

COMPARISON OF CONDUCTOR PERFORMANCE

PERFORMED FOR

ALCAN CABLE

ATLANTA, GEORGIA

EXECUTIVE SUMMARY

A program was designed and carried out for Alcan Cable, by **Southern Development Investment Group (SDIG) / Georgia Power Research Center**, to:

- Compare performance of connections of AA-8030 aluminum alloy conductors with mechanical screw type connectors against similar connections of electrically equivalent copper conductors in a heat cycling test that is more severe than industry accepted standards (UL 486B or CSA C22.2 No. 65 & ANSI C119.4) and in a torque test.
- Compare physical properties of conductor materials before and after the heat cycling test.

The industry accepted heat cycling tests are used to predict a long-term performance of a connection. The connections of AA-8030 aluminum alloy conductors with mechanical screw type connectors performed as well as, or better than, similar connections of electrically equivalent copper conductors in the heat cycling test that is more severe than the industry accepted standards. These connections were made using a wide range of torque and different methods of preparation. The absolute temperature (T), temperature stability (DT), and resistance stability (R) criteria of the heat cycling test (ANSI C 119.4) were used to evaluate the performance of the connections. Tables 1 and 2 summarize the results from sixteen connections evaluated for each size of conductor used in this test program.

TABLE 1: ANSI C119.4 RESULTS FOR XHHW-2 (RW90-600V)* AA-8030 ALUMINUM ALLOY CONDUCTORS															
CDR. SIZE	AWG # 2			AWG # 2/0			AWG # 4/0			500 KCMIL			750 KCMIL		
	T	DT	R	T	DT	R	T	DT	R	T	DT	R	T	DT	R
TESTED	16			16			16			16			16		
MET REQUIREMENT	16	16	16	16	16	15	16	16	16	16	16	15	16	16	15
DID NOT MEET REQUIREMENT	-	-	-	-	-	1	-	-	-	-	-	1	-	-	1

TABLE 2: ANSI C119.4 RESULTS FOR THHN-2 (T90)* COPPER CONDUCTORS															
CDR. SIZE	AWG # 4			AWG # 1			AWG # 2/0			350 KCMIL			500 KCMIL		
	T	DT	R	T	DT	R	T	DT	R	T	DT	R	T	DT	R
TESTED	16			16			16			16			16		
MET REQUIREMENT	16	16	16	16	16	16	16	16	16	16	16	16	16	16	12
DID NOT MEET REQUIREMENT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4

* CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project

The values of percent retained running torque, after the heat cycling test, suggest that there is little difference between the performances of the connections of AA-8030 aluminum alloy and equivalent copper conductors with the mechanical screw type connectors tested in this project. Also, the variability observed in the measurement process to obtain retained running torque values indicates that this may not be a good indicator to predict the long-term performance of such connections. Further inference can be made, from the data, that it may be possible that the mechanical screw type connectors may be capable of demonstrating even wider tolerance to the range of tightening torque than the range examined in this project with these conductors.

Thus, the absolute temperature, temperature stability, and resistance stability criteria of the heat cycling test are better predictors of the long-term performance of a mechanical screw type connection than retained torque. Regardless of whether it is installed with copper or AA-8030 conductors.

Stable performance exhibited by both copper and AA-8030 conductors in the heat cycling test is reflected in the retained values of the physical properties of the conductor materials after the heat cycling test.

INTRODUCTION

Reliable performance from connections of conductors and connectors is essential to the operation of any electrical system. In the competitive environment of today, however, a new criterion has emerged as the search continues for more economical ways of achieving, and surpassing, the high expectations of installers, legislators, and end users. Aluminum alloy conductors offer an option to copper conductors, and Alcan Cable believes that they match the performance of copper in electrical circuits governed by code requirements.

In order to put substance to this claim, a program was designed and carried out for Alcan Cable, by **Southern Development Investment Group (SDIG) / Georgia Power Research Center**, with the following objectives.

- To verify that connections of AA-8030 aluminum alloy conductors with mechanical screw type connectors perform as well as the similar connections of electrically equivalent copper conductors in a heat cycling test that is more severe than industry accepted standards (UL 486B or CSA C22.2 No. 65¹ & ANSI C119.4).
- To verify that connections of AA-8030 aluminum alloy conductors with mechanical screw type connectors perform as well as the similar connections of copper conductors in a torque retention test.
- To compare physical properties of AA-8030 and copper conductor materials before and after heat cycling test.

Testing can provide an important means of assessing connection performance relative to different connector designs and conductor types. Chosen with care, tests can also provide a convenient indicator of expected life under normal conditions of use.

There are a number of different tests which simulate the aging of connectors, the most important of which require cyclical current loading in order to duplicate the repetitive expansion and contraction phases of metal-to-metal contacts encountered in pressure type connectors. Electrical utility standards are generally more demanding due to higher circuit loadings, size for size, than would usually be permitted under National Electrical Code rules.

Electrical installations in residential, commercial, institutional and industrial sectors are required to meet or exceed the requirements of the National Electrical Code (NEC), NFPA 70 standard in US or Canadian Electrical Code (CE Code)², CSA C22.1 standard in Canada. Wire connectors intended for use with aluminum conductors recognized in the NEC are evaluated in accordance with the Underwriters Laboratories (UL) standard for Wire Connectors for Aluminum Conductors - UL 486B. Generally, connectors for aluminum conductors are manufactured and so evaluated that they are also acceptable for copper conductors. In addition to the necessary listing of connectors by an

¹ UL 486B and CSA C22.2 No. 65 are equivalent standards used in US and Canada, respectively. For simplicity, only UL 486B requirements are referenced hereafter in this report.

² NEC and CE Code are equivalent codes used in US and Canada, respectively. For simplicity, only NEC requirements are referenced hereafter in this report.

independent laboratory, the conductor material for aluminum conductors is required to be of an AA-8000 series electric grade aluminum alloy conductor material to satisfy NEC requirements. Alcan Cable has registered the aluminum alloy AA-8030.

Utility engineers often specify that connectors used in their transmission and distribution systems meet or exceed the requirements of the National Electric Safety Code (NESC), ANSI C2 standard of the American National Standards Institute. Wire connectors intended for use between aluminum-to-aluminum or aluminum-to-copper bare overhead conductors are generally evaluated according to the ANSI Standard C119.4. Some electrical utilities believe that connections found in compliance with this standard can be expected to last 30 years of normal use in distribution circuits.

A comparison of requirements for heat cycling test extracted from the two standards, as shown in the Appendix - 1B, suggests that ANSI C119.4 requirements are more severe. The level of severity is increased if insulated conductors are substituted for bare conductors, as the test current must be increased by 20%-28% to achieve the same temperature on the control conductor. UL listed connectors, when tested with bare conductors of the same type that are used in insulated form in UL 486B test protocol, also meet the requirements of ANSI Standard C119.4. In cognizance of all the facts, the ANSI Standard C119.4 was adopted as the principal means of evaluation of connection performance, with the modification, as described, that insulated conductors instead of bare conductors were employed for test purposes.

For the purposes of the evaluation of conductor performance at the connections, commercially available UL listed mechanical screw type connectors were tightened to insulated conductors selected for this project. To evaluate a full range of products, data from five sizes of Type XHHW-2 conductors with AA-8030 aluminum alloy and their electrically equivalent sizes of Type THHN-2 conductors with copper are presented in this report. The ampacities of copper conductor are comparable with those of the aluminum conductors, as shown in Table 3. These ampacities were obtained from Table 310-16 of the NEC. The tempers of the conductors were identified as annealed (or H2X) for AA-8030 and annealed for copper.

It was further decided to evaluate the additional variables of conductor preparation, tightening torque, retention of connector set-screw tightening torque, and the physical properties of the conductor materials after the heat-cycle test. Two conditions of preparation were established, "Recommended Preparation" and "No preparation". Similarly, three levels of torque were applied in this evaluation, "High", "Recommended", and "Low". Not all six combinations of conductor preparation and torque were evaluated. "Recommended Preparation" with all three levels of torque and "No Preparation" with "Recommended Torque" made-up the four conditions which were evaluated. Four connections for each condition were prepared in a series loop consisting of all sixteen connections and subjected to the Current Cycle Submersion Test (CCST). **The testing was conducted at the Georgia Power Research Center, by the Southern Development Investment Group (SDIG), in Forest Park, Georgia.**

TEST CONDUCTORS AND CONNECTORS

Alcan Cable provided all of the aluminum and copper conductors that are typical of normal commercial production for use in the test. The listed terminal connectors were purchased from ILSCO and are typical of normal commercial production. The mechanical screw type terminal connectors are listed by Underwriters Laboratories, Inc.

and designated “AL9CU”, indicating that they are 90° C rated for use with copper or aluminum conductors. Since the testing for 90° C rating for connectors is more severe than for 75° C rating, it was decided to use AL9CU rated connectors and test their connections accordingly. **Table 3** contains the conductor material and sizes compared in the test program. **Table 4** contains the connector manufacturer’s catalog numbers, conductor sizes, torque levels, and connector set screw (slot/hex) size.

TABLE 3: CONDUCTOR MATERIALS AND SIZES

AA-8030			COPPER*		
SIZE of XHHW-2 (RW90-600V)**	AMPACITY	TEST CURRENT ⁺	SIZE of THHN-2 (T90)**	AMPACITY	TEST CURRENT ⁺
AWG # 2 CP	100	215	AWG # 4 CPR	95	204
AWG # 2/0 CP	150	347	AWG # 1 CPR	150	335
AWG # 4/0 CP	205	475	AWG # 2/0 CPR	195	448
500 kcmil CP	350	832	350 kcmil CPR	350	833
750 kcmil CP	435	1095	500 kcmil CPR	430	1058

CP = Compact CPR = Compressed

* Copper conductors of comparable ampacity at 90° C from the Table 310-16 of the National Electrical Code are selected.

** CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

⁺ Test current is the current, in amperes, required to raise the temperature of the control conductor in a given test loop by 100° C above ambient air temperature in the Current Cycle Submersion Test.

TEST EQUIPMENT

The following equipment was employed to conduct the Current Cycle Submersion Tests and Torque Retention Tests.

- Current Cycle Submersion Test Tank Fixture.
- Apple III / Hewlett Packard 3421A Data Acquisition System (Cal. Date 6-7-94)
- Apple III / Hewlett Packard 3421A Data Acquisition System (Cal. Date 4-20-94)
- SNAP-ON Torque Wrench Model # TEC-100FU, Serial # 4066 (Cal. Date 11-14-94)
- SNAP-ON Torque Wrench Model # TE12-FUA, Serial # 16008 (Cal. Date 11-14-94)
- SNAP-ON Torque Wrench Model # TE-50F FUA, Serial # 5100 (Cal. Date 11-14-94)
- SNAP-ON Torque Wrench Model # TECP1-FUA, Serial # 1151 (Cal. Date 11-14-94)

TABLE 4: CONDUCTORS, CONNECTORS AND TORQUE LEVELS

COND. SIZE AWG/Kcmil	ILSCO CONNECTOR Catalog No., Screw Size	TORQUE LEVELS (INCH-POUNDS)		
		Low Torque (UL-486B)	Recommended Torque	High Torque
2 Al & 4 Cu	TA-2 5/16x24,5/16	40	50	60
1 Cu	TA-0 3/8x24,3/8	40	50	60
2/0 Al & 2/0 Cu	TA-2/0 7/16x20,3/16	100	120	140
4/0 Al	TA-250 11/16x16,5/16	225	275	325
500 Al 500 Cu	TA-600-2NS 13/16x16,1/2	400	500	600
350 Cu	TA-350-2NS 3/4x16, 3/8	300	375	450
750 Al	TA-800-2NS 15/16x16,1/2	400	500	600

TEST PROGRAM

Current Cycle Submersion Test

The ANSI C119.4, 100 cycle Current Cycle Submersion Test (CCST) was chosen to evaluate the temperature and resistance performance of the connectors. The 100 cycle CCST method is an evolution of, and an alternate to, the ANSI C119.4 Standard for “Electrical Connectors - Connectors for Use Between Aluminum-to-Aluminum or Aluminum-to-Copper Bare Overhead Conductors”, 500 cycle test. The CCST method differs from the traditional ANSI C119.4 Current Cycle Test (CCT) in that test connectors are rapidly cooled by immersion in chilled water at the beginning of the current ‘off’ cycle. **Comparative testing has demonstrated that the CCST method will provide the same performance test results as the traditional CCT in fewer test cycles³.** A detailed description of the CCST is included in the Appendix-1A.

³ Lambert, F. , “An Accelerated Performance Test of Electrical Connectors”
IEEE/PES
Anaheim, CA Sept. 14-19, 1986

A test loop was required for each size of the conductor to complete the test program. Each test loop consisted of 16 connectors, incorporating four different installation conditions, joined in a series loop with welded equalizers. The welded equalizers provide an equipotential plane to assure that all conductor strands are in contact with each other for resistance measurements and also to prevent the thermal influence of one connector on another.

The four installation conditions are as follows:

- Four connections with recommended torque and recommended conductor preparation.⁴
- Four connections with recommended torque and no conductor preparation.
- Four connections with high torque (typically about 20% above recommended) and recommended conductor preparation.
- Four connections with low torque (typically about 20% below recommended) and recommended conductor preparation.

Prior to assembly of the test loop, the pads of the connectors were also abraded with a wire brush to remove any oxide build-up on the surface as outlined in the ANSI C119.4 standard.⁵ Immediately after cleaning, a thin layer of Alcoa EJC #2 oxide inhibitor was applied to the surface. A small section of aluminum bus bar, the same size as the pad of the connector, was then wire brushed and sandwiched between the pads of the connectors and bolted together with appropriate hardware. The bolts were tightened using the torque values outlined in Table 2 of the ANSI C119.4 standard.

After placing the loop in the Current Cycle Submersion Test fixture, thermocouple and resistance leads were attached. The current was adjusted, during the first three cycles, to achieve a steady-state temperature rise of 100°C above ambient air temperature on the control conductor. Each loop was subjected to a minimum of 100 cycles with each cycle consisting of a current 'on' and current 'off' period. The length of the 'on' / 'off' period is in accordance with Table 4 of the ANSI C119.4 standard.

During the current 'off' period the test connectors were submerged in water chilled to 4° C. At the end of the current 'off' period, the chilled water tank was lowered and the loop was energized for the next cycle. Temperature measurements of the connectors and the control conductor were taken at the end of each heating cycle with the current 'on'. Type 'T', sub-miniature, stainless steel sheathed thermocouples were used to monitor the temperature of the connectors and the control conductor. One, 0.033 inch diameter, 0.25 inch deep hole was drilled into the body of the connector for thermocouple installation. The hole was located in the current transfer path where the highest

⁴ Recommended conductor preparation consists of mechanically abrading (wire brushing) the conductor strands to remove any oxide build-up and the application of a corrosion inhibiting compound. For this test Alcoa Electrical Joint Compound (EJC #2) was used.

⁵ In field installations the plating on the connectors, if present, is not abraded. Connectors are plated to provide protection from oxidation.

temperature was anticipated. The control conductor was monitored with two thermocouples placed in the center of the length of conductor.

Resistance measurements were taken at the end of cycle one, and every tenth cycle thereafter, through cycle 100. Resistance measurements were made across each connector, from equalizer to equalizer, after the connectors had returned to ambient temperature. The connector temperature was recorded with each set of resistance measurements to allow the correction of measured resistance values to 20°C. The corrected values were used to evaluate the performance of each connector.

Torque Retention Test

At the conclusion of the 100 cycle Current Cycle Submersion Test, each test connector was subjected to a torque retention test. The torque values required to turn the connector set screws, in a clockwise (tightening) direction, were measured and recorded to provide an indication of the effect of the heating and cooling cycling on the contact force between the set screw and conductor.

The torque on the set screws after cycling was determined by tightening the screws in a clockwise direction until they began to rotate. Generally, but not always, the torque required to start the screw rotating exceeds the initial torque applied at installation. This torque is generally referred to as the “breaking” or “starting” torque, and represents the torque required to overcome the friction and binding between the bottom of the screw and the conductor and in the threads of the screw and connector.

Once the friction is overcome there is an abrupt reduction in torque to a much lower magnitude as the screw begins to rotate. This is referred to as “running” torque and is the minimum torque required to rotate the screw immediately after the starting torque is overcome.

The actual magnitude of the starting torque, whether less or more than the initial torque, will depend on a number of factors. These factors include the following:

- Friction or sticking between the screw and body of the connector and the conductor.
- The magnitude of the force exerted by the screw on the conductor.
- Relaxation of this force due to creep relaxation of the conductor under the screw.
- The possibility of the screw threads being exposed to a corrosion inhibiting compound during installation.⁶

⁶ This is the only factor that can be introduced by human error. All other factors are a function of the physical properties of the material. For this test, care was taken not to expose the threaded portion of the connector to the corrosion inhibiting compound.

If the force exerted by the screw on the conductor remains high, the starting torque will be high. If there is a considerable reduction in this contact force due to creep of the conductor under the effect of time or temperature, the starting torque may be much lower than that at installation. Therefore, since starting torque is affected by friction and binding of the screw threads, running torque is generally accepted as a much better indication of the degree of force relaxation.

Physical Testing

The ultimate tensile strength, yield strength, and elongation properties of the conductor materials were measured at the Technology Center of Alcan Cable in Williamsport, Pennsylvania. The primary reason for conducting these measurements at the Alcan Cable facility was the nature of the equipment available at this location and the experience of the people in conducting such tests. These properties were measured before and after CCST.

The following equipment available at the Technology Center was employed to conduct the above-mentioned measurements.

- INSTRON Model 4483, Serial # G4383 with Load Cell Type 2525-818, Serial # 059 (Cal. Date 1-31-95) and with Load Cell Type 2525-807, Serial # 175 (Cal. Date 4-11-95). This equipment is equipped with an automated control, data collection, and data analysis system from INSTRON.

TEST RESULTS AND CONCLUSIONS

AA-8030 Aluminum Alloy Conductors against Copper Conductors:

The results show that connections installed on AA-8030 aluminum alloy perform as well as, or better than, connections installed on copper conductors of equivalent ampacity in the Current Cycle Submersion Test. Overall, the maximum temperature values, resistance stability values and temperature stability values were very close.

1. Current Cycle Submersion Test (Temperature Performance)

ANSI C119.4 graphs detailing temperature and resistance performance of four connections with recommended torque and recommended conductor preparation for 4/0 XHHW-2 (RW90-600V) AA-8030 conductor and its electrically equivalent 2/0 THHN-2 (T90) copper conductor are included in the Appendix-2A and Appendix-2B, respectively⁷. Note that **TEMPERATURE DIFFERENCE** data are shown on these ANSI C119.4 graphs. This is in accordance with the ANSI C119.4 Test Standard. Temperature difference is determined by subtracting the recorded temperature of the connector from the recorded temperature of the control conductor at the time of the measurement. Therefore, a higher temperature difference indicates that the connection temperature is COOLER than a lower temperature difference. A temperature difference of 0° C, or a negative temperature difference value, indicates that the connection is operating at a temperature equal to, or greater than, the control conductor and is considered a failure.

Also shown on the ANSI C119.4 temperature graphs is a **MINIMUM ACCEPTABLE TEMPERATURE DIFFERENCE**, defined as the average temperature differences calculated over the course of the test for that connection, less 10° C. Any temperature less than this limit reflects thermal instability and is also grounds to fail the connection. This method provides a means to normalize data gathered at varying ambient temperatures.

Additionally, bar graphs comparing average temperature and average resistance performance of four connections with recommended torque and recommended conductor preparation for 4/0 XHHW-2 (RW90-600V) AA-8030 conductor and its electrically equivalent 2/0 THHN-2 (T90) copper conductor are included in the Appendix-2C and Appendix-2D, respectively⁸. These graphs provide a comparison of the performance of AA-8030 aluminum alloy conductors against copper conductors in the CCST.

⁷ CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

⁸ Ibid.

TABLE 5 and **TABLE 6** summarize the overall compliance of AA-8030 and copper conductors, respectively, with the performance criteria of the test.

The results of the 100 cycle CCST indicate that the thermal performance of connections of mechanical screw type connectors installed on AA-8030 aluminum alloy conductors is comparable to, or better than, the similar connections installed on electrically equivalent copper conductors.

The data shows that for connectors installed on 2/0 AWG, AA-8030 aluminum alloy conductors and smaller, AA-8030 aluminum alloy connections operate at a temperature slightly above that of the connectors installed on the copper conductors of equivalent ampacity. For AA-8030 aluminum alloy conductors 4/0 AWG and above, test connectors operate at a temperature less than that of electrically equivalent copper conductors. **GRAPH 1** shows the average maximum temperatures recorded for AA-8030 and copper conductors tested.

Further examination of the temperature data suggests that if AA-8030 conductors were subjected to the same level of current as their copper equivalent sizes, then all of the AA-8030 connections would operate at a lower temperature than the connections with copper conductors. There are two reasons for this assertion. First, the ampacity rating for the AA-8030 conductors are at least equal to, or greater than, the ampacity rating for the equivalent copper conductors. The second reason is that all, except one, copper conductors required higher current to obtain 100° C rise above the ambient temperature for the control conductor than the corresponding AA-8030 conductor. The one that did not require a higher current was 350 kcmil and it required only 1 Ampere less current (832 Amperes versus 833 Amperes) than the corresponding 500 kcmil AA-8030 conductor. In spite of this difference, 500 kcmil AA-8030 still operated at a lower temperature than 350 kcmil copper conductor.

Thus, when AA-8030 conductors are used in place of their equivalent copper conductors, the connections with AA-8030 conductors are likely to operate at a lower temperatures than the equivalent copper conductors.

The above statement is an important observation since it is generally misconceived that the connections with aluminum conductors operate at slightly higher temperature than their equivalent copper sizes.

Further, the compliance with the absolute temperature and temperature stability criteria suggests that both copper and AA-8030 conductors exhibit significant tolerance to the levels of torque used and the methods of preparation employed. This is not to suggest that one should ignore the recommended practices for good connections. **Recommended practice for connection preparation for AA-8030 aluminum alloy conductors is also a good practice for copper conductors.**

TABLE 5: ANSI C119.4 RESULTS FOR XHHW-2 (RW90-600V)* AA-8030 ALUMINUM ALLOY CONDUCTORS															
CONNECTOR NUMBER	AWG # 2			AWG # 2/0			AWG # 4/0			500 KCMIL			750 KCMIL		
	T	DT	R	T	DT	R	T	DT	R	T	DT	R	T	DT	R
1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
6	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
7	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
9	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
11	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
12	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
13	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
14	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
16	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

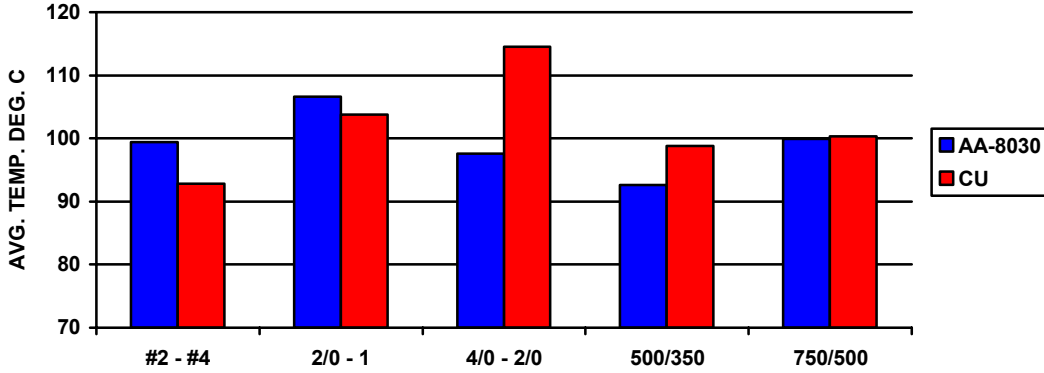
TABLE 6: ANSI C119.4 RESULTS FOR THHN-2 (T90)* COPPER CONDUCTORS															
CONNECTOR NUMBER	AWG # 4			AWG # 1			AWG # 2/0			350 KCMIL			500 KCMIL		
	T	DT	R	T	DT	R	T	DT	R	T	DT	R	T	DT	R
1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
6	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
9	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
11	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
12	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
13	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
14	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
16	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

1-4 = Recommended Torque & Recommended Preparation
 5-8 = Recommended Torque & No Preparation
 9-12 = High Torque & Recommended Preparation
 13-16 = Low Torque & Recommended Preparation
 T = Absolute Temperature Requirement
 DT = Temperature Stability Requirement
 R = Resistance Stability Requirement

Y = Met the Requirement
N = Did not meet the Requirement

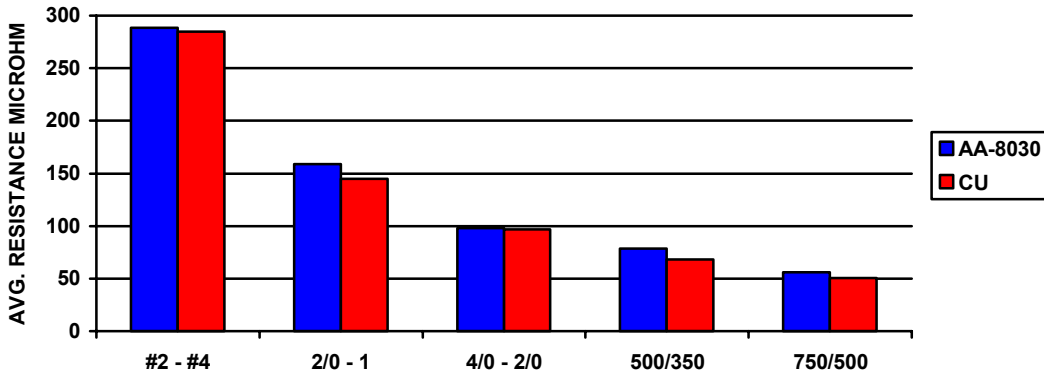
* CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

**AVERAGE MAXIMUM TEMPERATURE VALUES FROM 100 CYCLE
CCST TEST FOR AA-8030 & COPPER CONDUCTORS**



**GRAPH 1: XHHW-2 (RW90-600V) AA-8030 & THHN-2 (T90) COPPER
CONDUCTOR SIZES**

**AVERAGE MAXIMUM RESISTANCE VALUES FROM 100 CYCLE
CCST TEST FOR AA-8030 & COPPER CONDUCTORS**



**GRAPH 2: XHHW-2 (RW90-600V) AA-8030 & THHN-2 (T90) COPPER
CONDUCTOR SIZES**

* CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

2. Current Cycle Submersion Test (Resistance Performance)

Test results show that the resistance stability of connectors installed on AA-8030 aluminum alloy conductors are equally as stable as those connectors installed on copper conductors of equivalent ampacity. **GRAPH 2** shows the average maximum resistance values recorded for AA-8030 and copper conductors tested. Three resistance stability failures were observed on AA-8030 conductors, while four failures were observed on copper conductors. In both instances, for copper and aluminum, the connectors failed by a maximum of two microhms. For AA-8030 conductors, one failure occurred on one each of 2/0 AWG, 500 kcmil, and 750 kcmil conductors. All three were recorded from recommended torque and no conductor preparation condition for installation of the connector. For copper conductors, all failures occurred on 500 kcmil conductor. Two failures, each, were recorded from high torque and recommended conductor preparation and low torque and recommended conductor preparation conditions for installation of the connector.

Examination of the data for temperature performance, performed earlier, is equally applicable here for the resistance performance.

Thus, when AA-8030 conductors are used in place of their equivalent copper conductors, the connections with AA-8030 conductors are likely to operate at a lower resistance than the equivalent copper conductors.

Resistance stability criterion supports the observation made using the absolute temperature and temperature stability criteria regarding the recommended practice for connection preparation. **Once again, the recommended practice for connection preparation for AA-8030 aluminum alloy conductors is also a good practice for copper conductors.**

3. Torque Retention Test Performance

A graph comparing frequency distribution for percent retained torque values after CCST performed on XHHW-2 (RW90-600V) AA-8030 and THHN-2 (T90) copper conductors is included in the Appendix-2E⁹.

The average percent retained running torque value for connectors installed on the five sizes of AA-8030 conductors is 90.6% with a standard deviation of 16.0%. For connectors installed on five electrically equivalent sizes of copper conductors, the average percent retained running torque value is 106.3% with a standard deviation of 15.8%. Percent retained running torque values from the connections installed on #2 AWG AA-8030 were significantly different (lower) than the similar values from all remaining connections on AA-8030 and copper conductors. Further, the average percent

⁹ CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

retained running torque value for connectors installed on the other four sizes of AA-8030 conductors is 95.5% with a standard deviation of 12.7%. These changes in the average and standard deviations suggest some cause for such variation. However, all connections installed on #2 AA-8030 conductor met the requirements of CCST criteria in a manner consistent with the connections installed on other sizes of AA-8030 and all sizes of copper conductors.

Given the reliance on physical sensing of the movement of the screws or nuts and the measurement capability of the instruments used for this purpose, further work is necessary to reduce the variability in the measurement of retained torque. Resources required for making such improvements would have to be weighed against the benefits to be derived from such measurements. It may be possible that the mechanical screw type connectors, regardless whether they are installed on AA-8030 or copper conductors, may be capable of demonstrating even wider tolerance to the level of tightening torque than examined in this project with these conductors. This is not to suggest that one should ignore the recommended practices for good connections.

Aforementioned analysis of the data suggests that the difference between the overall average values of percent retained torque from connections installed on AA-8030 and copper conductors is significantly less than the standard deviations observed from connections installed on either of these conductors. **Therefore, given the variability in measurement of torque retention, there is little difference between the performances of the connections of AA-8030 aluminum alloy and equivalent copper conductors. The absolute temperature, temperature stability, and resistance stability criteria of the heat cycling test are far better predictors of the long-term performance of a connection, whether it is with copper or AA-8030 conductors, than the retained torque.**

4. Physical Properties

Graphs detailing percent retained physical properties after CCST as function of connection preparation method are included in the Appendix-2F.

Both copper and AA-8030 conductors exhibit excellent retention of their physical properties after CCST. Ultimate tensile strength, yield strength and elongation from the samples of the conductors after CCST were compared to the values of the same properties before CCST for all five sizes of both, copper and AA-8030, conductors. Overall average percent retained values for these properties for copper conductors are 99.7%, 100.2%, and 89.5%, respectively. Similarly, overall average percent retained values for these properties for AA-8030 conductors are 100.2%, 96.8% and 92.1%, respectively.

Stable performance exhibited by both copper and AA-8030 conductors in the CCST is reflected in the retained values of the physical properties of the conductor materials after the CCST.

APPENDICES

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2A	ANSI C119.4 Graphs of Temperature Difference & Resistance Values for four connections made using recommended torque and recommended practice method for 4/0 XHHW-2 (RW90-600V)* AA-8030 Conductors
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* CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

AN ACCELERATED PERFORMANCE TEST OF ELECTRICAL CONNECTORS

This Appendix contains a brief explanation of an accelerated test procedure for electrical connectors developed at the Georgia Power Research Center. This procedure, the Current Cycle Submersion Test (CCST), requires only 100 cycles to produce results similar to the 500 cycle ANSI C119.4 test.

TEST PROCEDURE:

The ANSI C119.4 500 cycle test procedure has remained virtually unchanged since the adoption in 1962. Years of experience have proven the adequacy of this test procedure. The Current Cycle Submersion Test procedure is intended only to accelerate the aging effects of the existing test. It is not intended to change the severity of the 500 cycle test.

In keeping with this philosophy, the new test procedure has incorporated most of the requirements of ANSI C119.4, Section 6., "Current Cycle Test Procedures." The connectors are assembled in a series loop with equalizers. The equalizers provide an equipotential plane for resistance measurements and also minimize the thermal influence of one connector on another. The exposed length of conductor between the connector and equalizer is in accordance with Table 2 of the ANSI standard.

A control conductor is installed in accordance with ANSI C119.4, Section 6.5, in order to accurately measure the conductor temperature. The current amperage is adjusted during the first five current 'on' cycles to result in a steady state temperature rise of 100°C above ambient air on the control conductor. This current is maintained during the remainder of the test regardless of the rise in control conductor temperature. Each cycle of the test consists of a current 'on' period in accordance with Table 4 of the ANSI standard. The length of the current 'off' period is ½ hour.

At the beginning of the current 'off' period, the connectors are quickly submerged in a water bath maintained at a temperature between 2°C and 7°C. Two submersion methods are employed in this series of tests. Method one is accomplished by raising a water tank to submerge the connectors at a rate of approximately one inch per second with minimum mechanical disturbance. At the end of the current 'off' period, the tank is lowered and the current 'on' period begins. Method two is accomplished by lowering the series loop into a tank of chilled water to submerge the connectors at a rate of approximately 0.1 inch per second with minimum mechanical disturbance.

Temperature measurements are made of each connector and the control conductor just prior to the end of the current 'on' period. Temperature measurements shall be taken at cycles 1, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100. Resistance measurements are taken for each connector at the end of the current 'off' period after the connector temperature has been established at ambient air temperature. Resistance is measured

from equalizer to equalizer and corrected to 20°C for evaluation. Resistance measurements shall be taken at cycles 1, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100.

CURRENT CYCLE SUBMERSION TEST:

Performance Requirements:

1. The resistance of any one connector at any time during the test shall not vary more than $\pm 5\%$ from average of all the measured resistances of that connector, or

$$0.95 \leq \frac{(R_{\text{conn},i})}{\frac{\sum_{i=1}^N R_{\text{conn},i}}{N}} \leq 1.05$$

where: $R_{\text{conn},i}$ = measured resistance value at time i

N= total number of resistance measurements

2. The temperature of a conductor shall not exceed the temperature of the control conductor at any time.
3. The temperature difference between the control conductor and the connector (including allowance for measurement error) shall not vary from the average of the sum of the measured temperature differences between the control conductor and the connector by more than 10°C, or

$$\frac{\sum_{i=1}^K (T_{\text{cond},i} - T_{\text{conn},i})}{K} - (T_{\text{cond},i} - T_{\text{conn},i}) \leq 10^{\circ}\text{C}$$

where: $T_{\text{conn},i}$ = measured connector temperature at time i
 $T_{\text{cond},i}$ = measured control conductor temperature at time i
 K = total number of temperature measurements

Comparison of the Requirements of UL 486B & ANSI C119.4 Test Methods for Heat Cycling Test

SUMMARY TABLE

PARAMETER	UL 486B	ANSI C119.4
No. of Cycles	500 CCT	500 (CCT) or 100 (CCST)
Conductor Type	Insulated (USE or USE-2 for Aluminum)	Bare
Conductor Preparation	None	Wire Brush & Use of EJC
Torque	Specified	Specified
Current	Specified	To attain 100° C Rise
Current On/Off Times	Specified	Specified
Sample Length	Specified	Specified
Stripped Length and Tolerance	Specified	Specified

COMPARISON OF TEST CRITERIA

- **Absolute Temperature**

UL 486B: Connector temperature cannot exceed 125° C temperature rise above the ambient temperature for any recorded cycle (record temperature for at least one cycle every day).

ANSI C119.4: Connector temperature cannot exceed the control conductor temperature for any cycle (recorded just prior to the end of the 'on' period).

- **Temperature Stability**

UL 486B: Stability Factor: "S"= $((\text{Connector}-\text{Control}) - \Sigma(\text{Connector}-\text{Control})/N)$ can not exceed $\pm 10^\circ \text{C}$ when determined for each of the 11 (i.e. $N=11$) measurements taken at 25, 50, 75, 100, 125, 175, 225, 275, 350, 425, and 500 cycles.

ANSI C119.4: Temperature difference between a connection and the control, in a given loop, shall not be less than the minimum control limit.

Control Limit = Avg... of the differences - 10°C

- **Resistance Stability**

UL 486B: Not specified

ANSI C119.4:

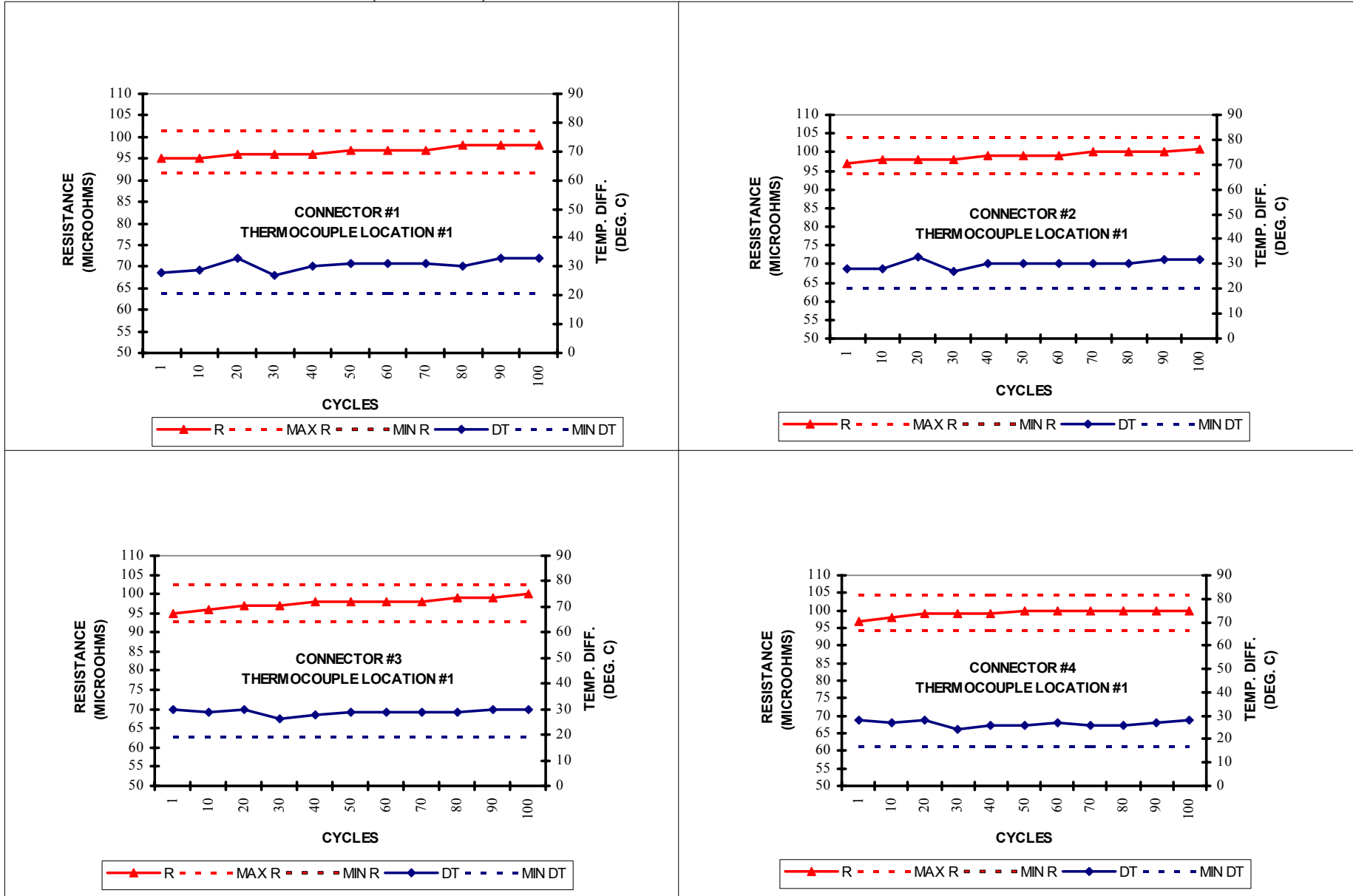
- Resistance of any connection shall not exceed the limits.

Resistance limits = $\pm 5\%$ from average of all the measured resistances of that connection at the end of 1, 10, 20, ..., and 100 cycle.

COMPARISON OF THE TWO TEST METHODS FOR THIS TEST PROGRAM

CDR.	T310-16 AMP. 90° C	CONN. AL9CU	CDR. RANGE	UL 486B ⁺					ANSI C119.4 (CCST)					ACTUAL CURRENT AMP.
				TORQ. IN.LB.	ON HR.	OFF HR.	LENGTH IN.	CURRENT AMP.**	TORQ.*** IN.LB	ON HR	OFF**** HR	LENGTH IN.	EST***** CURRENT	
XHHW-2 (RW90-600V)⁺ AA-8030 ALUMINUM CONDUCTORS														
#2	100	TA-2	2-14	40	1	1	18	190	50	1	0.5	12	170	215
#2/0	150	TA-2/0	2/0-6	100	1	1	18	295	120	1	0.5	12	270	347
#4/0	205	TA-250	250-6	225	1.5	1.5	18	390	275	1	0.5	12	380	475
500 kcmil	350	TA-600-2NS	600-2	400	2	2	18	680	500	1.5	0.5	24	685	832
750 kcmil	435	TA-800-2NS	800-300	400	2	2	26	870	500	1.5	0.5	24	930	1095
THHN-2 (T90)⁺ COPPER CONDUCTORS														
#4	95	TA-2	2-14	40	1	1	12	175	50	1	0.5	12	130	204
#1	150	TA-0	1/0-14	40	1	1	18	275	50	1	0.5	12	290	335
#2/0	195	TA-2/0	2/0-6	100	1	1	18	370	120	1	0.5	12	400	448
350 kcmil	350	TA-350-2NS	350-6	300	1.5	1.5	18	705	375	1.5	0.5	24	780	833
500 kcmil	430	TA-600-2NS	600-2	400	2	2	18	870	500	1.5	0.5	24	990	1058
Notes:	⁺ CSA C22.2 No. 65 is an equivalent standard, used in Canada, to UL 486B standard used in US. [*] CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project. ^{**} Estimated current in UL 486B is for Type USE conductors. ^{***} ANSI C119.4 provides a recommended torque value. However, fastener size reference is different. Hence, manufacturer's recommendation is shown here. ^{****} In CCST method the connections are immersed in still, chilled water (5 C +/- 4 C) within 30 seconds of the start of the current -OFF period. Remain immersed for 15 minutes after the temperature of the connector is reduced to the temp. of the water. ^{*****} Estimated current in CCST is for bare conductors. 1. Length of the control conductor is twice that of the sample length in both test methods.													

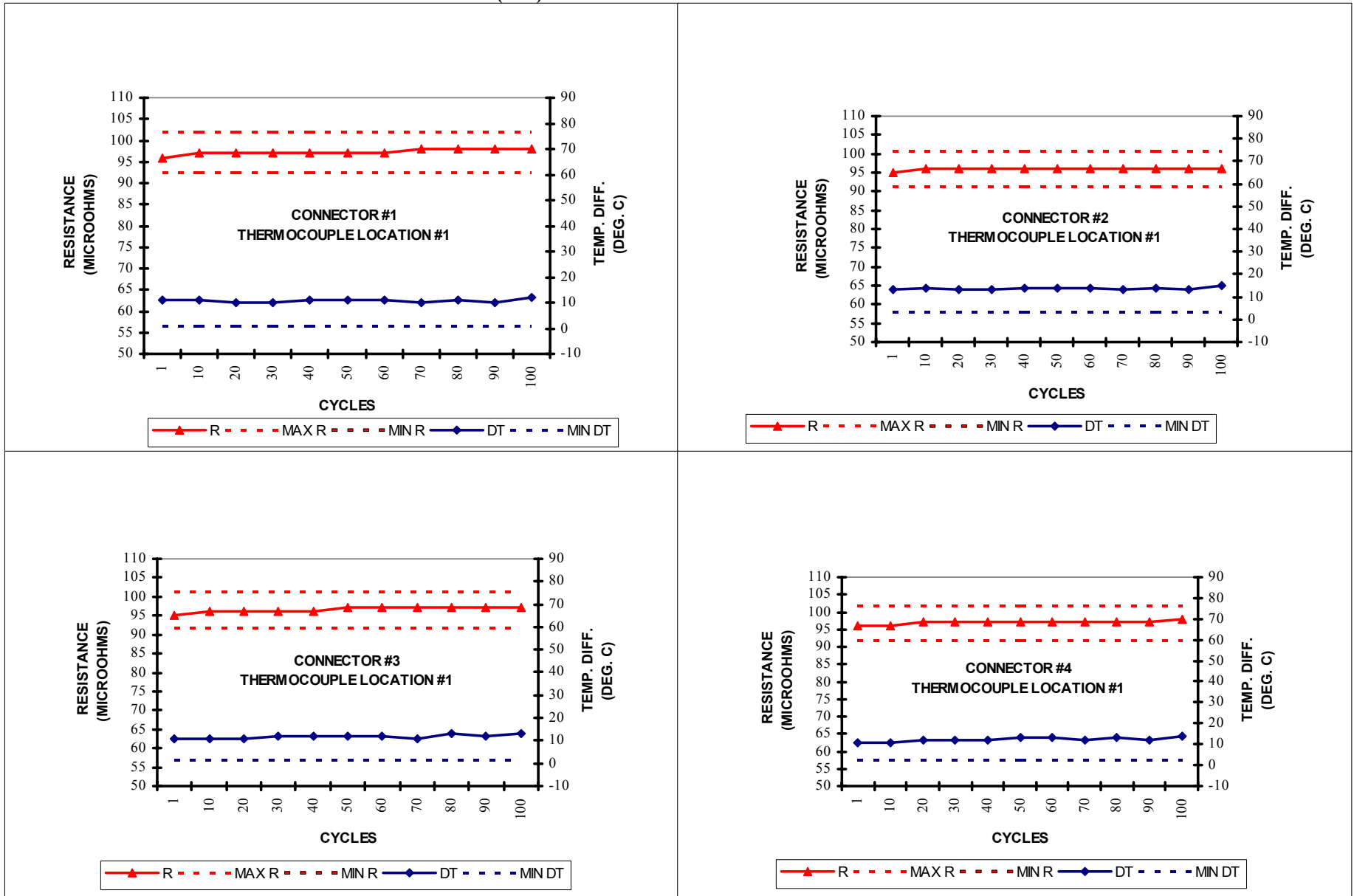
**COMPARISON OF CONDUCTOR PERFORMANCE FOR ALCAN CABLE
ANSI C119.4 TEMPERATURE DIFFERENCE AND RESISTANCE VALUES FROM CURRENT CYCLE SUBMERSION TEST (100 CYCLE)
PERFORMED ON 4/0 AWG XHHW-2 (RW90-600V)* AA-8030 ALUMINUM ALLOY CONDUCTORS USING LISTED SCREW TYPE CONNECTORS**



CONNECTIONS WITH RECOMMENDED TORQUE AND RECOMMENDED PREPARATION

* CSA listed RW90 conductors with aluminum alloy conductor material and 600 Volt insulation thickness are equivalent products to UL listed XHHW-2 products shown above and evaluated in this project.

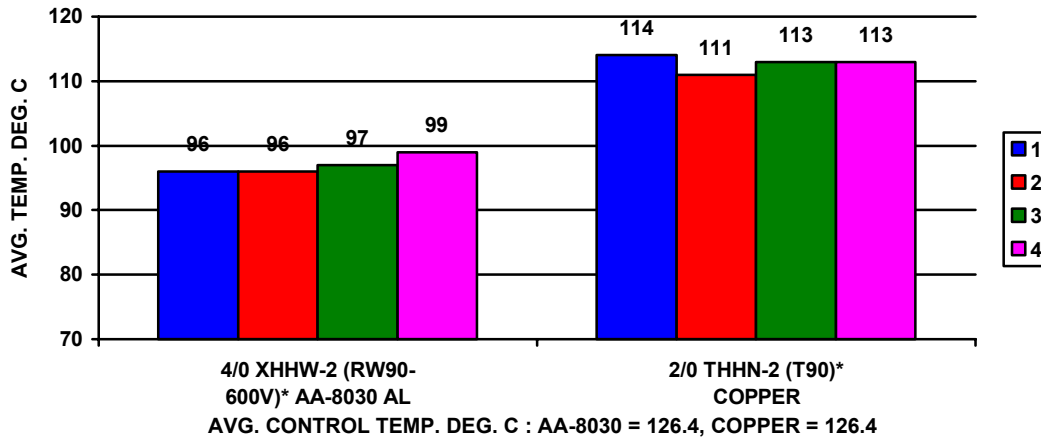
**COMPARISON OF CONDUCTOR PERFORMANCE FOR ALCAN CABLE
ANSI C119.4 TEMPERATURE DIFFERENCE AND RESISTANCE VALUES FROM CURRENT CYCLE SUBMERSION TEST (100 CYCLE)
PERFORMED ON 2/0 AWG THHN-2 (T90)* COPPER CONDUCTORS USING LISTED SCREW TYPE CONNECTORS**



CONNECTIONS WITH RECOMMENDED TORQUE AND RECOMMENDED PREPARATION

* CSA listed T90 conductors are equivalent products to UL listed THHN-2 products shown above and evaluated in this project.

**COMPARISON OF CONDUCTOR PERFORMANCE FOR ALCAN CABLE
AVERAGE TEMPERATURE VALUES FROM CURRENT CYCLE SUBMERSION
TEST (100 CYCLE) PERFORMED ON AA-8030 ALUMINUM ALLOY AND
COPPER CONDUCTORS USING LISTED SCREW TYPE CONNECTORS**

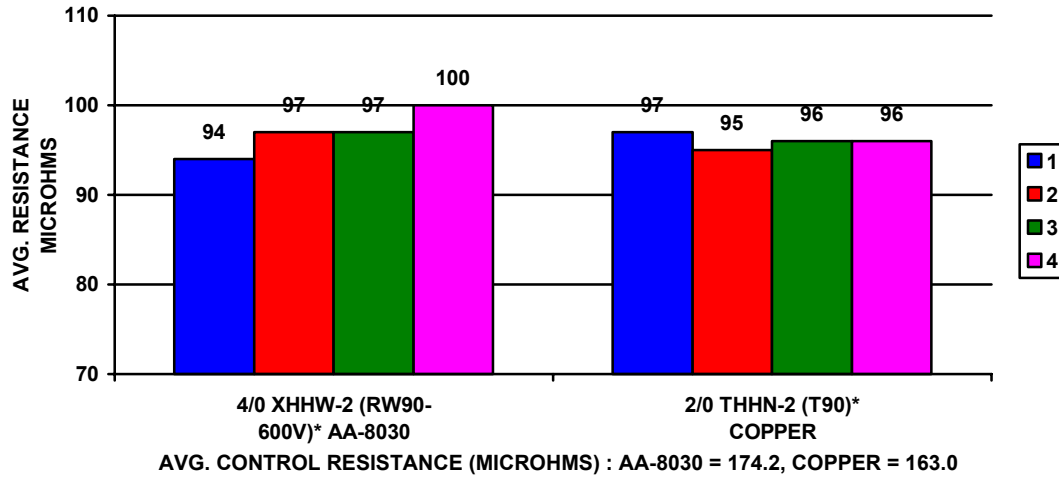


**FOUR CONNECTORS WITH RECOMMENDED TORQUE AND
RECOMMENDED PREPARATION**

TESTED AT GEORGIA POWER RESEARCH CENTER

* CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

**COMPARISON OF CONDUCTOR PERFORMANCE FOR ALCAN CABLE
AVERAGE RESISTANCE VALUES FROM CURRENT CYCLE SUBMERSION
TEST (100 CYCLE) PERFORMED ON AA-8030 ALUMINUM ALLOY AND
COPPER CONDUCTORS USING LISTED SCREW TYPE CONNECTORS**

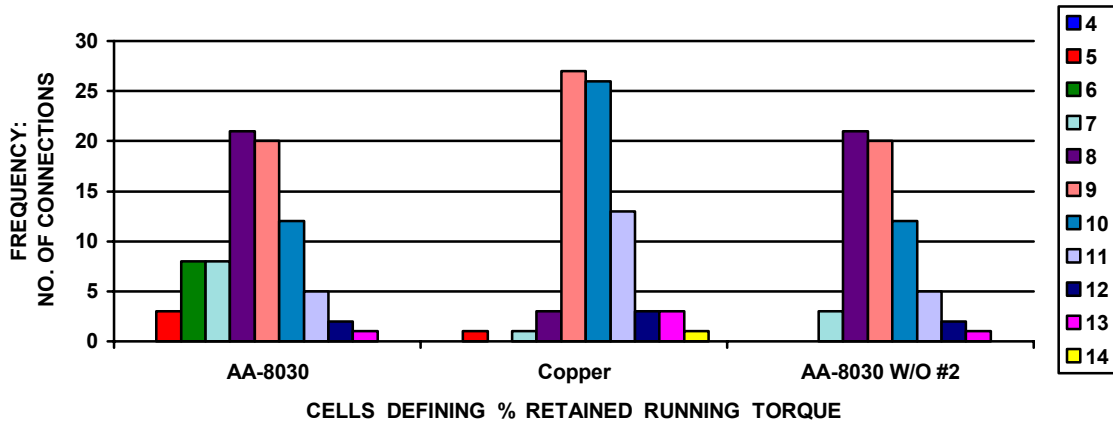


**FOUR CONNECTORS WITH RECOMMENDED TORQUE AND
RECOMMENDED PREPARATION**

TESTED AT GEORGIA POWER RESEARCH CENTER

* CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

**COMPARISON OF CONDUCTOR PERFORMANCE FOR ALCAN CABLE
FREQUENCY DISTRIBUTION FOR % RETAINED RUNNING TORQUE VALUES AFTER CURRENT
CYCLE SUBMERSION TEST (100 CYCLE) PERFORMED ON XHHW-2 (RW90)* AA-8030 ALUMINUM
ALLOY AND THHN-2 (T90)* COPPER CONDUCTORS USING LISTED SCREW TYPE CONNECTORS**

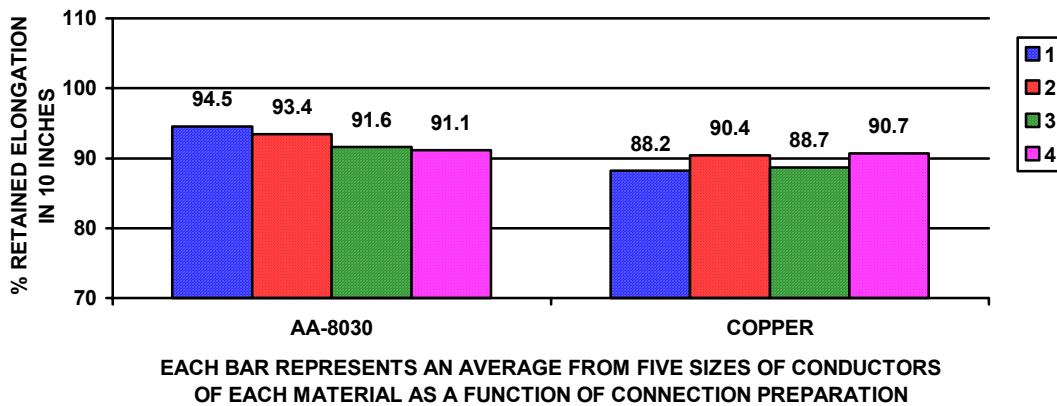
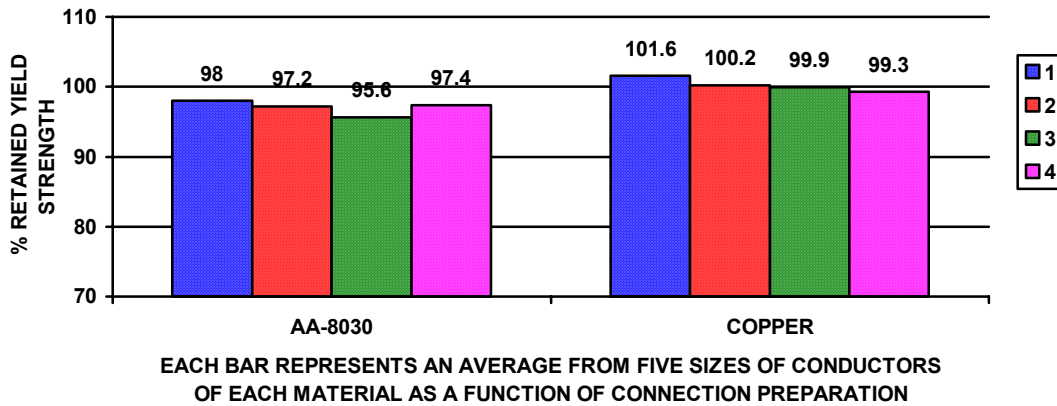
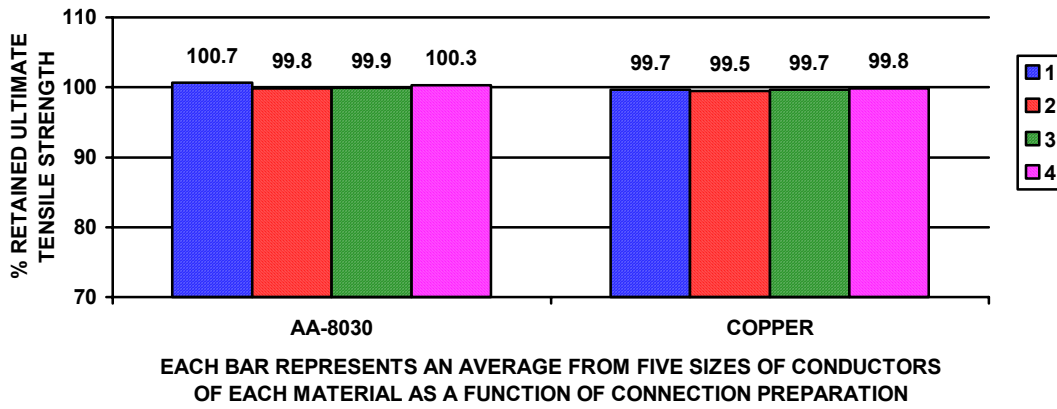


* CSA listed RW90 with aluminum alloy conductor material and 600 Volt insulation thickness and T90 with copper conductor are equivalent products to UL listed XHHW-2 and THHN-2 products, respectively, shown above and evaluated in this project.

CELL NUMBER	4	5	6	7	8	9	10	11	12	13	14
RANGE FOR % RETAINED RUNNING TORQUE	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150
FREQUENCY FOR AA-8030 CONNECTIONS		3	8	8	21	20	12	5	2	1	
FREQUENCY FOR COPPER CONNECTIONS		1		1	3	27	26	13	3	3	1
FREQUENCY FOR AA-8030 W/O #2 CONNECTIONS				3	21	20	12	5	2	1	

- Notes:
1. Performance from five sizes of AA-8030 conductors is compared against the five electrically equivalent sizes of copper conductors in this data.
 2. Retained torque measurements from 80 connections were expressed in % retained of the original tightening torque used for each connection.
 3. A loop consisting of 16 connections was made per conductor size for each conductor type for CCST . These 16 connections were further divided into groups of four by the following installation conditions:
 1. Recommended torque & recommended conductor preparation
 2. Recommended torque & no conductor preparation
 3. High torque & recommended conductor preparation
 4. Low torque & recommended conductor preparation
 4. Running torque measurements from two connections on a copper conductor could not be obtained.
 5. Cell numbers 1 through 3 are not shown as there were no torque measurements that would fall under those ranges.

% RETAINED UTS, YIELD & ELONGATION OF SPECIMENS AFTER CCST AS A FUNCTION OF CONNECTION PREPARATION



- 1 = RECOMMENDED TORQUE AND RECOMMENDED CONDUCTOR PREPARATION
- 2 = RECOMMENDED TORQUE AND NO CONDUCTOR PREPARATION
- 3 = HIGH TORQUE AND RECOMMENDED CONDUCTOR PREPARATION
- 4 = LOW TORQUE AND RECOMMENDED CONDUCTOR PREPARATION