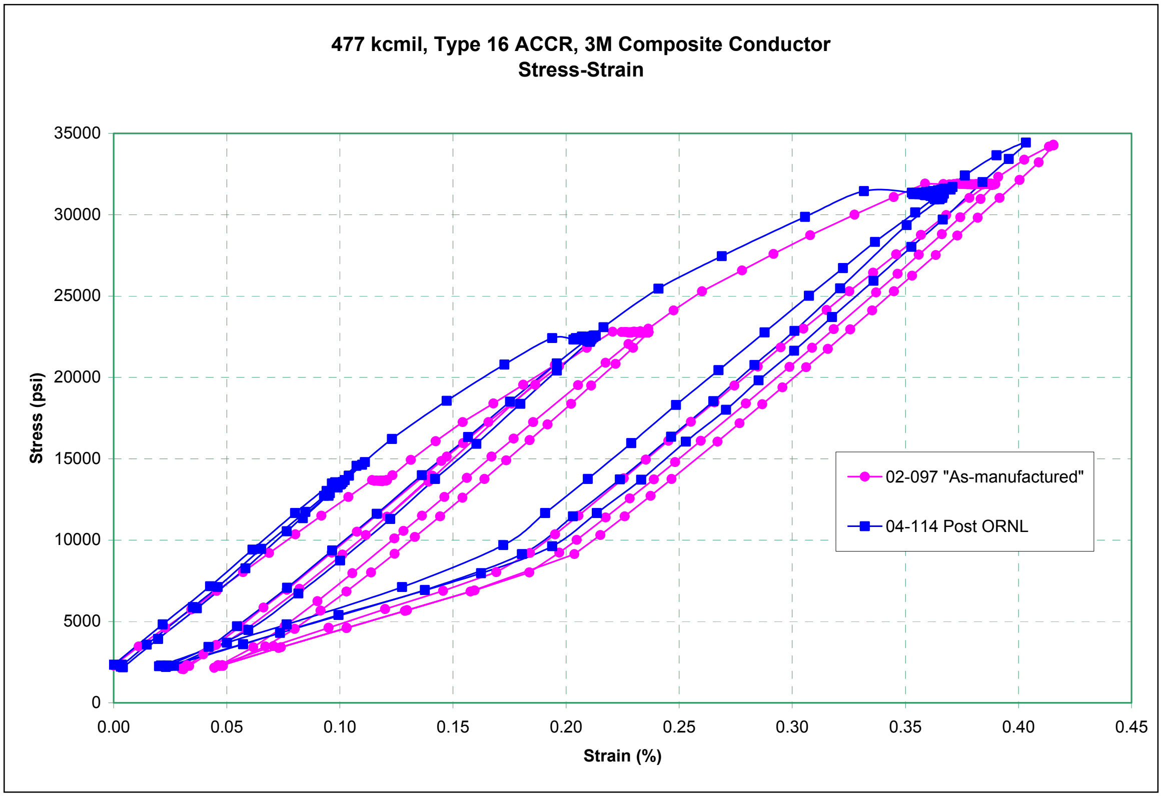


Figure 3, plot of raw conductor stress-strain data recorded during conductor stress-strain test (blue), and same data for conductor tested from same lot before the field test (pink)

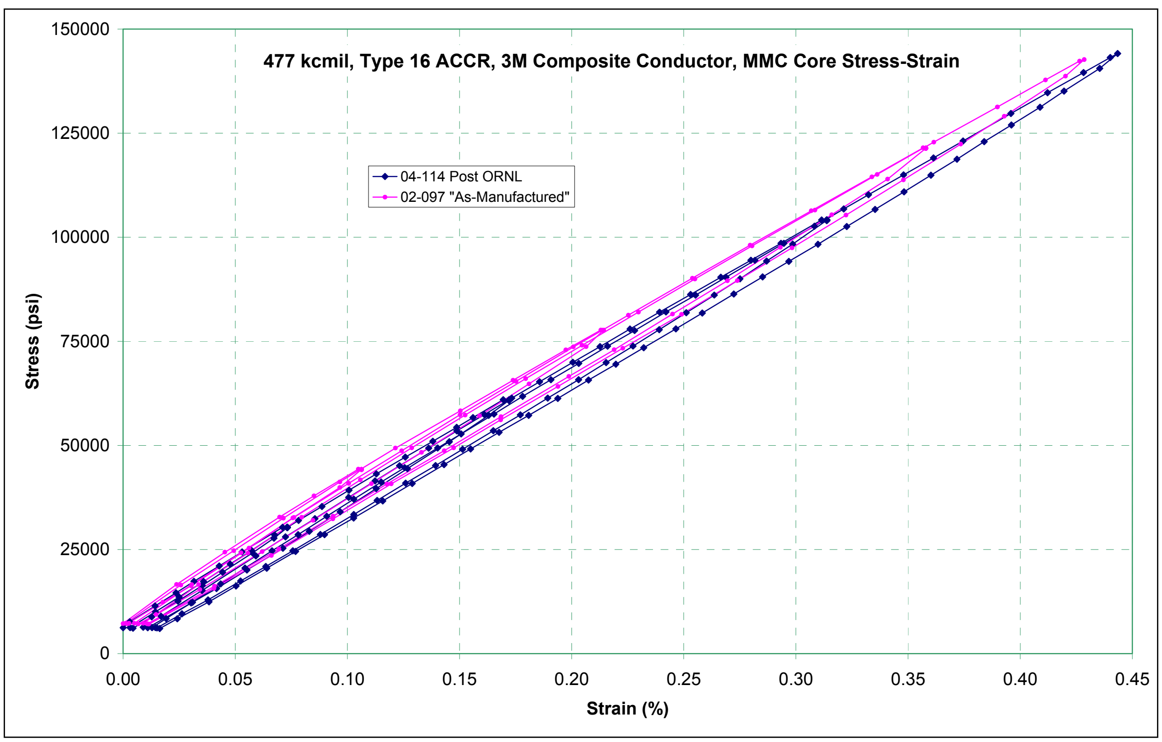


Figure 4, plot of raw core stress-strain data recorded during conductor stress-strain test (blue), and same data for conductor tested from same lot before the field test (pink)

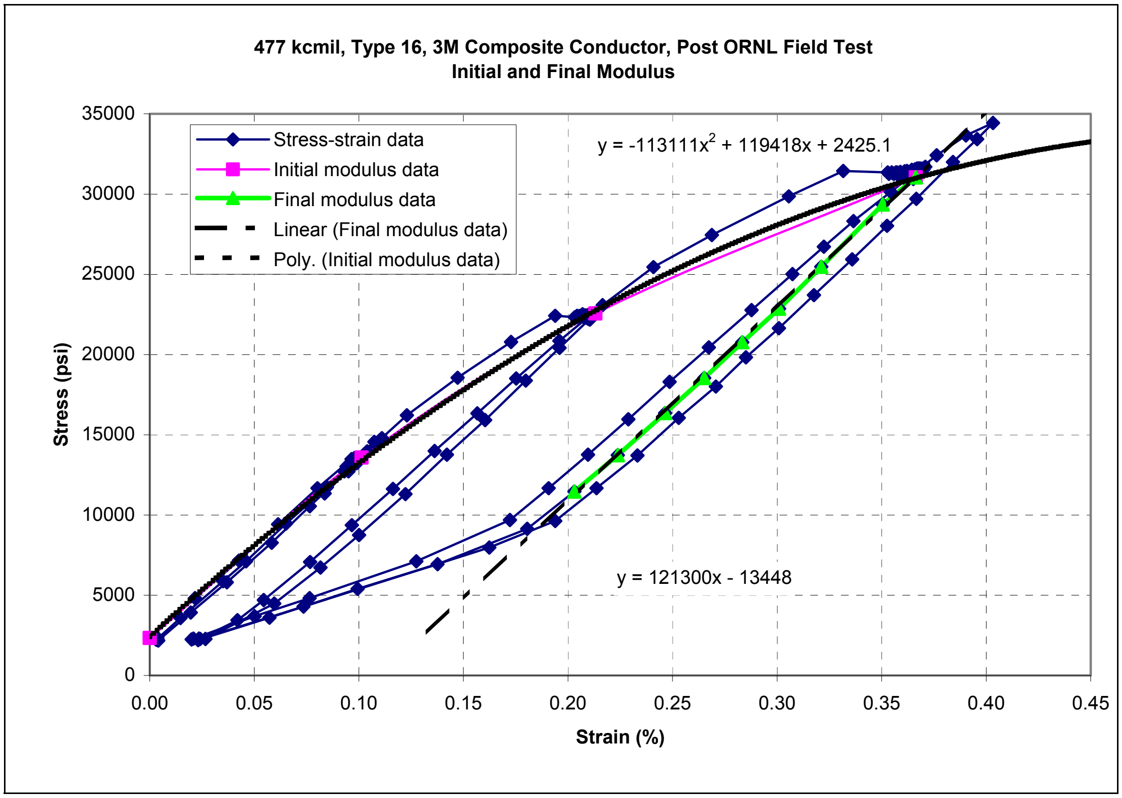


Figure 5, construction of conductor "initial" and final modulus on stress-strain data

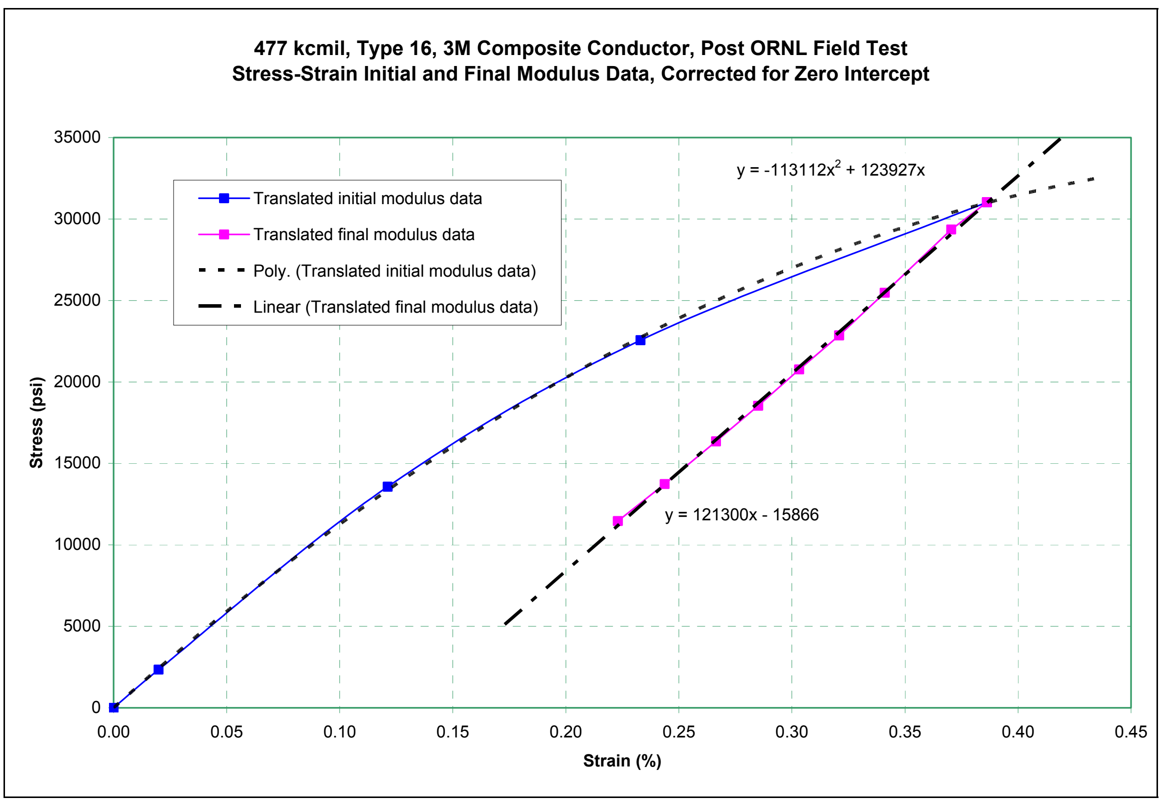


Figure 6, "initial" and final conductor modulus, translated to zero along strain axis

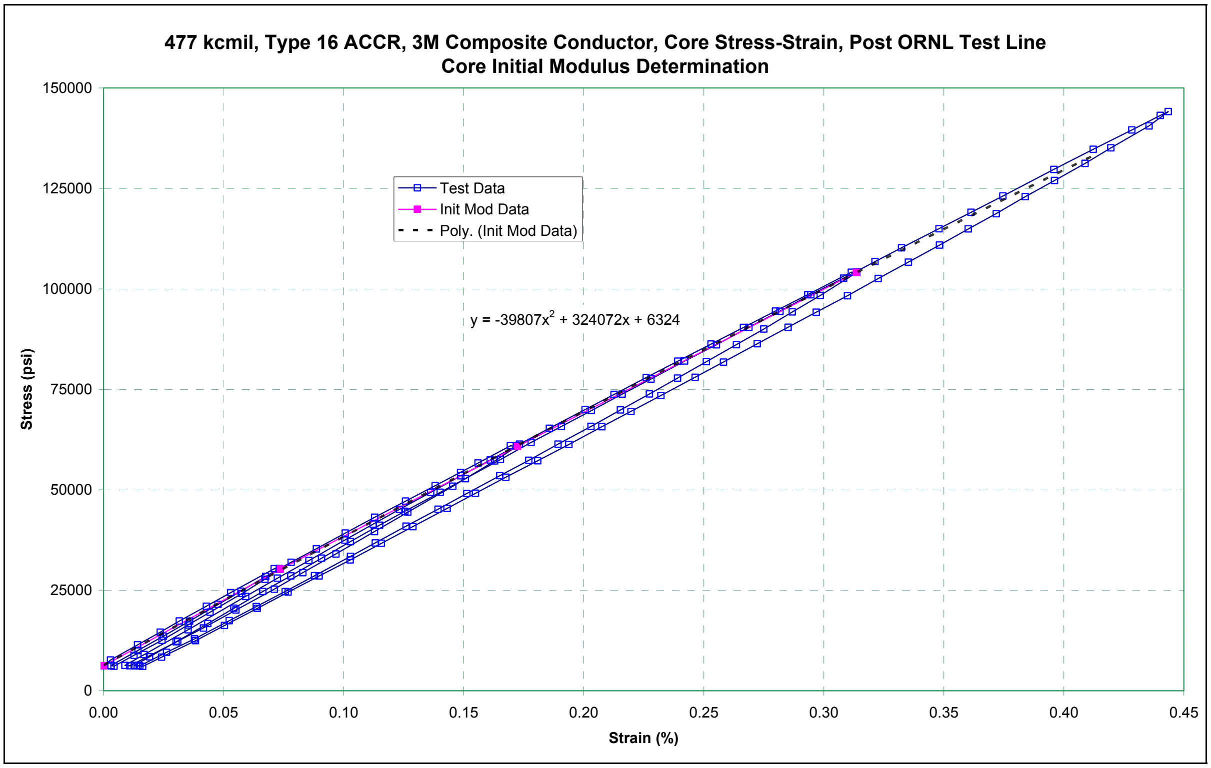


Figure 7, construction of core “initial” modulus on stress-strain data

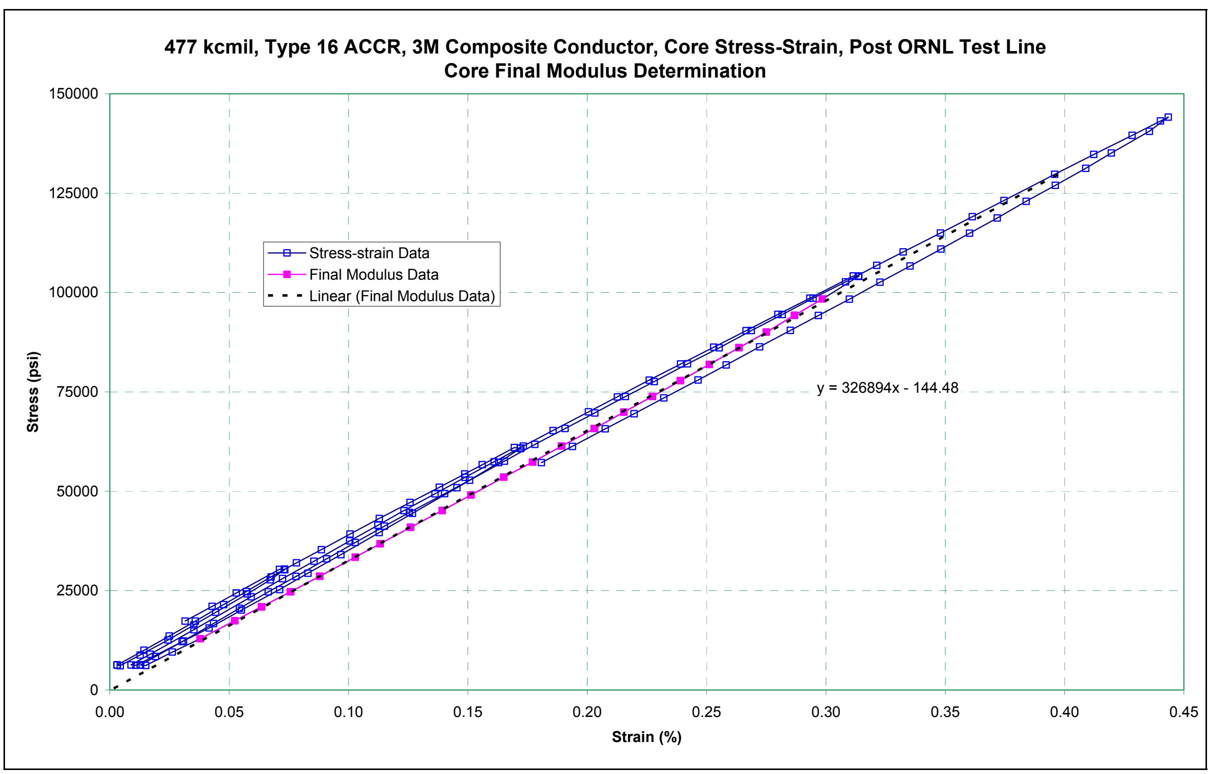


Figure 8, construction of core final modulus on stress-strain data

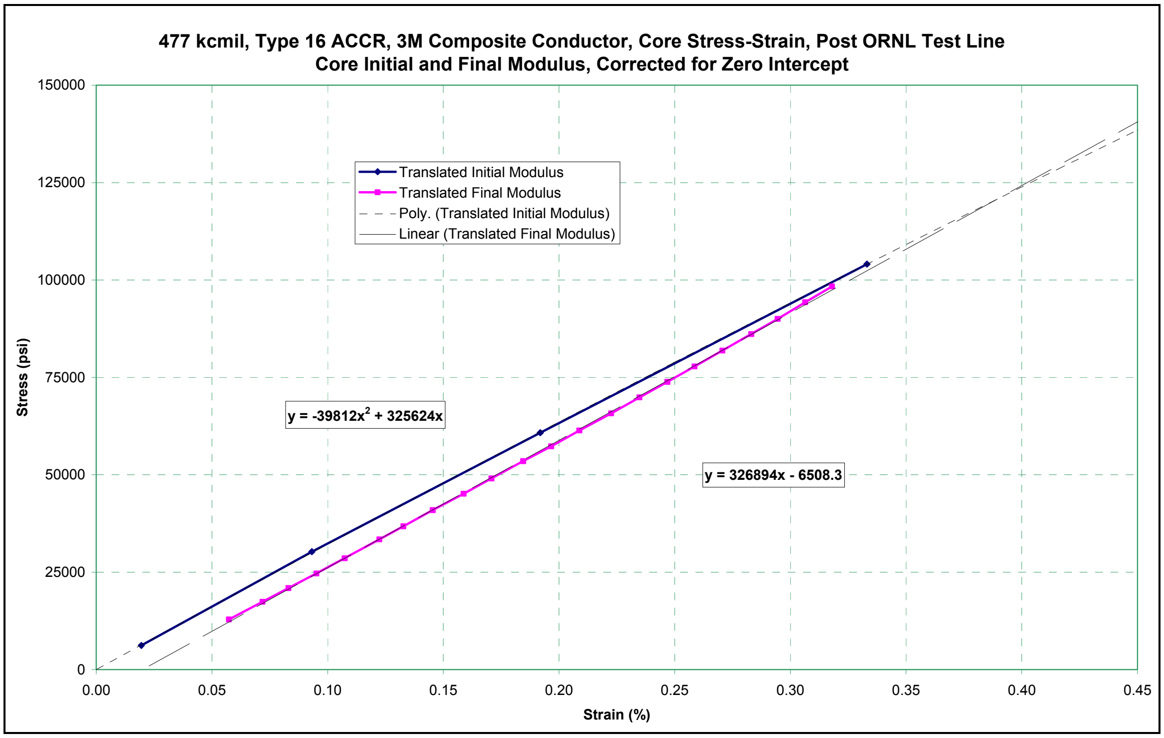


Figure 9, initial and final core modulus, translated to zero along strain axis

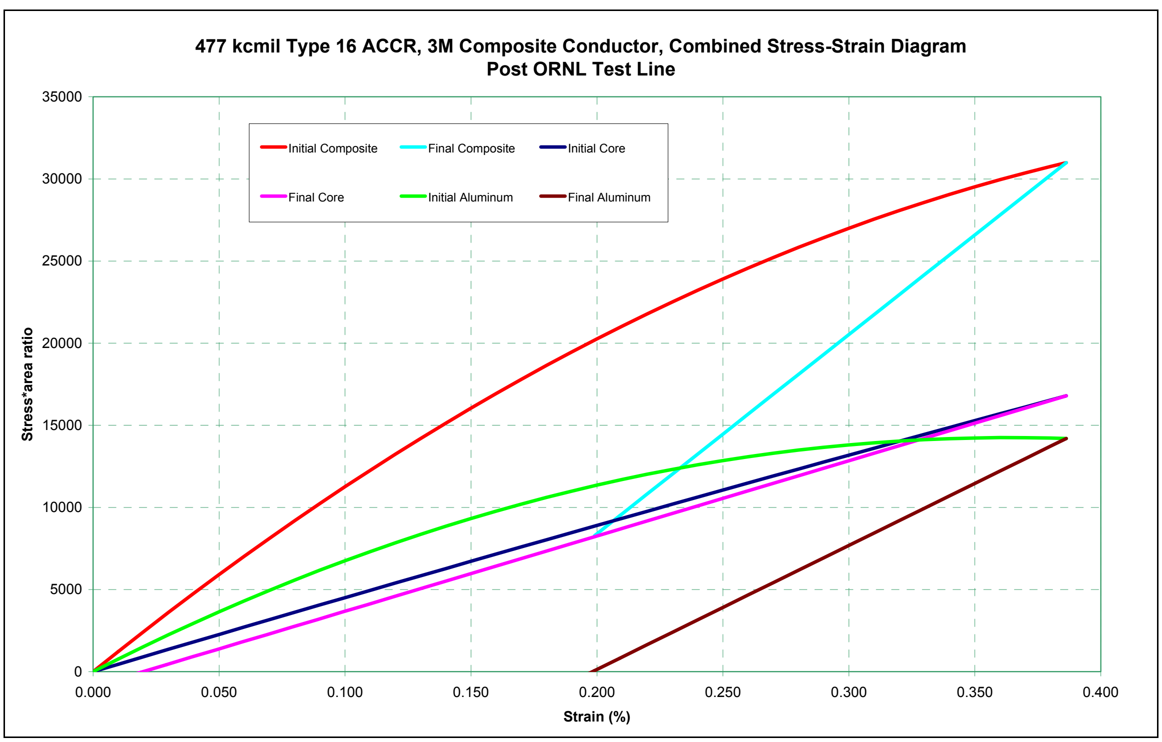


Figure 10, combined stress-strain graph (see following page for equations)

Equations for stress-strain properties (field aged ORNL data are in normal text, as-manufactured equations are shown in *blue italics text*):

Composite conductor properties, direct test values:

Initial Modulus for Stress Strain Curve: Stress (psi) = -113111*(Strain%)^2 + 119418*(Strain%)+2425
Initial Modulus for Stress Strain Curve: Stress (psi) = -68976(Strain%)^2 + 102762*(Strain%)+2288*

Final Modulus for Stress Strain Curve: Stress (psi) = 121300*(Strain%) – 13488
Final Modulus for Stress Strain Curve: Stress (psi) = 121890(Strain%) – 15806*

Composite conductor properties, numerical calculation for zero intercept:

Initial Modulus for Stress Strain Curve: Stress (psi) = -113112*(Strain%)^2 + 123927*(Strain%)

Final Modulus for Stress Strain Curve: Stress (psi) = 121300*(Strain%) – 15866

Core strand properties, direct test values:

Initial Modulus for Stress Strain Curve: Stress (psi) = -39807*(Strain%)^2 + 324072*(Strain%)+6324
Initial Modulus for Stress Strain Curve: Stress (psi) = -87916(Strain%)2 + 349294*(Strain%)+7440*

Final Modulus for Stress Strain Curve: Stress (psi) = 326894*(Strain%) – 144
Final Modulus for Stress Strain Curve: Stress (psi) = 326311(Strain%) + 2020*

Core strand properties, numerical calculation for zero intercept:

Initial Modulus for Stress Strain Curve: Stress (psi) = -39812*(Strain%)^2 + 325624*(Strain%)

Final Modulus for Stress Strain Curve: Stress (psi) = 326894*(Strain%) – 6508

Aluminum Properties:

Initial Modulus for Stress Strain Curve: Stress (psi) = -125058*(Strain%)^2 + 91056*(Strain%)
Initial Modulus for Stress Strain Curve: Stress (psi) = -65890(Strain%)^2 + 65671*(Strain%)*

Final Modulus for Stress Strain Curve: Stress (psi) = 87794*(Strain%) – 17399
Final Modulus for Stress Strain Curve: Stress (psi) = 85890(Strain%) – 117926*