DC Resistance and Resistivity Evaluation for 795 kcmil 3M Brand Composite Conductor

Minnesota Mining and Manufacturing (3M) Company
Purchase Order 0000702316

NEETRAC Project Number: 02-319

January, 2002

A Center of
The Georgia Institute of Technology

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Summary:

3M contracted with NEETRAC for an evaluation of the DC resistance characteristics of 795 ACCR conductor. Conductor resistance, core resistance, and resistivity of MMC core and aluminum strands are measured. Conductor resistance was variable depending on the method used to apply current to the sample. The measurement method is not sensitive test lead resistance or sample connection resistance. Therefore, the only explanation for the variation in sample resistance is resistance of the interface between the MMC core and the aluminum conductor. Interface resistance was found to depend on clamping force, and is eliminated by use of welded equalizers to terminate the conductor sample. Consistent measurements slightly below published values were obtained on samples with welded ends.

The implications of interface resistance on the performance of in-service conductor were evaluated. The conclusion is that the free-span conductor resistance is free of interface resistance effects. It is simply not credible that radial voltage gradients can exist over more than a few inches of conductor length. There is no evidence of interface resistance effects on compression connectors subject to lab tests. If interface resistance is present adjacent to compression connectors, it is not a significant contributor to connector resistance. The phenomenon is significant for laboratory resistance measurements, but has no measurable effect on the resistance of in-service conductor or connectors.

Samples:

1) Twenty (20) feet of 795 kcmil, type 16, 3M Brand ACCR conductor, from reel received on 6/3/2002.

References:

1) "Proprietary Information Agreement …." Dated 3/27/01
2) 3M Purchase Order 0000702316.
3) PRJ 02-319, NEETRAC Project Plan

Equipment Used:

1) AVO (formerly Biddle) digital low resistance Ohmmeter, calibration control # CQ 1083
2) Brooklyn Reference Standard thermometer, Serial # 86-706, calibration control # CN 0155
3) National Instruments/HP 3421 A data acquisition system, calibration control # CQ 0026
4) HP 6177 B DC current supply
5) HP 3468A digital multimeter, calibration control # CQ 0106
6) Starrett digital caliper micrometer, calibration control # CQ 4019

7) Empro Model HA 10100 4-wire resistance standard, serial # 691
8) Tettex conductor resistance bridge

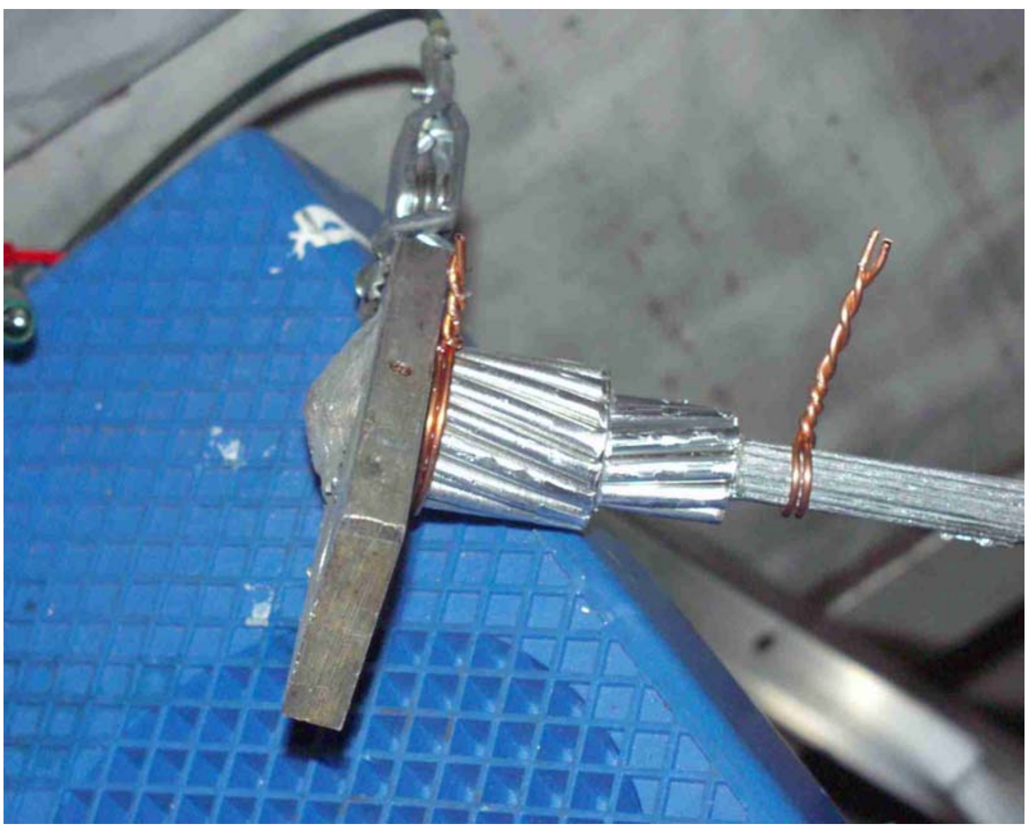
Procedure:

1) Conductor Resistance, welded equalizers:

A 20-ft sample was cut from the reel. Hose clamps were applied to the conductor on both sides of any cut to ensure that the “as-manufactured” lay of all conductor layers is preserved. The goal is to produce laboratory samples that behave similar to conductor in service on long spans.

Aluminum 3/8” plate was cut and drilled to fit over the conductor ends. A puddle weld was used to connect the sample ends to the aluminum plate, and thereby provide an equipotential plane for all conductor strands and layers. Any inter-layer resistance will be short-circuited by the puddle weld. The equalizers were used for the current terminals for 4-wire resistance measurements.

Measuring the voltage drop across a defined length of conductor is critical to reliable resistance measurement. For the voltage terminations, solid copper strands were wrapped around the conductor near the equalizer. The wire was twisted to near the breaking point to ensure secure electrical contact with the conductor. The sample was pulled straight, and a measurement was made of the distance between the voltage electrodes on each end of the sample. This measurement provides the gage length to use in the resistance calculation. Photograph 1 shows the voltage termination for the conductor (left) and the core (right). The photograph was taken after the aluminum strands were cut from the sample to expose the core.



Photograph 1, Equalizer, and voltage lead for conductor and core
(photograph taken after the sample was modified for the core measurement)

Three diverse and independent techniques were employed to make the resistance measurements. All methods used the same sample terminals and a 4-wire measurement technique. Conductor resistance is temperature dependent. Therefore the sample temperature must be known for a valid measurement. Resistance data are typically normalized to a 20^{o} C reference temperature using the temperature coefficient for the conductor material. Because the coefficient for the ACCR conductor is not certain, all readings were taken at 20^{o} C +/- 0.5^{o} C room temperature. A coefficient of 0.0036/^{o} C was used for the small correction from ambient to 20^{o} C. The room is temperature-controlled. Samples were left in the room overnight to ensure thermal equilibrium. Care was taken to ensure that handling or proximity to heat sources (humans) did not significantly warm the samples. The details of each technique are as follows:

1) An AVO digital low resistance ohmmeter was used in 4-wire mode. This unit is new, and certified +/- 0.2% accuracy. Its performance on resistance standards indicates accuracy comfortably exceeds this specification. The unit has selectable ranges and current levels to optimize accuracy. Averaging is employed to improve repeatability, and explains why the AVO unit returns more consistent values on repeated measurements. This unit is considered the most dependable of the systems employed.

2) The NEETRAC connector lab uses a National Instruments interface with HP 3421A data acquisition system for routine connector testing in accordance with ANSI C119.4. This system is capable of making resistance measurements referenced to a built-in resistance standard. The system engages a 10-Amp DC current supply. A current loop is established as follows:

   a. (+) terminal of the power supply
   b. reference resistor
   c. sample
   d. (–) terminal of the power supply

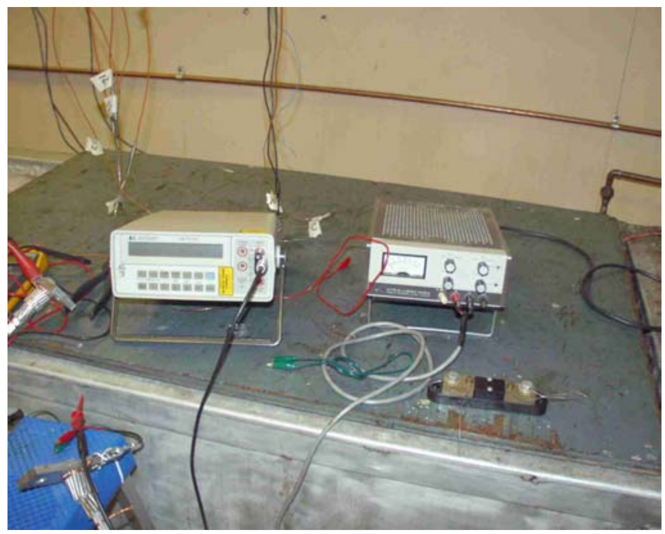
   The data acquisition system reads the voltage drop across the voltage terminals of the 4-wire resistance standard, and the voltage drop across the sample. A ratio calculation is used that directly couples the sample resistance measurement to the resistance standard. Therefore, the system provides dependable data as long at the voltage measurement system is linear. The system used is calibrated on regular intervals, and is proven dependable.

   The connector lab system is designed for connector testing, and has only a single-range and a single current setting (10 Amperes). Therefore, its accuracy is poor with high-resistance samples. This unit was unsuitable for the core strands because of sample heating and the scaling issue.

3) For a “sanity check” on the packaged instrument systems, a modular system was implemented using a DC current source, a high-resolution digital multimeter, and a reference resistor. This technique is robust, because a resistance standard is directly compared to the sample by the same voltage indicator. This method lacked resolution for low-resistance conductor measurements, but was suitable for the strand measurements where low current was necessary to prevent warming.

The reference thermometer used for ambient temperature measurement has an accuracy specification of +/- 0.01^{o} C. The error estimate for the measurement of sample temperature was estimated at +/- 0.5 ^{o} C to account for temperature differences between the sample and ambient due to sample handling and room gradients.

A spreadsheet was developed to analyze resistance results. Data from the three systems are consistent, and well within the error estimates. Low resistance measurement is sensitive and prone to subtle errors. For example, it was found that just touching a sample for a few moments changed the resistance due to warming. Moving the voltage electrode to the equalizer produced changes of several percent, defying the common perception that an equalizer is “equipotential”. Moving the voltage probe from one end of the equalizer to the other produced a change of approximately 1%. When properly implemented, the 4-wire technique prevents errors caused by voltage gradients in the equalizers and voltage drop in the instrument leads. Photograph 2 shows the AVO DLRO, which is state-of-the-art for this type of measurement. Photograph 3 shows the DC power supply, the DMM, and the 4-wire calibration shunt used for the confirmatory measurements.



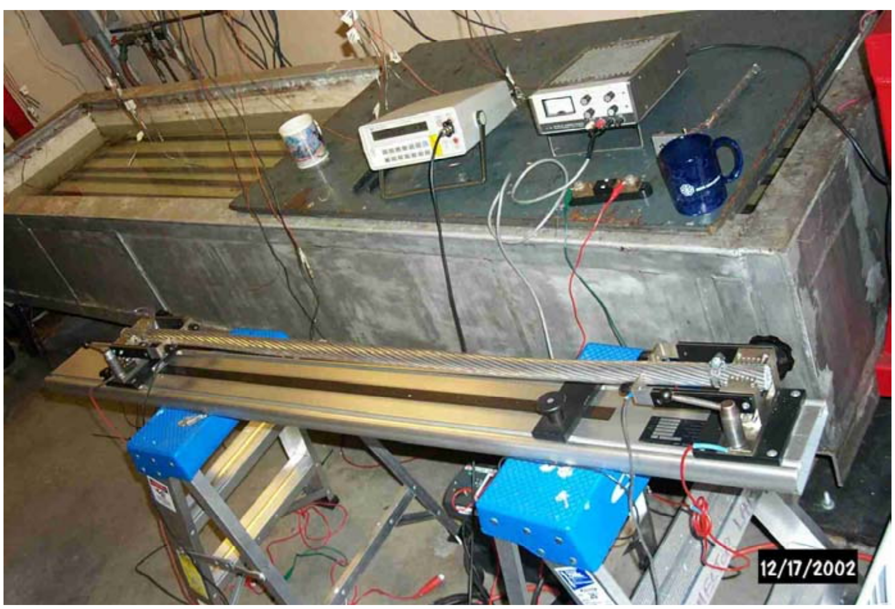
Photographs 2 and 3, AVO and modular test equipment, respectively
(HP 3421A (PC-based) system is not shown)

Table 1 shows results for the composite conductor with welded equalizers: All measurements are below the published nominal values for the 795 ACCR conductor.

Table 1, DC Resistance Data for 795 Composite Conductor 20-ft gage section, welded equalizers			
	AVO DLRO	**HP 3421A**	**DMM/Shunt**
Gage Section	**19 ft – 11 5/8" (19.969 ft)**		
Temperature (° C)	**19.7**	**19.7**	**19.7**
Resistance Readings (Micro-Ohms)	**412.8**	**415.9**	**414.2**
	412.8	**415.5**	**n/a**
	412.8	**415.1**	**n/a**
Average	**412.80**	**415.50**	**n/a**
Ohms/mile	**0.10915**	**0.10986**	**0.10952**
Ohms/mile @ 20° C	**0.10927**	**0.10998**	**0.10964**
3M Nominal	**0.1100**	**0.1100**	**0.1100**
Discrepancy	**-0.75%**	**-0.10%**	**-0.41**
Error Estimates:			
Length (+/- 1/8"):	**0.05%**	**0.05%**	**0.05%**
Resistance:	**0.2%**	**0.5%**	**1%**
Temperature (+/- 0.5° C):	**0.18%**	**0.18%**	**0.18%**
RMS Error:	**0.27%**	**0.52%**	**1.02%**

2) Conductor Resistance, Tettex resistance bridge:

A Tettex resistance bridge is purpose-built for conductor resistance measurements. A V-wedge vice is used for current leads. Knife-edge contacts spaced a precise distance provide the voltage terminals for a 4-wire resistance measurement. The gage section is 3 feet. Photograph 4 shows the 795 ACCR sample in the Tettex bridge. Electronics provided with the system are obsolete, but the unit provides terminals for any 4-wire resistance system. The purpose for this measurement was to assess the effect of welded equalizers on the sample resistance. Note that the location of the voltage probes is more precise than the wrapped wire used on the 20-ft sample. This method suffers from relatively short gage length, but nonetheless is a method commonly used for strand and conductor resistance measurements.



Photograph 4, Tettex Resistance Bridge

Table 2 shows the test data and calculated values for 795 ACCR using the Tettex bridge. Measurements are variable, and in excess of the values using welded equalizers for the current connections. Variable results are caused by variable clamping force for the current terminations. This shows the test method includes measurement of effects in excess of the free-span resistance.

Table 2, DC Resistance Data for 795 Composite Conductor, Tettex Resistance Bridge			
	AVO DLRO	**HP 3421A**	**DMM/Shunt**
Gage Section	**3.000 ft**		
Temperature (^{o} C)	**20.3**	**20.4**	**20.4**
Resistance Readings (Micro-Ohms)	**67.9**	**67.9**	**68.03**
	67.8	**67.3**	**N/a**
	67.8	**67.8**	**N/a**
Average	**67.83**	**67.68**	**N/a**
Ohms/mile	**0.11939**	**0.11911**	**0.11973**
Ohms/mile @ 20^o C	**0.11926**	**0.11894**	**0.11956**
3M Nominal	**0.1100**	**0.1100**	**0.1100**
Discrepancy	**8.56%**	**8.31%**	**8.87%**
Error Estimates:			
Length (+/- 0.001 ft):	**0.03%**	**0.03%**	**0.03%**
Resistance:	**0.2%**	**0.5%**	**1%**
Temperature (+/- 0.5^o C):	**0.18%**	**0.18%**	**0.18%**
RMS Error:	**0.27%**	**0.53%**	**1.02%**

3) Core Resistance, Welded Equalizers:

A tubing cutter was used to cut the aluminum strands from the composite conductor sample. A section of the core was exposed. The wrap tape was removed, and the MMC strands wire brushed to ensure solid electrical contact. A set of voltage electrodes were wrapped around the core and twisted to ensure adequate contact pressure. The welded equalizers remained in place, and were used to attach the current leads. The gage section was slightly shorter than the conductor sample, because the aluminum strands could not be cut close to the equalizers. Table 3 shows the test data.

Table 3, DC Resistance Data for 795 Core, 20 ft gage, welded equalizers			
	AVO DLRO	**HP 3421A**	**DMM/Shunt**
Gage Section	**19.547 ft**		
Temperature (^{o} C)	**20.5**	**20.8**	**20.5**
Resistance Readings (Micro-Ohms)	**6211.0**	**6230.8**	**6204.0**
	6211.0	**6231.8**	**N/a**
	6211.0	**6229.0**	**N/a**
Average	**6211.0**	**6230.52**	**N/a**
Ohms/mile	**1.6777**	**1.6830**	**1.6758**
Error Estimates:			
Length (+/- 1/8 inch):	**0.05%**	**0.05%**	**0.05%**
Resistance:	**0.2%**	**0.3%**	**1%**
Temperature (+/- 0.5^o C):	**0.18%**	**0.18%**	**0.18%**
RMS Error:	**0.27%**	**0.35%**	**1.02%**

4) Volume Resistivity, Aluminum Strands

Three samples of the aluminum strands were cut to fit the Tettex resistance bridge. The aluminum had been through a strander, and needed to be straightened. The samples were straightened to within 1/8 inch of straight by hand working and rolling on a flat surface. Cold work during straightening was minimized, but undoubtedly the sample was strain hardened during the stranding and straightening processes. Resistivity requirements for EC aluminum are intended for material before stranding. The stranding and straightening damage was light, so these measurements should be representative of the pre-stranding material condition.

Each of the three strands was measured for diameter at five (5) locations and two perpendicular directions (10 measurements total). The volume was calculated based on the average diameter and the 3.000 gage section of the Tettex bridge. Table 4 shows the results:

Table 4, DC Resistivity Data for 795 Aluminum Strands, 3 ft gage, Tettex resistance bridge			
Sample 1 Data			
	AVO DLRO	**HP 3421A**	**DMM/Shunt**
Ohms/1000 ft@20° C	**0.56261**	**0.56492**	**0.55827**
Average Diameter (Based on 10 measurements)	**0.1758**		
Area (inches^2)	**0.02427**		
Volume Resistivity @20° C (Ohm-in^2/1000 Ft)	**0.01365**	**0.01371**	**0.01355**
%IACS	**59.65%**	**59.40%**	**60.11%**
Sample 2 Data			
Ohms/1000 ft@20° C	**0.56284**	**0.56493**	**0.57248**
Average Diameter (Based on 10 measurements)	**0.1755**		
Area (inches^2)	**0.02419**		
Volume Resistivity @20° C (Ohm-in^2/1000 Ft)	**0.01362**	**0.01367**	**0.01385**
%IACS	**59.82%**	**59.60%**	**58.81%**
Sample 3 Data			
Ohms/1000 ft@20° C	**0.56331**	**0.56315**	**0.55973**
Average Diameter (Based on 10 measurements)	**0.1749**		
Area (inches^2)	**0.02403**		
Volume Resistivity @20° C (Ohm-in^2/1000 Ft)	**0.01354**	**0.01353**	**0.01345**
%IACS	**60.17**	**60.19%**	**60.55%**
Error Estimates:			
Length (+/- 1/8 inch):	**0.03%**	**0.05%**	**0.05%**
Resistance:	**0.2%**	**0.3%**	**1%**
Temperature (+/- 0.5° C):	**0.18%**	**0.18%**	**0.18%**
Area	**0.38%**	**0.38%**	**0.38%**
RMS Error:	**0.47%**	**0.47%**	**1.09%**

5) Volume Resistivity, MMC Core Strands

Three samples of the core strands were tested in a manner similar to the method used for the aluminum strand samples. One difference is that raw resistance values are reported, rather then values normalized to 20° C. The lab temperature was maintained close to 20° C, so errors due to this difference are small. The second difference is that the HP 3421A (connector lab) system was not used because its current level (10 Amps) and measurement range (conductors) are unsuitable for measuring the resistance of the core strands. The AVO unit has selectable current (10 Amperes for conductor and aluminum strands, and 1 Ampere for the small core strands). The DC current supply used with the DMM was set at 0.5 Amperes for all tests. Table 5 shows the results:

Table 5, DC Resistivity Data for MMC Core Strands, 3 ft gage, Tettex resistance bridge

Sample 1 Data			
	AVO DLRO	**HP 3421A**	**DMM/Shunt**
Ohms/1000 ft@20.2° C	**6.0079**	**n/a**	**6.01533**
Average Diameter (Based on 10 measurements)	**0.08301**		
Area (inches^2)	**0.00541**		
Volume Resistivity @20.2° C (Ohm-in^2/1000 Ft)	**0.03251**	**n/a**	**0.03255**
%IACS	**25.05%**	**n/a**	**25.02%**
Sample 2 Data			
Ohms/1000 ft@20.3° C	**6.19456**	**n/a**	**6.20200**
Average Diameter (Based on 10 measurements)	**0.08253**		
Area (inches^2)	**0.00535**		
Volume Resistivity @20.3° C (Ohm-in^2/1000 Ft)	**0.03314**	**n/a**	**0.03318**
%IACS	**24.58%**	**n/a**	**24.55%**
Sample 3 Data			
Ohms/1000 ft@20.3° C	**6.03700**	**n/a**	**6.03253**
Average Diameter (Based on 10 measurements)	**0.08316**		
Area (inches^2)	**0.00543**		
Volume Resistivity @20.3° C (Ohm-in^2/1000 Ft)	**0.03279**	**n/a**	**0.03277**
%IACS	**24.84%**	**n/a**	**24.86%**
Error Estimates:			
Length (+/- 1/8 inch):	**0.03%**	**n/a**	**0.05%**
Resistance:	**0.2%**	**n/a**	**0.2%**
Temperature (+/- 0.5° C):	**0.18%**	**n/a**	**0.18%**
Area (based on 0.0005 in diameter error)	**0.38%**	**n/a**	**0.38%**
RMS Error:	**0.47%**	**n/a**	**0.47%**

6) Surface to core interface resistance:

A 6-inch sample was cut from the reel. Hose clamps were used to secure a composite conductor section nominally 2 inches long. The aluminum strands outboard of the 2-inch test section were removed, exposing the core. The exact measurement of the conductor test section after cutting was 2.015 inches. The wrapping tape was removed from the exposed core section, taking care not to pull any tape from the interface between the core and the aluminum strands.

Twisted copper voltage leads were applied in the same manner as shown in photograph 1. One voltage electrode was located on the core, within the thickness of a sheet of paper from contact with the aluminum strands. The second voltage electrode was fitted to the conductor OD, as close to the exposed core section as practical. Current electrodes were established by clamping the core section in the Tettex current vice, and by a spring-loaded clamp on the conductor OD, at the opposite end. The arrangement provided for a 2-inch long interface between the MMC core and the aluminum OD. The separation between the voltage electrodes on the conductor long axis was approximately 1/8 inch. The current path is from the core strands (clamped in the Tettex vice, but not welded), through the tape interface, and then through two aluminum layers. The measured voltage drop therefore represents the resistance of 2.015 inches of interface between the conductor surface and the core surface. This measurement was made at a lab ambient temperature of 20.7^{o} C. Readings on the DLRO were stable at 72.7 +/- 0.1 micro-Ohm. This is approximately equal to the resistance of 3 ½ feet of 795 ACCR conductor.

Conclusions:

Measured resistance of 795 ACCR samples is slightly below the published value of 0.1100 Ohms/mile. Core resistance is 1.69 Ohms/mile. Volume resistivity of the conductor materials measures 59 – 61% IACS for the Al-Zr strands, and 24.5 – 25% IACS for the composite core strands. These values conform to the 3M material specifications

Careful measurements were made to resolve concerns related to resistance readings taken on ACCR conductor samples. Interface resistance between the aluminum layers and the core were one theory. The data collected show 10% higher unit resistance for a sample with equalizers clamped on the OD, versus a sample with equalizers puddle welded to the ends. The puddle weld ensures that all strands are at the same voltage at the equalizer. With the equalizer bolted to the conductor OD, there are apparently radial voltage gradients that increase the sample resistance measurement. Direct measurement of the interface resistance produces a resistance approximately equal to the resistance of 3 ½ feet of 795 ACCR conductor. Curiously, the unit resistance measured on the clamped 3-ft conductor sample is only 10% higher than the unit resistance measured on the 20-ft sample with welded equalizers. Therefore, the interface resistance was likely much lower for the conductor resistance test than for the direct measurement of interface resistance. A relationship between contact pressure and resistance is well established, and probably accounts for the discrepancy.

Interface resistance is likely associated only with the connector, and therefore will not significantly influence the resistance (or temperature) of the free span conductor. Past testing on ACCR connectors demonstrated that connector temperature is lower than conductor temperature. Connector resistance is lower than the same length of free conductor. This suggests that interface resistance is not a significant factor in connector performance. Interface resistance is an issue for resistance measurements, where short conductor lengths have total resistance of similar magnitude to the interface resistance. Welded equalizers are needed to obtain readings representative of the free span resistance. This procedure best represents free-span resistance characteristics, and has been adopted for measurements on ACCR conductors.