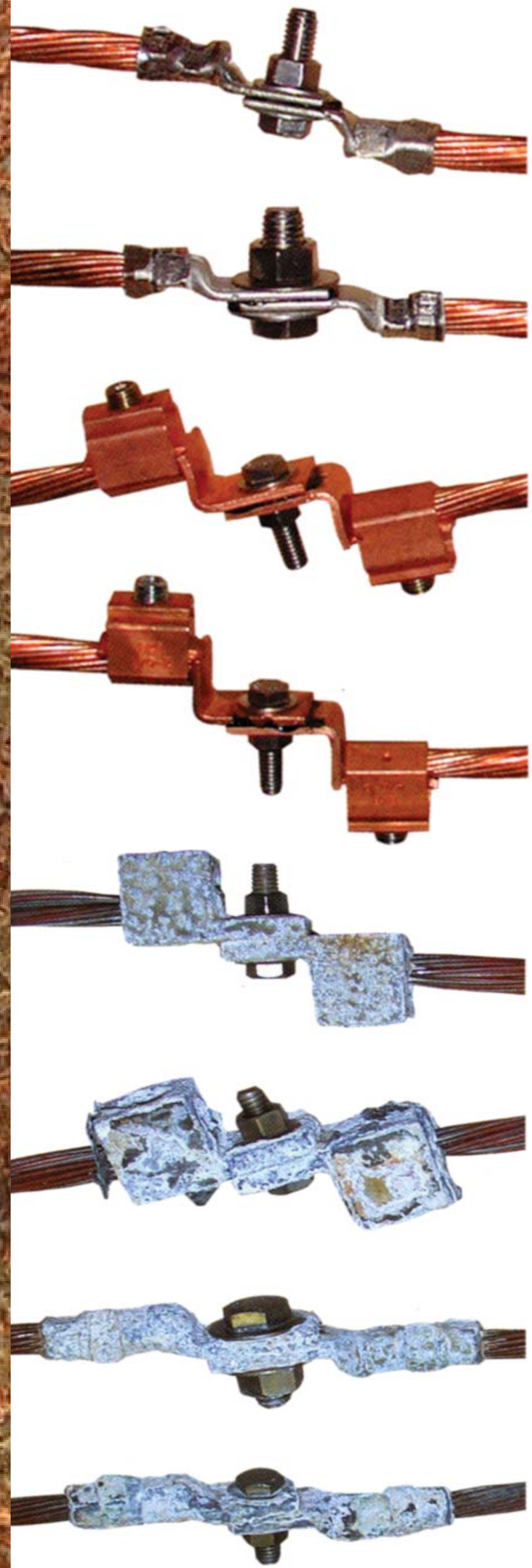
Corrosion and Current Burst Testing of Copper and Aluminum Power Connectors for Use with Copper and Aluminum Conductor



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POWERTECH LABS INC.

Final Report

CORROSION AND CURRENT BURST TESTING OF COPPER AND ALUMINUM ELECTRICAL POWER CONNECTORS FOR USE WITH COPPER AND ALUMINUM CONDUCTOR

PROJECT 13598-23-00
REPORT 13598-03-REP1

Prepared for:
Canadian Copper and Brass Development Association

Abstract:
Crimped and mechanically bolted aluminum and copper connectors are commonly used for terminating electrical power cables. In this study, copper-to-copper, aluminum-to-copper, and aluminum-to-aluminum connections were subjected to accelerated aging which consisted of 2000 hours of corrosive environmental exposure and electrical current burst testing. The all-copper connectors had the best performance in this test.

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1. INTRODUCTION

This work was conducted at the request of the Canadian Copper and Brass Development Association (CCBDA) in Toronto, Ontario. For industrial and commercial applications, crimped and mechanically bolted aluminum and copper connectors are commonly used for terminating power cables. This study compares the performance of aluminum and copper connectors under accelerated aging conditions.

2. BACKGROUND

Copper connectors are available for use with copper conductor, and aluminum connectors are available for use with copper and aluminum conductor. Test standards for power connectors include the CSA C57 or ANSI C119.4 500 cycle current cycling test, which is intended to establish long term performance. There are significant differences in the material and electrical properties of aluminum and copper and their oxides which may affect their long term performance.

Aluminum oxidizes readily when exposed to air, and a strongly attached, hard outer layer of electrically insulating oxide quickly forms around the metal. For this reason, aluminum connectors are often manufactured with an outer tin coating which is intended to prevent surface oxidation of the connector from occurring. Aluminum crimp connectors are also pre-filled with oxide inhibiting compound to reduce oxidation between the conductor and connector when in service. Aluminum conductors must always be wire brushed to remove the oxide layer, and oxide inhibiting compound is immediately applied to reduce oxidation.

Copper also oxidizes when exposed to air, but the oxide which forms is relatively soft and conductive, although not as conductive as the base metal. For this reason, copper connectors can often be installed without oxide inhibitor. Wire brushing of the conductor, although recommended, is not as critical as with aluminum. Copper connectors are often manufactured with a tin coating to reduce surface oxidation and discolouration, but they are also available without tin coating.

When copper and aluminum are brought into direct contact in the presence of moisture, a strong galvanic reaction takes place due to the dissimilar properties of the metals. For this reason, aluminum connectors cannot be used with copper conductor unless an interface material which is more compatible with both copper and aluminum is present, such as tin. However, tin is also susceptible to oxidation, and if the tin layer is compromised then galvanic corrosion between the base metals can still occur.

The differences in properties of copper and aluminum may result in a significant performance difference in the various types of electrical connectors when in long term service.

3. OBJECTIVES

The objective of this project was to compare the contact resistance at the junction between the connector and conductor under equivalent severe environmental conditions for the following three configurations:

- copper connectors on copper conductor,
- aluminum connectors on copper conductor, and
- aluminum connectors on aluminum conductor.

The connectors, conductor, and oxide inhibitor used to make the samples were standard commercially available varieties obtained from several different manufacturers.

4. TEST SAMPLES

The test samples used in the study were combinations of copper and aluminum conductors and connectors, with all components being standard off-the-shelf varieties. Copper conductor was bare 19-strand 2/0 AWG, and aluminum conductor was Alcan NUAL 18-strand compact 4/0 AWG. Conductor sizes were selected to be approximately the same ampacity. Connectors were a combination of compression and mechanical bolted type 1-hole lug connectors. All aluminum compression connectors were tin plated and supplied pre-filled with oxide inhibitor. A complete list of the test samples is provided in Table 1, and a photograph of the samples before installation is shown in Figure 1.

4.1 CONNECTOR INSTALLATION PROCEDURES

Connectors were installed according to the manufacturer's recommendations, and using the following procedures:

- All conductors were wire brushed immediately before installing the connectors, as shown in Figure 2.
- Thomas & Betts Contax® CTB8 Oxide inhibitor was applied to the aluminum conductor for installation of mechanical connectors.
- No oxide inhibitor was applied to any of the copper-to-copper connections.
- Compression connectors were crimped using a Thomas & Betts (Blackburn) model TBM5 crimping tool, as shown in Figure 3.
- Mechanical connectors were installed using torque levels as shown in Table 2.

Table 1. Connector samples used for the testing.

Sample No.	Connector Material	Conductor Material	Connector				
			Type	**Manufacturer**	**Size**	**Plating**	**Model**
A1/A2	Aluminum	Aluminum	Mechanical	Thomas & Betts	#6-250	Tin	ADR 25
A3/A4	Aluminum	Aluminum	Compression	Thomas & Betts	4/0	Tin	ATL40-12
A5/A6	Aluminum	Aluminum	Compression	Homac	4/0	Tin	5A-3/0-48
A7/A8	Aluminum	Aluminum	Mechanical	Ilsco	#6-250	Tin	TA 350
A9/A10	Aluminum	Aluminum	Compression	Burndy	4/0	Tin	YA28A3
B1/B2	Aluminum	Copper	Compression	Burndy	2/0	Tin	YA26AL
B3/B4	Aluminum	Copper	Compression	Ilsco	2/0	Tin	IACL-2/0
B5/B6	Aluminum	Copper	Compression	Thomas & Betts	2/0	Tin	ATL20-12
B7/B8	Aluminum	Copper	Mechanical	Ilsco	#6-250	Tin	TA 350
B9/B10	Aluminum	Copper	Mechanical	Thomas & Betts	#6-250	Tin	ADR 25
C1/C2	Copper	Copper	Compression	Burndy	2/0	Tin	YA1-26T38
C3/C4	Copper	Copper	Compression	Ilsco	2/0	Tin	CRA 2/0
C5/C6	Copper	Copper	Compression	Thomas & Betts	2/0	Tin	CTL-20-12
C7/C8	Copper	Copper	Mechanical	Ilsco	#6-250	None	SLU 300
C9/C10	Copper	Copper	Mechanical	Thomas & Betts	#2-4/0	None	BTC 4102

Figure 1. Connector samples used for corrosion and current burst testing.

Figure 2. Wire brushing conductor samples during installation.

Figure 3. Crimping connector samples.

Table 2. Mechanical connector torque levels for installation (Ref 1).

Conductor Size	Screw Size	Torque	
		in.lb	N.m
2/0	7/16”	120	13.6
2/0-4/0	11/16”	275	31.1
2/0-4/0	3/4”	375	42.4

4.2 CONNECTOR SAMPLE ASSEMBLIES

Each connector sample was installed on approximately 0.5 m of conductor, with a current equalizer on the end of the conductor opposite each connector. Welded aluminum equalizers were used on the aluminum conductor, and brazed copper equalizers were used on the copper conductor. Three groups of 10 samples each were connected together back-to-back to form three series circuits, which were labeled as sample sets ‘A’ (all aluminum), ‘B’ (copper conductor with aluminum connectors), and ‘C’ (all copper). A photograph of a complete connector assembly, with 10 connectors and equalizers, is shown in Figure 4.

In addition, control conductors were subjected to the corrosion and current burst testing along with the connector and conductor samples, which consisted of 1 m lengths of copper and aluminum bare conductor with no connector attached.

Figure 4. Connector sample assembly with equalizers and conductor (copper conductor/aluminum connector samples shown).

5. TEST PROCEDURES

The testing consisted of periods of corrosive environmental exposure, followed by application of high current. This was intended to produce conditions in which connectors that are susceptible to corrosion show an increase in contact resistance as the testing progresses.

The cyclic testing was conducted in the following sequence:

- Salt fog corrosion cycling was carried out for 500 hour blocks of time.
- Current burst tests were carried out following each 500 hour salt fog period.
- DC resistance readings of each connector were made approximately every 170 hours during the corrosion testing, and before and after each set of current burst tests.
- A total of four sets of salt fog and current burst tests were conducted, for a total of approximately 2000 hours of salt fog testing.

5.1 CORROSION CYCLING

Connector sample groups were arranged on a three tier PVC rack in an environmental chamber with the conductors and connectors oriented horizontally, and the connectors suspended in clear air. The positions of the connector sets were exchanged periodically so that more consistent environmental exposure from sample to sample was achieved over the testing period. The samples installed in the weathering chamber are shown in Figure 5.

Figure 5. Connector samples set up in the weathering chamber.

Each 4 hour corrosion testing cycle consisted of the following steps:
1. Salt fog spray for a period of 1 hour 45 minutes, consisting of a fine mist of aerated 3% NaCl solution buffered to a pH of 5.5 using nitric acid.
2. Dry heat for a period of 2 hours, reaching a maximum of 70°C during the 2 hour period.
3. Clear water rinse for a period of 15 minutes.

The cycle was repeated continuously during the corrosion testing.

5.2 CURRENT BURST TESTING

The reason for conducting current burst testing was to encourage accelerated degradation at the connector contact with the conductor. For the test, current levels of 1750 A_{rms} for 4/0 aluminum conductor, and 1800 A_{rms} for 2/0 copper conductor were determined to be sufficient to produce the desired effect. For each test, the current was held at these levels long enough to raise the temperature of the control conductor to 250°C, as determined by thermocouple measurement at the center of the control conductor span. Typically, this required an application of current for approximately 50 seconds, starting with a conductor at near room temperature. The calculation to determine these levels is described in detail in the Appendix.

Samples were subjected to current burst testing as follows:
- Each set of 10 connectors, which were joined together in series, were subjected to current burst testing simultaneously.
- The control conductor was placed in series with the connector assembly. A thermocouple was attached to the center of the length of each control conductor to measure the conductor temperature during current burst testing.
- Five short duration bursts of high current were applied in succession. The control sample was allowed to cool to 40°C or less between each current burst.

The contact resistance of each connector was measured at room temperature using a micro-ohmmeter before and after each set of five current burst tests.

5.3 DC RESISTANCE MEASUREMENTS

All contact resistances were measured on dry samples at room temperature (20°C) using a LEM model D3700 micro-ohmmeter. Since resistances were all measured at the same temperature level, no correction was applied.

Resistances were measured from the equalizer to the body of the connector, so that an average reading was obtained for each connector. Four point resistance measurements were made to eliminate lead resistance errors, and measurements were made at a current level of 10 A DC.

6. RESULTS

6.1 ALUMINUM-TO-ALUMINUM CONNECTIONS (SAMPLE SET A)

Photographs of the connector samples before the test, after approximately 1000 hours of corrosion, and after approximately 2000 hours of corrosion testing are shown in Figures 6 through 8.

At the last set of current burst tests (2000 hours), a problem with the welded aluminum equalizers became apparent when one of the equalizers, on sample no. A7, was damaged by excessive heating during the first current shot. It appeared that some of the welded aluminum equalizers were being excessively degraded by the corrosive environmental exposure. At this point an additional test became necessary to confirm which equalizers were suspect for the remaining samples. An additional measurement of the current distribution in the conductor strands was made by measuring the voltage drop over a fixed distance on each of the 11 outer strands with a fixed DC current of 10 A applied to the entire conductor from equalizer to connector. The equalizer/connector groups which had a small variability between the voltage readings are assumed to have had an evenly distributed current, which indicates that the equalizer and connector were still making a consistent connection. The equalizer/connector groups which had a large variability had either a poor equalizer or a poor connector connection, or both. A graph of the measured voltage values, which have been normalized to the average reading for each connector, is shown in Figure 9. It can be seen from the results that samples A1, A3, A7, A8, and A10 had a poor current distribution, and are suspect. For these samples, the old equalizer was cut off, the conductor was thoroughly cleaned and wire brushed, and a new equalized connection was made using a new aluminum compression connector as shown in Figure 10. The equalizer-to-connector resistances were then re-measured for these samples, and a small correction resistance was added to compensate for the amount of conductor which was cut off. The new values were used as the final resistance readings, with the additional error introduced by the modification of the equalizers taken into account when assessing the connectors.

A graph with the original, uncorrected measured resistances of the aluminum connectors throughout the tests are shown in Figure 11. A graph with the corrected measured resistances of the aluminum connectors with re-made equalizers are shown in Figure 12. For the connectors with re-made equalizers, since the only valid readings were made at the beginning and end of the test, all other readings are omitted.

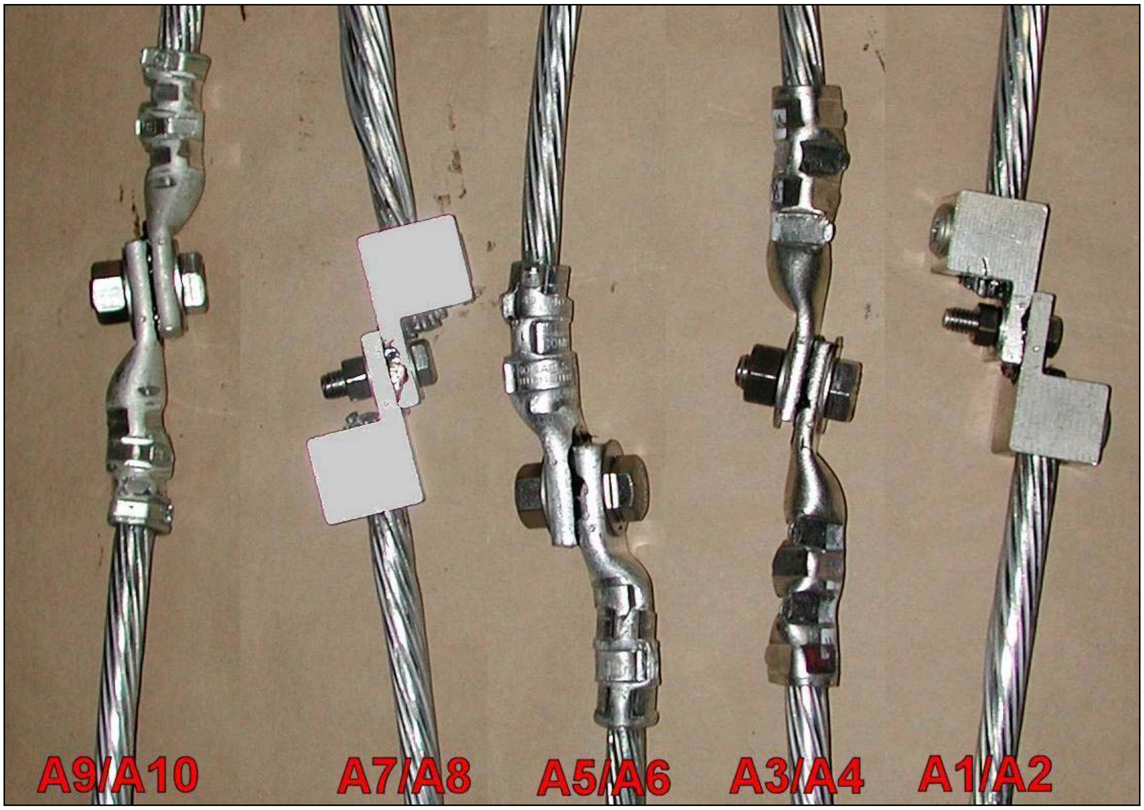

Figure 6. Aluminum-to-aluminum samples before testing.

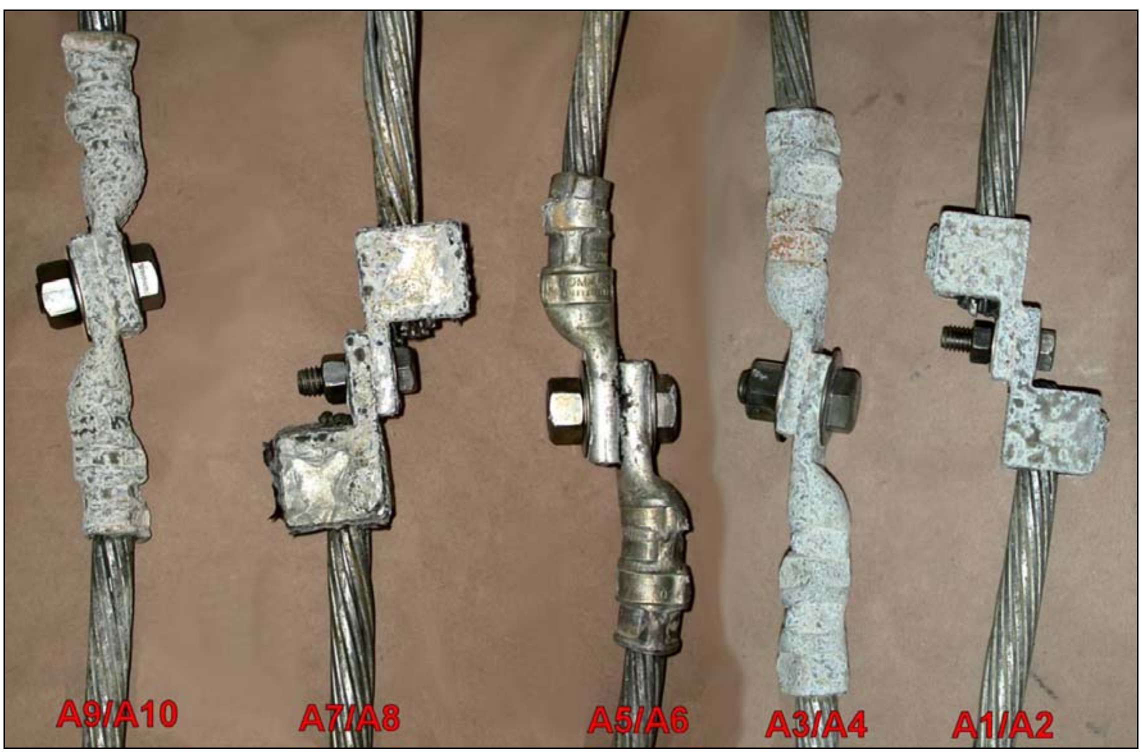

Figure 7. Aluminum-to-aluminum samples after 1000 hours of testing.

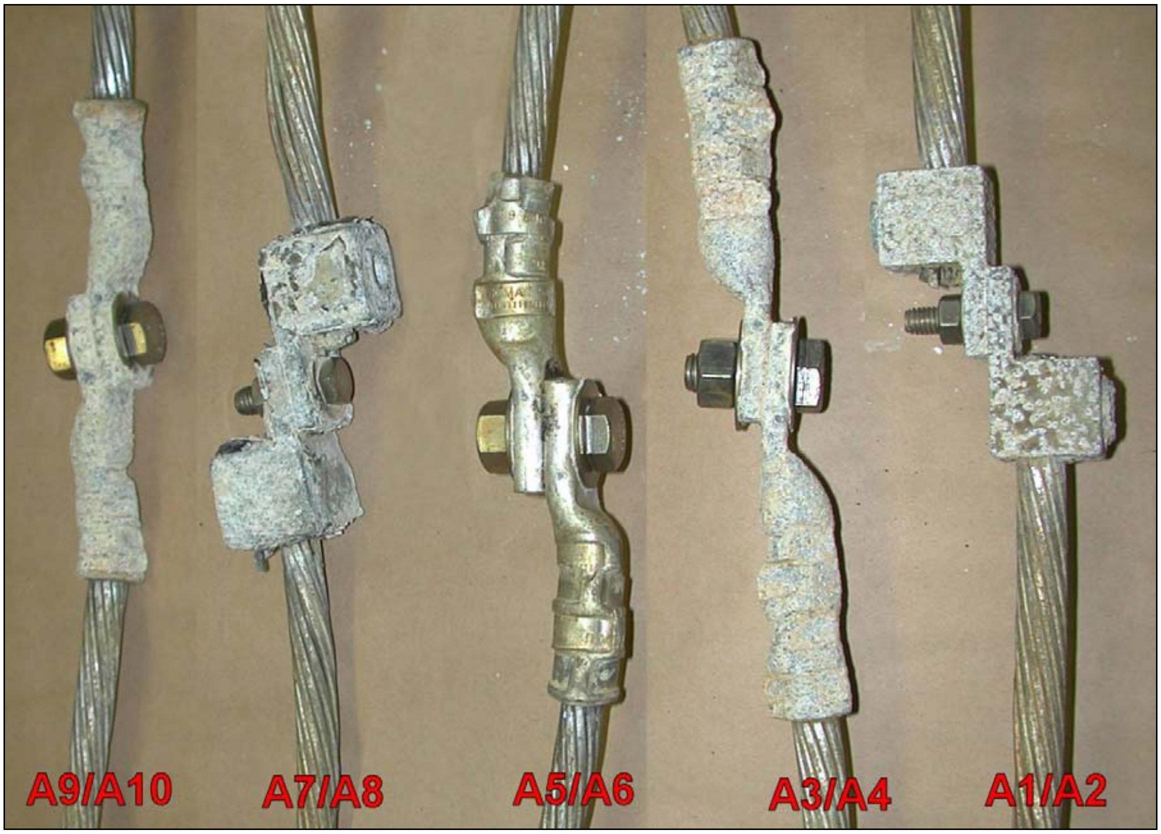

Figure 8. Aluminum-to-aluminum samples after 2000 hours of testing.

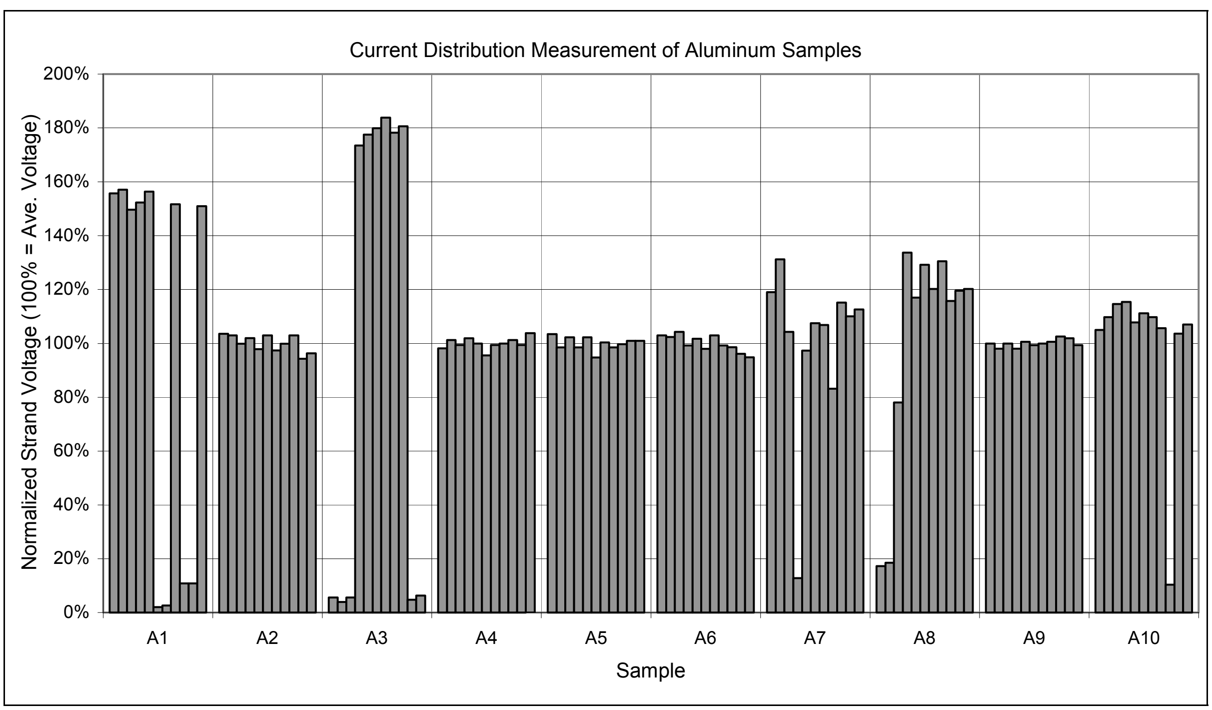

Figure 9. Current distribution measurement for the all-aluminum samples, normalized to the average voltage for each connector.

Figure 10. Typical remade equalizer using a new compression connector.

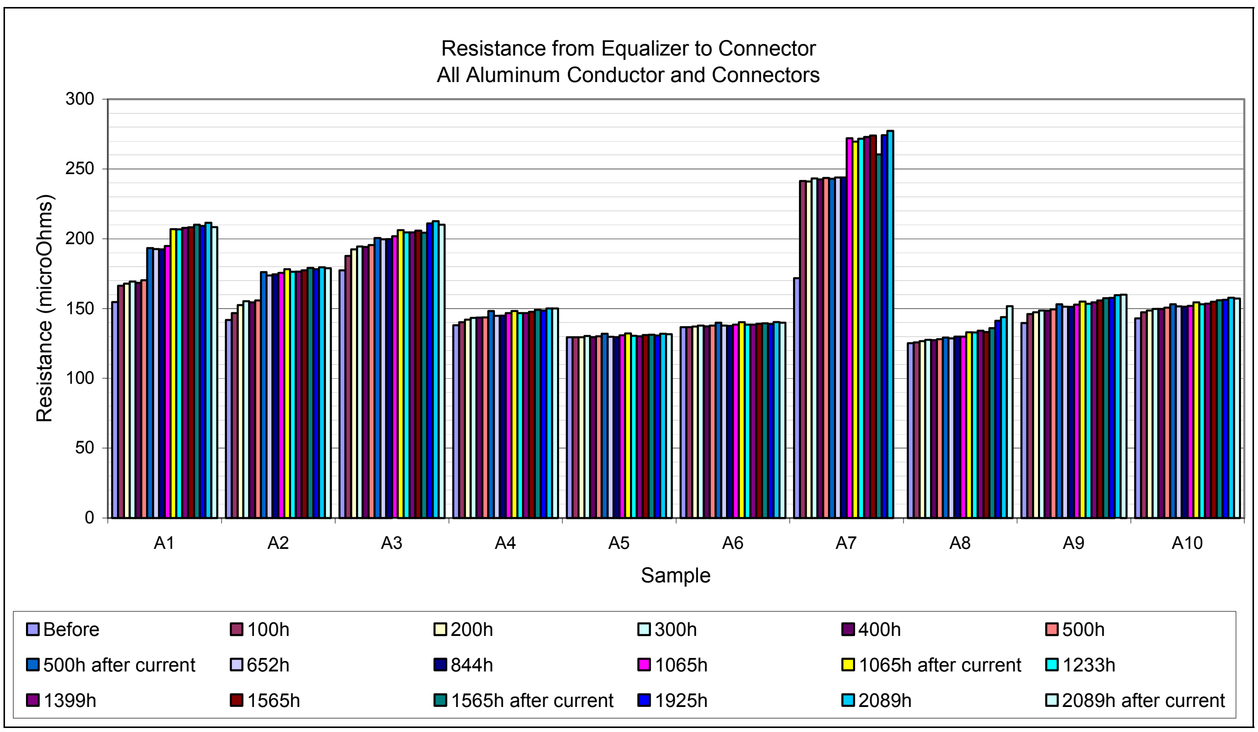

Figure 11. Original uncorrected resistance measurements for the aluminum samples throughout the test.

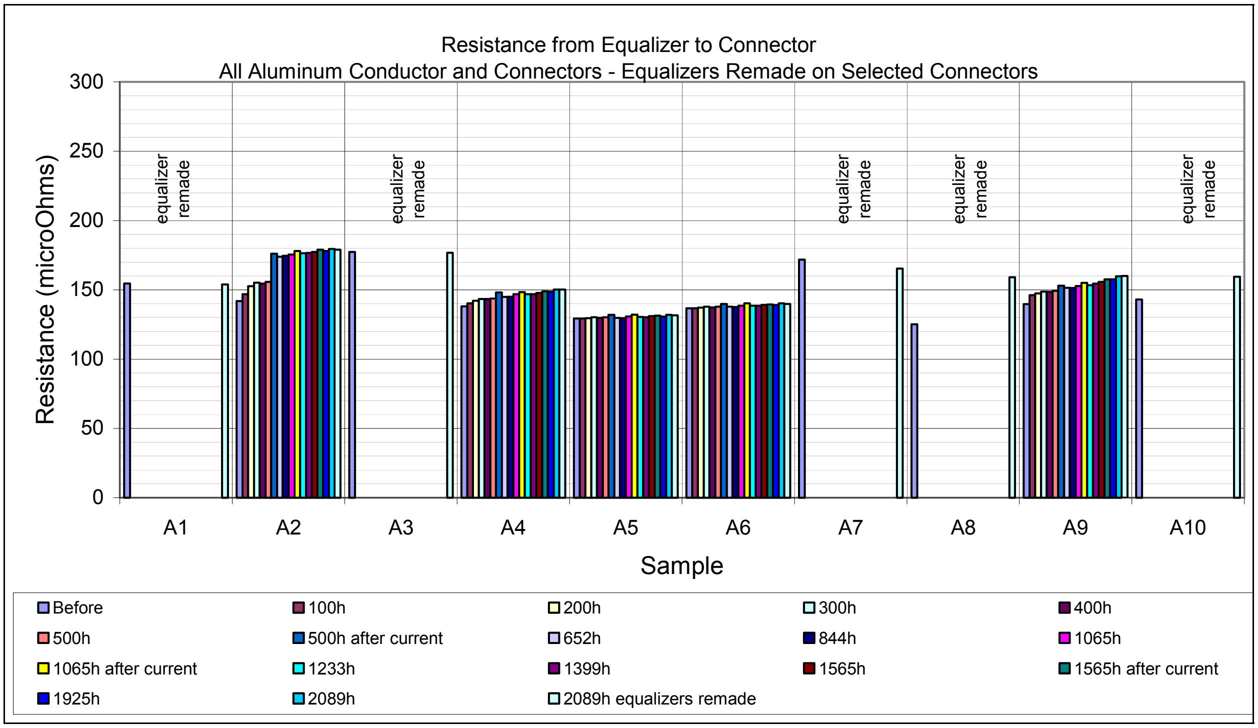

Figure 12. Resistance readings for aluminum samples, equalizers remade on A1, A3, A7, A8, and A10.

6.2 ALUMINUM-TO-COPPER CONNECTIONS (SAMPLE SET B)

Photographs of the connector samples before the test, after 1000 hours of corrosion, and after 2000 hours of corrosion testing are shown in Figures 13 through 15. A graph with the measured resistances of the aluminum connectors on copper conductors is shown in Figure 16.

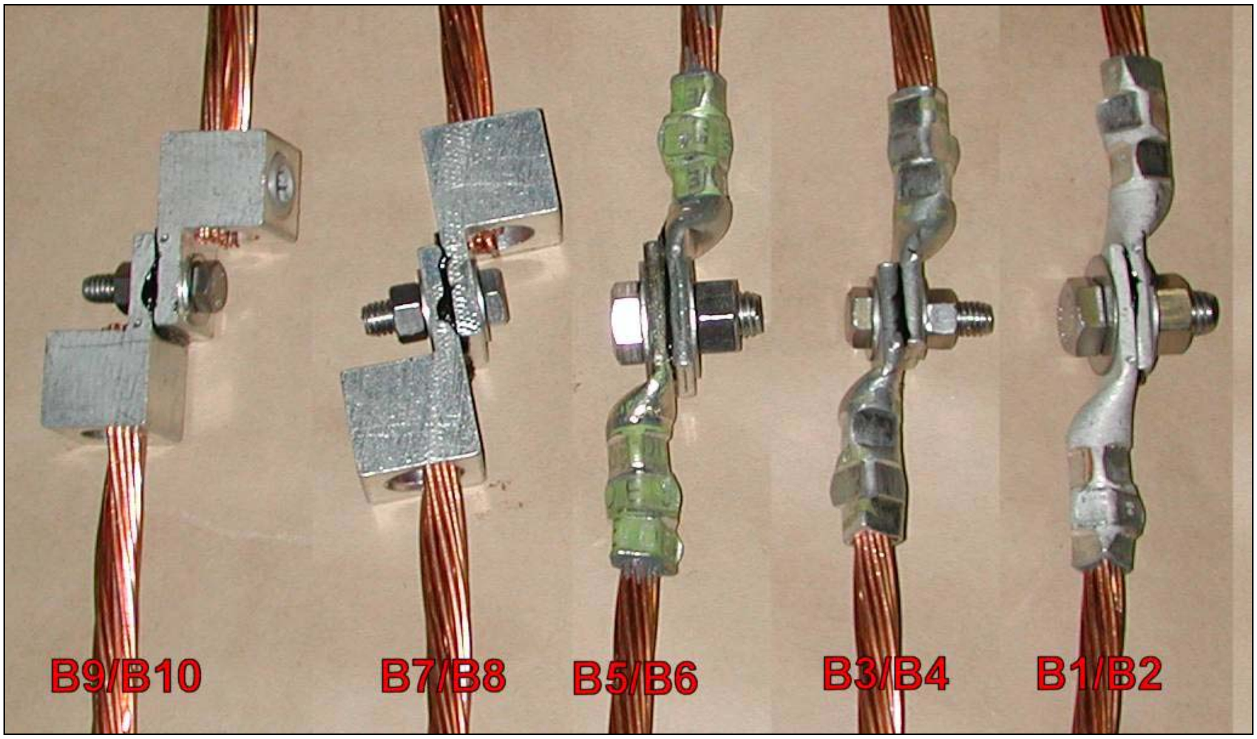

Figure 13. Aluminum-to-copper samples before testing.

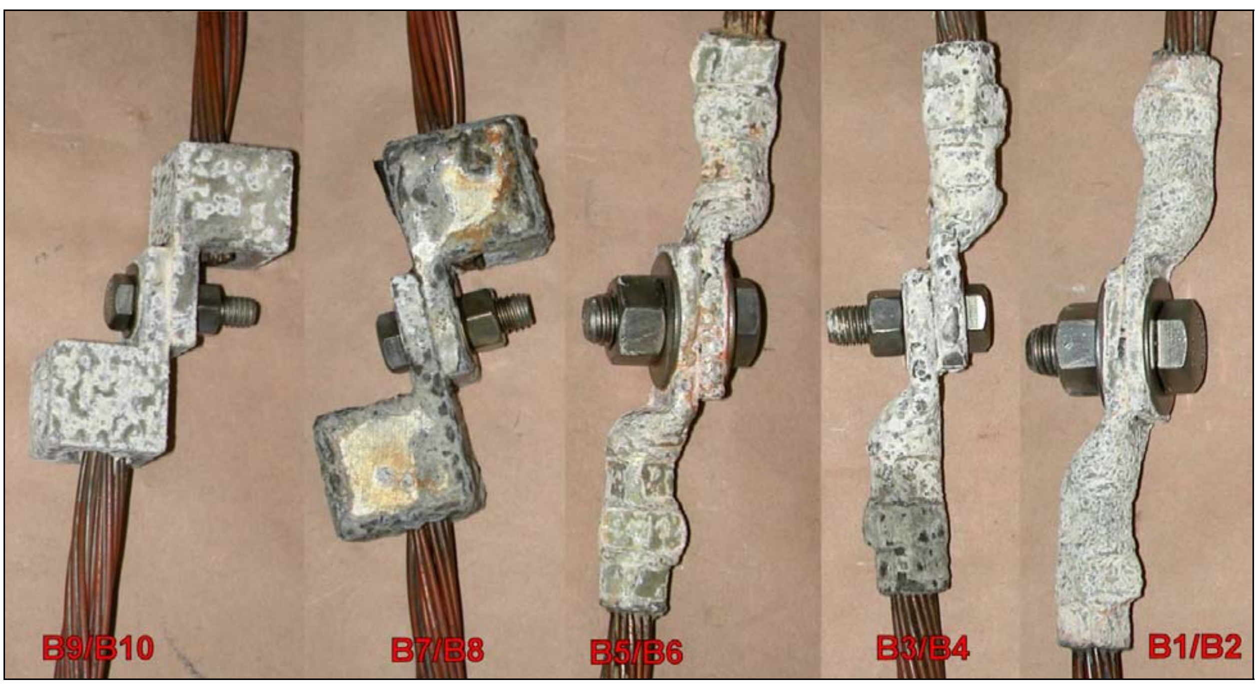

Figure 14. Aluminum-to-copper samples after 1000 hours of testing.

Figure 15. Aluminum-to-copper samples after 2000 hours of testing.

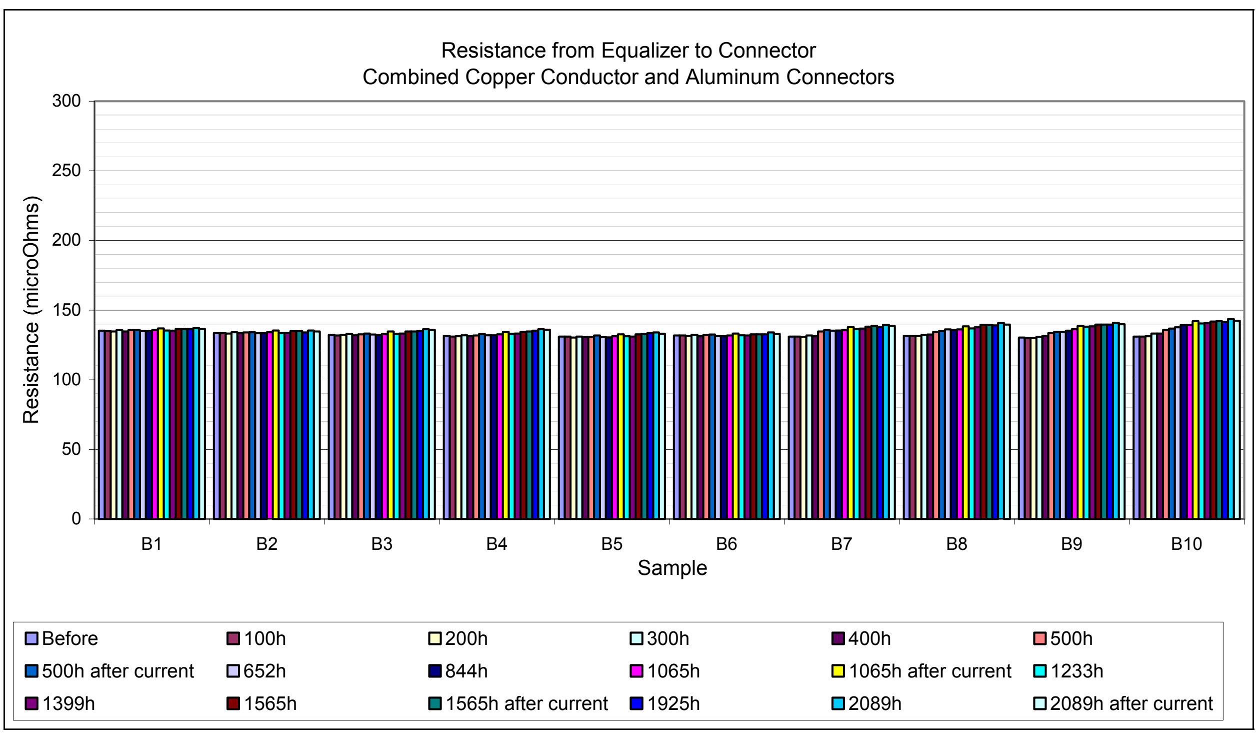

Figure 16. Resistance measurements for the aluminum-to-copper samples throughout the test.

6.3 COPPER-TO-COPPER CONNECTIONS (SAMPLE SET C)

Photographs of the connector samples before the test, after 1000 hours of corrosion, and after 2000 hours of corrosion testing are shown in Figures 17 through 19. A graph with the measured resistances of the all copper connectors is shown in Figure 20.

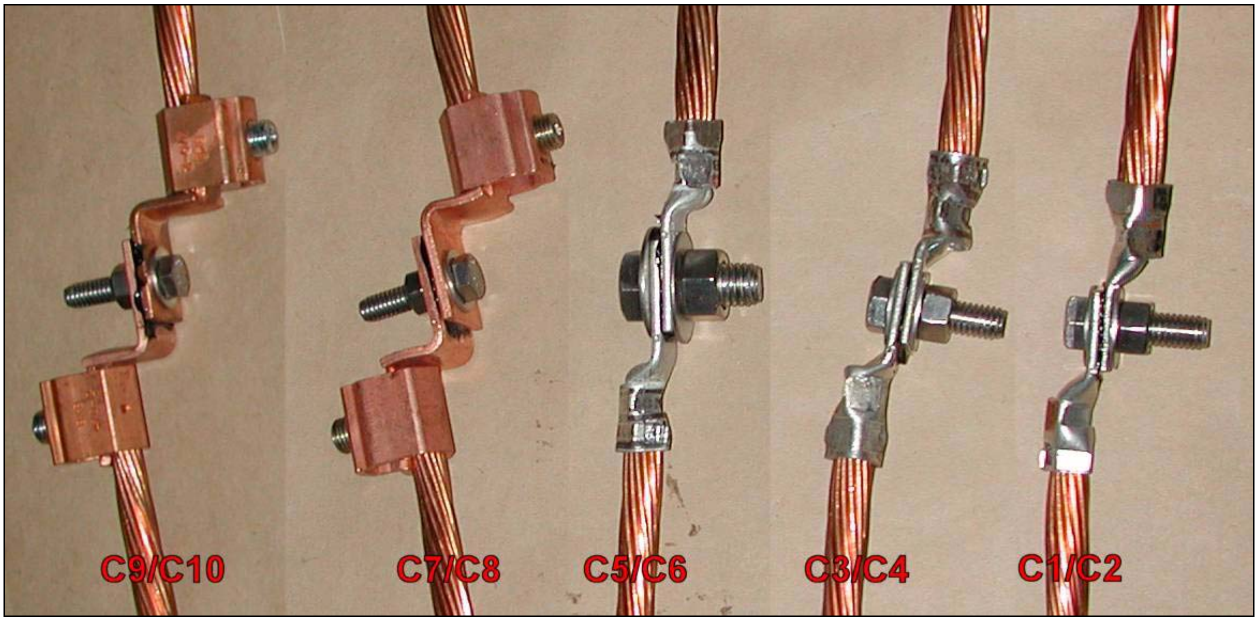

Figure 17. Copper samples before testing.

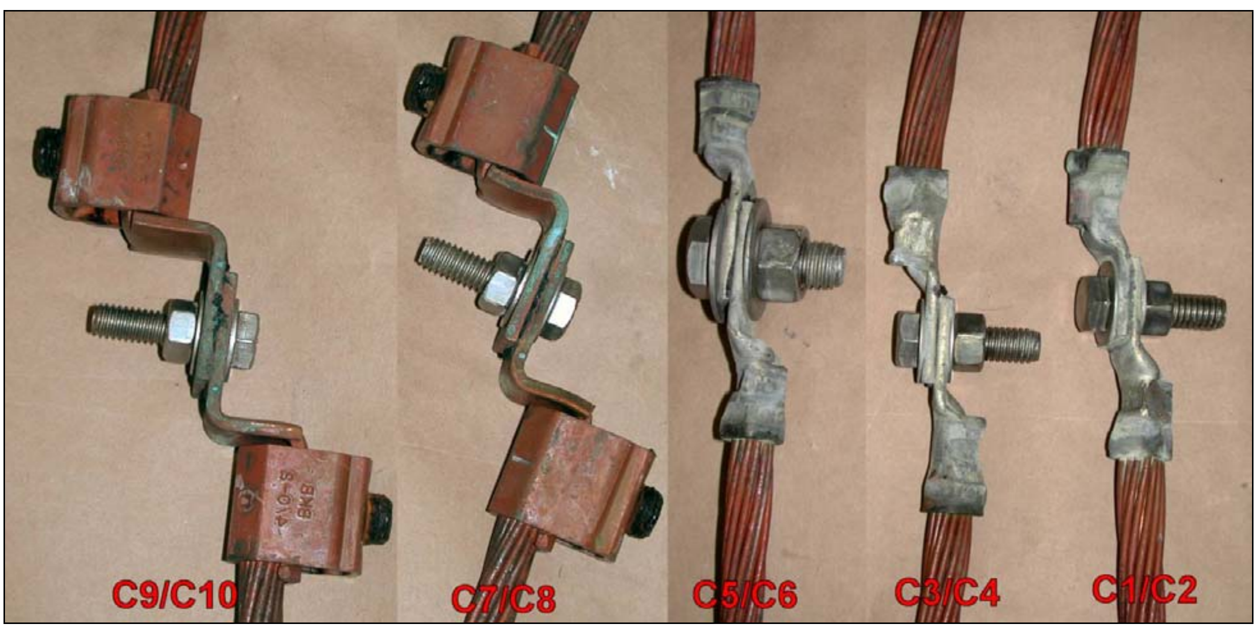

Figure 18. Copper samples after 1000 hours of testing.

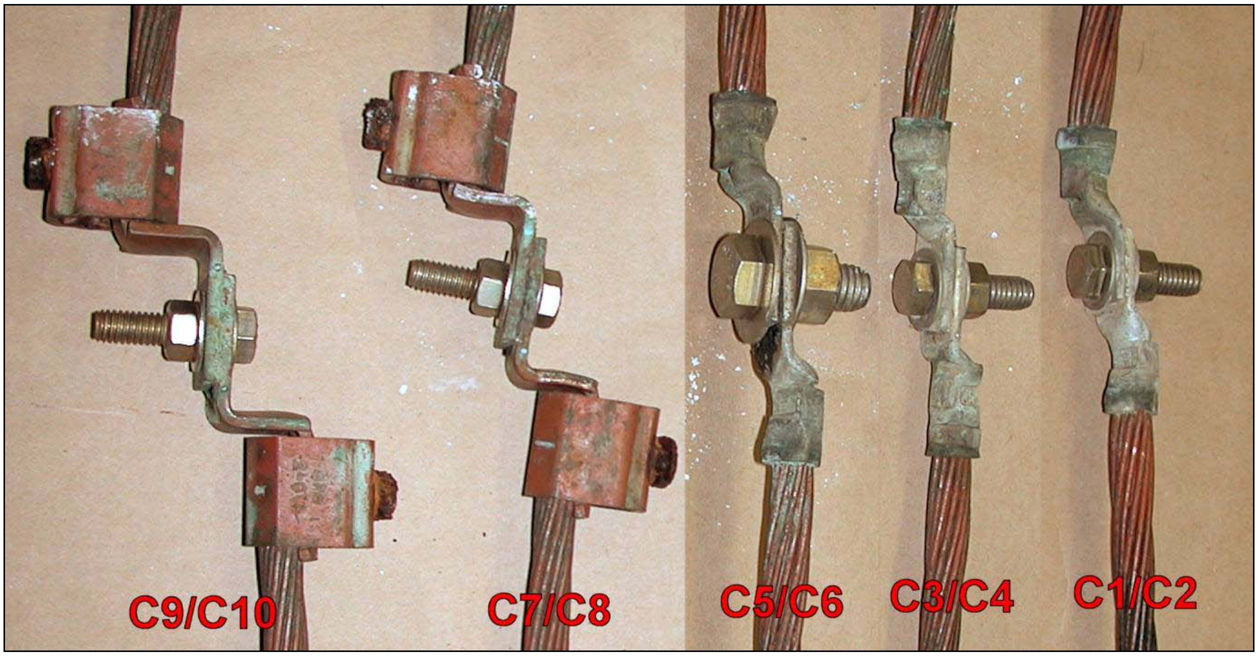

Figure 19. Copper samples after 2000 hours of testing.

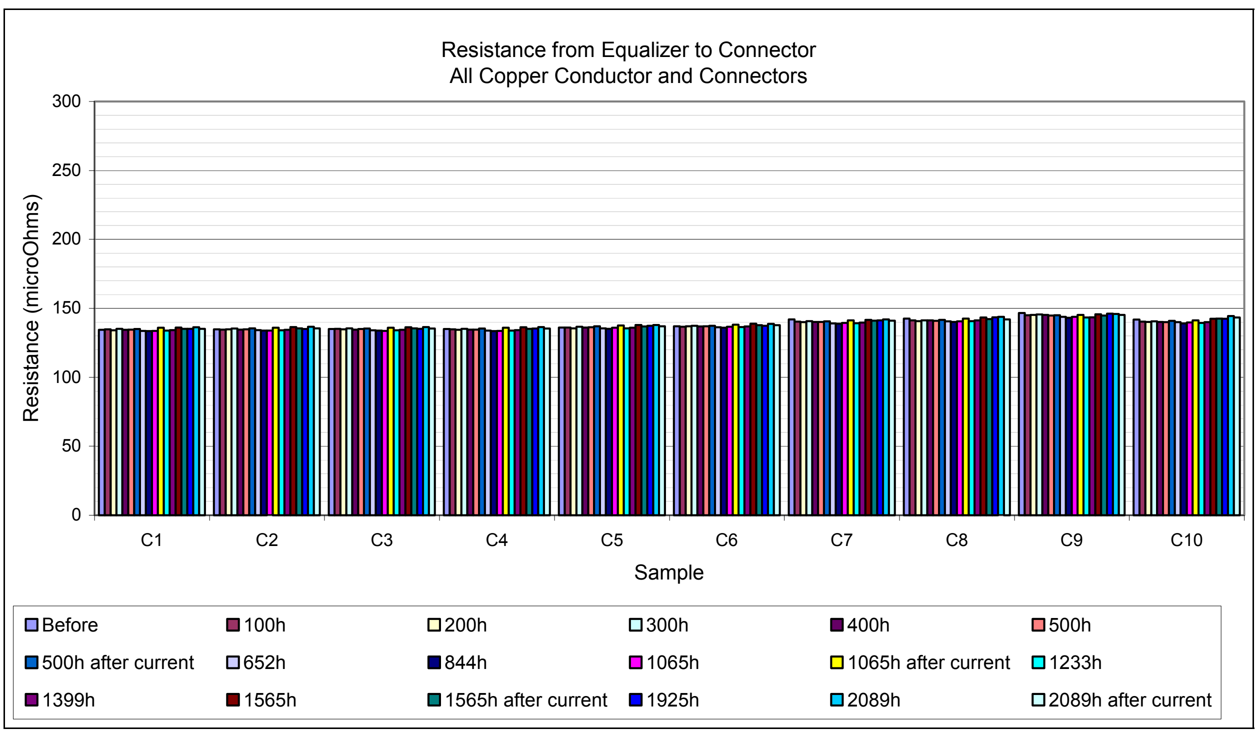

Figure 20. Resistance measurements for the all-copper samples throughout the test.

6.4 SUMMARY OF RESULTS

The measured resistance values are made up of a combination of the equalizer resistance, conductor resistance, and connector contact resistance. Since the conductor resistance dominates, even significant changes in the connector contact resistance may not result in a large change in the overall resistance reading. By calculating the resistance readings during the testing as a percentage of the initial resistance reading, the overall effect can be more easily seen. The percent change in resistance, compared to the initial resistance before testing, measured after each current burst test for all connectors in given in Table 3, and shown graphically in Figure 21.

Table 3. Change in resistance compared to the before test readings.

Sample No.	500h	1065h	1565h	2089h
A1	equalizer remade			-0.5%
A2	24%	26%	26%	26%
A3	equalizer remade			-0.4%
A4	7.4%	7.5%	7.9%	8.8%
A5	2.0%	2.1%	1.5%	1.7%
A6	2.3%	2.5%	2.0%	2.3%
A7	equalizer remade			-3.8%
A8	equalizer remade			27%
A9	10%	11%	13%	15%
A10	equalizer remade			12%
B1	0.3%	1.2%	0.9%	0.9%
B2	0.5%	1.4%	1.0%	0.9%
B3	0.7%	1.9%	1.9%	2.6%
B4	1.0%	2.2%	2.5%	3.4%
B5	0.6%	1.3%	1.4%	1.6%
B6	0.6%	1.1%	0.7%	0.9%
B7	3.4%	5.1%	5.7%	5.7%
B8	2.7%	5.2%	6.1%	6.3%
B9	3.3%	6.5%	7.3%	7.4%
B10	4.4%	8.5%	8.4%	8.8%
C1	0.4%	1.0%	0.6%	0.4%
C2	0.5%	0.9%	0.5%	0.5%
C3	0.3%	0.8%	0.4%	0.3%
C4	0.2%	0.7%	0.2%	0.3%
C5	0.6%	1.1%	0.5%	0.7%
C6	0.2%	0.8%	0.4%	0.5%
C7	-1.0%	-0.5%	-0.6%	-0.7%
C8	-0.6%	0.0%	-0.2%	-0.4%
C9	-1.1%	-1.0%	-1.2%	-1.0%
C10	-0.6%	-0.5%	0.5%	1.0%

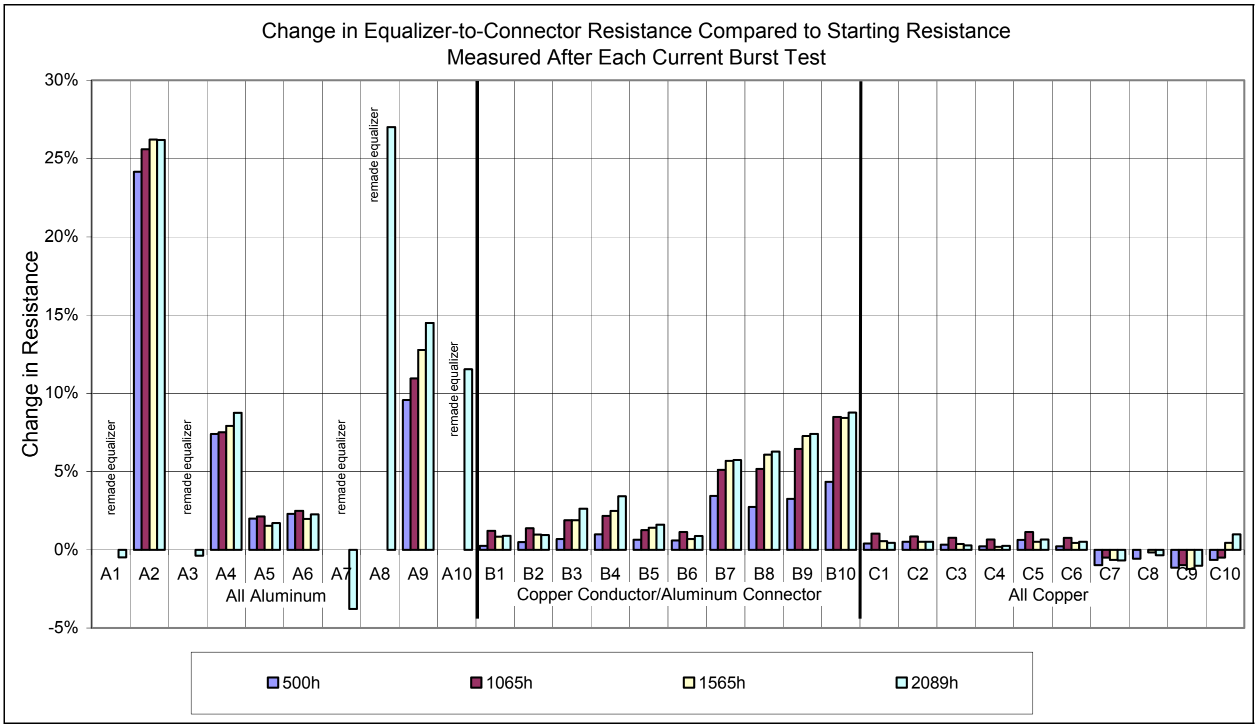

Figure 21. Change in resistance compared to the before test readings for all connectors.

On average, the before-test equalizer-to-connector resistance readings were approximately 145μΩ for the aluminum conductor samples, and 135μΩ for the copper conductor samples. Initial contact resistance readings from the conductor to the connector were measured at approximately 10-15μΩ, or approximately 10% of the total resistance reading. Assuming that most of the change in resistance during the test is due to an increase in connector contact resistance, then an increase in equalizer-to-connector resistance of 10% would correspond to an increase in connector contact resistance of over 100%. On this basis, an increase in the equalizer-to-connector resistance of 5% may be considered to be significant, and an increase of 10% or more may be considered to be a failure of the connector.

7. CONCLUSIONS

The final results of the corrosion and current burst testing are given in Table 4, which shows the number of samples of each type listed by percent change in resistance over the entire testing period:

Table 4. Number of test samples of each type listed by percent change in resistance during the test.

Connector Type	Conductor Type	Overall resistance increase compared to starting resistance:				
		decrease (<0%)	small increase (0%-1%)	moderate increase (1%-5%)	significant increase (5%-10%)	failure (>10%)
Aluminum	Aluminum	3	0	2	1	4
Aluminum	Copper	0	3	3	4	0
Copper	Copper	3	7	0	0	0

Aluminum connectors on aluminum conductor:
- 40% of the connector samples could be considered to have failed.
- 10% of the samples showed a significant increase in resistance.
- 20% of the samples showed a moderate increase in resistance.
- 30% of the samples showed a decrease in resistance.

Aluminum connectors on copper conductor:
- 40% of the samples showed a significant increase in resistance.
- 30% of the samples showed a moderate increase in resistance.
- 30% of the samples showed a small increase in resistance.

Copper connectors on copper conductor:
- 70% of the samples showed a small increase in resistance.
- 30% of the samples showed a decrease in resistance.

Overall, the best performance in this 2000 hour corrosion and current burst test was obtained by the all-copper connectors.

8. REFERENCES

1. T.L. McKoon, Georgia Power Project Report C94925, "Comparison of Conductor Performance", August 1995, Pg. 6.

2. Holm, Ragnar, "Electric Contacts", Fourth Edition, Springer-Verlag Berlin Heidelberg New York, 1967.

3. V.L. Buchholz, Powertech Project 1895-23-03, "A Short Term Power Connector Test to Replace the Current Cycle Testing of CSA Standard C57-1966", November 1991.

4. CSA C57-98, "Electric Power Connectors for Use in Overhead Line Conductors", March 1998.

APPENDIX:
DETERMINATION OF CURRENT BURST LEVEL

A mechanical or compression high current connection relies on good asperity contact at the connection interface to maintain a low contact resistance. Asperity contact is maintained by the residual contact force on the connector, which is supplied by the screw fitting in a mechanical connector, or the residual stress in the deformed metal in a compression connector.

Under corrosive conditions, a poor connection may build up insulating oxides in the spaces between the asperities and at the edges of the asperities. High level, short duration current bursts are applied to the samples for sufficient duration to produce elevated temperatures at the asperity interface between the connector and conductor. The intention is to produce softening or melting of the asperities at the interface during the test. In a connector which has a build up of oxides, softening or melting at the asperities may cause loss of asperity contact if the residual force on the connector is insufficient to re-establish asperity contact with the oxide layer present. In an oxide free connection, the residual force can actually improve asperity contact when the asperities soften, resulting in a lower contact resistance.

The objective is to apply current bursts at a level which produces interface melting in a contact which has a high enough resistance to result in interface softening in the standard CSA C57 500-cycle connector test (Ref. 4). Therefore, the current pulse level is determined as follows.

According to Holm (Ref. 2), the voltage drop across a contact is given by the following relation:

$$U_p^2 = 4L(T_I^2 - T_B^2) \quad ,$$

where:
U_p = peak voltage drop across contact
$L = 2.4 \times 10^{-8}\ V^2K^{-1}$
T_I = absolute temperature (K) of the contact spots in the interface
T_B = absolute temperature (K) of the bulk of the connector

A bulk temperature of 100°C is used in the calculation, which is the maximum control conductor temperature used in the C57 cycling test. The RMS voltage, U_{rms}, is obtained by dividing the peak voltage by √2.

The magnitude of the current, I, required to produce either softening or melting at the interface is given by:

$$I = \frac{U_{rms}}{R} \quad ,$$

where R = resistance at which either interface softening occurs in the C57 test, or melting occurs in the current burst test.

The current burst levels calculated are given in Table A.1.

The calculation indicates that current levels of approximately 1800 A_{rms} and 1750 A_{rms} are suitable for copper and aluminum respectively.

Table A.1. Calculated current burst levels.

Conductor Size	Conductor Material	Interface Softening Temperature (°C)	Interface Melting Temperature (°C)	Softening Voltage U_{rms} [1] (mV)	Melting Voltage U_{rms} [1] (mV)	CSA C57 Current[2] (A)	Softening or Melting Contact Resistance (mΩ)	Current Burst Level (A)
2/0	Cu	190	1083	60.1	286	380	0.158	1806
4/0	Al	150	660	43.7	187	408	0.107	1749

[1] Using a bulk temperature of 100°C from CSA C57.
[2] From Table 6 and Table 8 from CSA C57.