

OVERHEATING FAILURES OF ALUMINUM-WIRED

SPECIAL SERVICE CONNECTORS

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ABSTRACT

In this investigation, "special service" twist-on connectors are tested with aluminum and copper wire combinations. The "special service" connectors are qualified by a Canadian standard which applies to connectors for use with aluminum branch circuit conductors. Two brands of special service connectors are presently qualified by this standard and marketed. Both are rated for various combinations of aluminum and copper conductors. Samples of both brands are tested in this investigation. The tests are conducted within rated electrical and environmental conditions, with connections made according to the connector manufacturers' instructions. Overheating failures have occurred among the aluminum-wired special service connector combinations. The failures are accelerated by humid environment to a greater extent than by the application of electrical current. In contrast, connections which are copper-wired, using either standard or special service connectors, are stable and failure free.

The difference between the standard twist-on connectors and the special service connectors is in the material used for the connector spring. Improved compatibility between the spring material and the aluminum conductor, compared to the plated steel springs of the conventional twist-on connectors, has not dealt with several important failure mechanisms. The test results indicate that the new standard, as presently defined, cannot be relied on to screen out aluminum-wired connector combinations which will not survive long term operation within rated conditions. Thus, the objective of accelerated qualification testing - the prediction and assurance of safe and reliable operation in actual service - is not achieved in this case. The reasons are discussed, along with possible improvements.

INTRODUCTION

Splicing connectors are an important component of branch circuit wiring in buildings, as a variety of splices must be made in most installations. Additionally, and specific to aluminum-wired installations, short lengths ("pigtails") of copper conductor must be spliced to the aluminum conductor to permit use of devices not approved for direct connection to the aluminum wire. Except for receptacles and switches with CO/ALR rating, and most distribution panel equipment, the connection of other devices and apparatus presently on the market would require copper wire pigtail to conform to electrical code requirements in an aluminum-wired system.

Twist-on connectors are the most commonly used splicing connectors for residential branch circuit wiring in the United States and Canada. Many different brands and types are commonly available which are rated for use with aluminum-to-aluminum, aluminum-to-copper, and copper-to-copper conductor combinations. A single size twist-on connector may be applicable to a wide range of wire sizes and combinations.

The type of twist-on connector being considered consists of a conical metal coil spring within a constraining plastic insulator. Most brands on the market today in the United States and Canada have zinc or tin-plated steel springs, and they have

been found to have high failure rates when used with aluminum wire.¹

"Special service" connectors have been qualified by a relatively recent Canadian standard which includes static heating and "heat cycle" tests as the principal determinants of connection performance. Both tests involve the passage of current substantially higher than rated. Special service connectors presently on the market have presumably passed the qualification tests required by the standard.

Two brands of special service connectors are available, and both are similar in design to the conventional twist-on connectors of their respective brands. The significant difference is that the springs of the special service connectors are made of a tin-plated copper alloy. Both brands are claimed to be suitable for use with aluminum wire.

The most basic test of whether or not the special service connectors are suitable for use with aluminum wire is to assemble connections according to the manufacturer's instructions and operate them within their rated electrical and environmental conditions. This paper presents the results of such tests.

EXPERIMENTAL METHOD

Connectors Tested

Two brands of special service twist-on connectors are tested in this investigation. One brand indicates Canadian approvals only, on the package, while the other indicates approvals for use with aluminum wire in both the United States and Canada. Copper-wired control groups, using both special service and conventional twist-on connectors, are also tested. All connectors were purchased from consumer or contractor sources.

Connector Installation

Connections are made in series-connected groups, consisting of 152 mm (6 in) lengths of conductor spliced together with the twist-on connectors. In addition to the insulation stripped from the conductor ends for the splices, a short length of conductor insulation is removed along each section of wire to permit measurement of the potential drop of individual connection segments.

The connectors are installed according to the manufacturers' instructions provided on the packages. The conductors are not pretwisted. No antioxidant is used on the conductors or in the connectors. There

is no surface preparation of the conductors other than removal of the insulation with a wire stripper. All connections are tightened until there is a significant amount of twisting together of the conductors outside the connectors, or, for the larger sizes of conductors, to the limit of torque which can be applied by hand (without tools).

Conductors Tested

The aluminum conductors used in these tests include both EC and alloy aluminum. Connectors approved for use with aluminum wire must be suitable for both types for application to existing wiring systems as well as new installations. In the United States, alloy aluminum conductor must be used, for sizes #8 AWG and smaller, in new installations. Most existing aluminum residential installations are wired with the previously-approved EC grade of aluminum. In Canada, existing aluminum-wired residences have EC conductor, as the alloy material has not been marketed in that country. EC aluminum wire is still approved in Canada, with alloy aluminum also approved as an alternate material.

The EC aluminum conductors used in the tests include samples removed from residential structures in both the United States and Canada, as well as samples which had been purchased from electrical supply distributors. Alloy aluminum and copper wire samples were obtained from electrical supply distributors and retail sources, with the exception of the Canadian alloy, which was obtained from an industry source.

Aluminum conductors used in these tests are #12 and #10 AWG, solid. These are the sizes appropriate for 15 and 20 A branch circuits.

Connector/Conductor Combinations Tested

Table 1 shows the various connector and conductor combinations tested in this study. Connectors are identified by brand as X, Y, and Z, and the letters correspond to those previously used in Reference 1. The size of the connector is indicated by a subscript, as for instance Y₁ and Y₂. Connector Y₂ is the larger of the brand Y type. (Connectors identified without subscripts in Reference 1 are all the smaller size.) The aluminum conductors are identified by number, and here also the identifications are coordinated with those previously used in Reference 1.

The connection groups are also identified to coordinate with Reference 1, and it should be noted that two copper-wired groups (C and E) originally reported on in Reference 1 are included in this present paper, with updated results, for comparison.

CONNECTION GROUP	NO. OF CONNECTIONS	CONNECTOR TYPE	CURRENT-CARRYING CONDUCTORS	ADDITIONAL CONDUCTORS	TYPE OF ALUMINUM CONDUCTOR
C	30	Y ₁ Standard	(2) #14 Cu	---	---
E	20	Z ₁ Standard	(2) #14 Cu	---	---
G	33	Y ₂ Special Service	(2) #12 Al	(1) #14 Cu	Al #4, EC, Canada
H	33	Y ₁ Special Service	(2) #12 Al	---	Al #5, EC, U.S.
I	30	Y ₁ Special Service	(2) #14 Cu	---	---
J	20	Y ₂ Special Service	(2) #12 Al	---	Al #4, EC, Canada
K	30	Y ₂ Special Service	(1) #12 Al (1) #14 Cu	(1) #12 Al	Al #4, EC, Canada
L	28	X ₁ , X ₂ Spec. Serv.	Various Combinations		Al #4, EC, Canada
M	15	Y ₁ Special Service	(2) #12 Al	---	Al #6, Alloy, Canada
N ₁ ;N ₂	20;20	Y ₂ Special Service	(2) #10 Al	---	Al #7, EC, U.S.
O ₁ ;O ₂	20;20	Y ₁ Special Service	(2) #12 Al	---	Al #6, Alloy, Canada
P ₁ ;P ₂	20;20	Y ₁ Special Service	(2) #12 Al	---	Al #3, Alloy, U.S.
Q ₁ ;Q ₂	20;20	Y ₂ Special Service	(2) #10 Al	---	Al #8, EC, U.S.
R ₁ ;R ₂	20;20	Y ₁ Special Service	(2) #12 Al	---	Al #2, Alloy, U.S.
S ₁ ;S ₂	20;20	Z ₂ Standard	(2) #10 Cu	---	---

TABLE 1 - CONNECTION GROUP CONNECTOR/CONDUCTOR COMBINATIONS

There are 16 groups of aluminum-wired connections employing the special service twist-on connectors. There is one copper-wired group with special service connectors and there are four copper-wired groups employing standard (steel spring) twist-on connectors.

Two of the copper-wired groups (S₁ and S₂) use #10 AWG conductor, which is over-size for a 20 A circuit. This was done to obtain the same mechanical results with the copper conductor as with the #10 aluminum. With this size conductor it is difficult to achieve significant twisting together of the conductors inside the connector when it is applied by hand. Additionally, the mechanical security of the connections with this size wire was observed to be poor relative to the stiffness of the wire.

Applied Electrical Conditions

All connections tested are in circuits which are powered from a 115 Vac source. Wire-wound resistors are used as circuit loads. Current flows in the circuits for periods not exceeding one hour. Off periods are one-half hour minimum.

The applied current is kept within the circuit rating, as proper for the size of conductors in the various test groups. The duty cycle for a given specimen group is either 0%, 13%, or 50%. Where 0% is indicated, it means that no current is applied to the specimen group except for approximately 10 minutes per week during which measurements of potential drop are taken. Specific values for the applied current and duty cycle for the various specimen groups are provided in the tabulation of results.

Two test environments are used. The first represents conditions within a junction or outlet box in a residential perimeter wall. The temperature varies on a seasonal and daily basis, and has ranged between 6 C and 40 C. The relative humidity in this environment ranges between 40% and 60% during the year, with occasional higher values according to outside ambient conditions. The maximum observed has been 82% RH. This environment, involving varying temperature and relative humidity, is designated as the "normal" environment in the following sections.

The second environment used is constant at 35 C and 90% RH. This environment is designated as the "constant" environment in the following sections.

Both of the environments are within the expected application range for residential wiring. Specific identification of the specimen groups with their environment is provided in the tabulation of results.

Failure Criterion

The failure criterion used in earlier work on this type of connection, potential drop for the connection and the associated length of conductor of 40 mV, at the test current (Table 2), is used in this present study.¹ The criterion is based on the observation that connections exceeding that level rapidly progress to erratic behavior at substantially higher potential drop. The potential drop increase reflects contact resistance increases in the connection. The failure criterion represents a connection resistance approximately an order of magnitude greater than the average initial connection resistance of the aluminum-wired twist-on connections.

The amount of heat generated at a connection when it is passing current is directly related to the connection resistance. A fundamental principle of safety for the wiring in buildings is that high temperatures at connections are hazardous. While some protection is provided by enclosures, the high temperatures which can be developed at deteriorating branch circuit connections can lead to fire in many ways.² The lowest temperature at which the heating of a connection is considered to be hazardous is that which causes disintegration or flow of the insulation of the connector or conductors. Connections reaching this stage are considered to be "severe failures".

Failures of Aluminum-Wired Connections

Table 2 provides a summary of the electrical and environmental conditions, the time on test, and the number of connections that have failed for each group. There are no failures among the connections of the copper-wired groups (C, E, I, S₁, and S₂), either with the standard or the special service connectors.

Among the aluminum-wired connection groups, all of which are made with special service connectors, there are failures. Among the aluminum-wired groups that have been on test for the longer periods of time, there is a significant difference in the failure rate according to the number of conductors in the connection. Those with three conductors, one of which is copper, constitute a test of the "pigtailing" method of adapting aluminum wire to receptacle terminals not rated for use with aluminum wire.³ The failure rates are highest for these groups (G and K), with 25 of 63 connections (40%) having failed in 18 months of operation in normal environment within rated electrical conditions. One of these connections has become hot enough to deteriorate the conductor insulation and the insulating shell of the connector has cracked. This connection is shown in Figure 1.

Among the other aluminum-wired groups which have been on test for a relatively long time (H, J, L, and M), 9 failures have occurred in 96 connections (9% failures).

The remaining aluminum-wired groups (N₁ through R₂) are five identically-wired pairs of specimen groups. One of each pair (subscript "1") is subjected to the normal (varying) environment and is tested at 90% of rated current, 13% duty cycle. Among these specimen groups, in one month of testing, there are 6 failures in 100 connections.

The other member group of each pair (subscript "2") is subjected to the constant environment, 35 C and 90% RH, and has no current applied except for the purpose of taking measurements once a week. Among these specimen groups, in one month of testing, there are 35 failures in 100 connections. Note that in Table 2 the category of "severe failure" is not applicable for these connection groups, since without current flowing for any significant time there is no opportunity for high temperatures to develop.

GROUP (No. of connections)	TYPE OF CONNECTOR	CURRENT-CARRYING CONDUCTORS	CURRENT, AMPS	DUTY CYCLE, %	ENVIRONMENT	TIME, Mo.	NO. OF FAILURES	NO. OF SEVERE FAILURES
C (30)	Std.	Cu-Cu	13.5	13	Normal	24	0	0
E (20)	Std.	Cu-Cu	13.5	13	"	15	0	0
G (33)	Sp. Serv.	Al-Al	12	50	"	18	14	0
H (33)	Sp. Serv.	Al-Al	12	50	"	18	5	0
I (30)	Sp. Serv.	Cu-Cu	12	50	"	18	0	0
J (20)	Sp. Serv.	Al-Al	12	50	"	18	2	0
K (30)	Sp. Serv.	Al-Cu	12	50	"	18	11	1
L (28)	Sp. Serv.	Al-Cu/Al-Al	12	50	"	17	2	0
M (15)	Sp. Serv.	Al-Al	13.5	13	"	10	0	0
N ₁ (20)	Sp. Serv.	Al-Al	18	13	"	1	0	0
N ₂ (20)	Sp. Serv.	Al-Al	18*	0	Constant	1	6	NA**
O ₁ (20)	Sp. Serv.	Al-Al	13.5	13	Normal	1	0	0
O ₂ (20)	Sp. Serv.	Al-Al	13.5*	0	Constant	1	6	NA**
P ₁ (20)	Sp. Serv.	Al-Al	13.5	13	Normal	1	1	0
P ₂ (20)	Sp. Serv.	Al-Al	13.5*	0	Constant	1	5	NA**
Q ₁ (20)	Sp. Serv.	Al-Al	18	13	Normal	1	5	0
Q ₂ (20)	Sp. Serv.	Al-Al	18*	0	Constant	1	11	NA**
R ₁ (20)	Sp. Serv.	Al-Al	13.5	13	Normal	1	0	0
R ₂ (20)	Sp. Serv.	Al-Al	13.5*	0	Constant	1	7	NA**
S ₁ (20)	Std.	Cu-Cu	18	13	Normal	7	0	0
S ₂ (20)	Std.	Cu-Cu	18*	0	Constant	1	0	NA**

* Current applied only for potential drop measurement.

** Not applicable (see text)

TABLE 2 - TEST CONDITIONS AND FAILURES

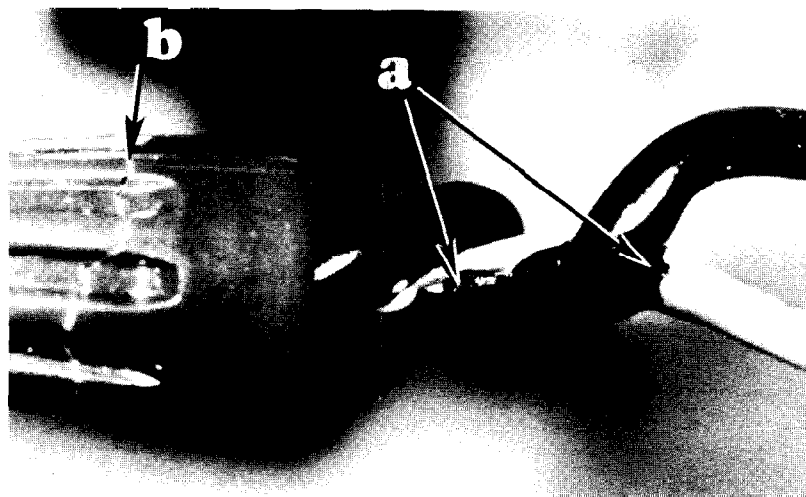


FIGURE 1 - FLOWING CONDUCTOR INSULATION (a) AND CRACKED CONNECTOR SHELL (b) DUE TO CONNECTION OVER-HEATING. SEVERE FAILURE, GROUP K.

Initial Resistance

The resistance of the newly-made twist-on connections has been determined by subtracting the bulk conductor resistance from the resistance of the connection group and dividing by the number of connections.¹ Initial failures are omitted from the group measurements for these calculations. The results are shown in Table 3.

The average initial connection resistance of the aluminum-wired twist-on connections made with special service connectors is an order of magnitude higher than those that are copper-wired. The resistance of the aluminum-wired connections is somewhat lower with the special service connectors than previously determined with conventional (steel spring) connectors.¹ This is most likely a consequence of the lower resistance of the copper alloy spring material of the special service connectors. For instance, the resistance of the spring wire in the Y₂ special service connector is measured to be approximately 60% of the resistance of the spring in the standard Y₂ connector.

GROUP (Wire)	NUMBER OF CONNECTIONS	AVERAGE INITIAL RESISTANCE, ohm
E (Cu)*	20	0.045x10 ⁻³
** (Cu)	20	0.025 "
** (Cu)	20	0.065 "
I (Cu)	30	0.015 "
S _{1&2} (Cu)	40	0.050 "
H (Al)	33	0.22 "
J (Al)	20	0.18 "
M (Al)	15	0.30 "
N _{1&2} (Al)	39***	0.23 "
O _{1&2} (Al)	40	0.32 "
P _{1&2} (Al)	40	0.35 "
Q _{1&2} (Al)	39***	0.48 "
R _{1&2} (Al)	39***	0.32 "

TABLE 3 - RESISTANCE OF NEWLY-MADE CONNECTIONS.

* Data from Reference 1

** Copper-wired groups from other experiments. Y₁ (standard) connector.

*** Initial failures deleted.

Potential Drop Measurements

Potential drop measurement results are shown in Table 4. The copper-wired groups are stable and failure-free. The aluminum-wired groups are not. Deteriorating aluminum-wired connections show slow increases in potential drop in the early stages of the failure process, followed by erratic operation at substantially higher levels, involving heat generation of the order of several watts. The maximum heat generation calculated from the observations of Table 4 is 10 watts for the worst case failure of group Q₁ (560 mV at 18 A).

Figure 2 shows the average connection potential drops for groups N₁ through S₂ as a function of time. The average potential drop is calculated with the failures omitted. Figure 3 shows the number of failures with time for the same groups.

GROUP (Wire)	TIME, mo.	FAILURES			SURVIVORS	
		NO. OF	AVG. POT. DROP, mV	MAX. POT. DROP, mV	NO. OF	AVG. POT. DROP, mV
C (Cu)	24	0	-	-	30	17
E (Cu)	15	0	-	-	20	18
G (Al)	18	14	88	256	19	23
H (Al)	18	5	59	74	28	18
I (Cu)	18	0	-	-	30	14
J (Al)	18	2	75	86	18	20
K (Al-Cu)	18	11	86	230	19	21
L (Al-Cu)	17	2	91	112	26	18
M (Al)	10	0	-	-	15	23
N ₁ (Al)	1	0	-	-	20	20
N ₂ (Al)	1	6	159	268	14	24
O ₁ (Al)	1	0	-	-	20	24
O ₂ (Al)	1	6	79	138	14	25
P ₁ (Al)	1	1	-	140	19	24
P ₂ (Al)	1	5	102	302	15	28
Q ₁ (Al)	1	5	220	560	15	24
Q ₂ (Al)	1	11	57	86	9	28
R ₁ (Al)	1	0	-	-	20	23
R ₂ (Al)	1	7	140	322	13	27
S ₁ (Cu)	7	0	-	-	20	10
S ₂ (Cu)	1	0	-	-	20	10

TABLE 4 - POTENTIAL DROP MEASUREMENTS

(Connection With Wire Segment)

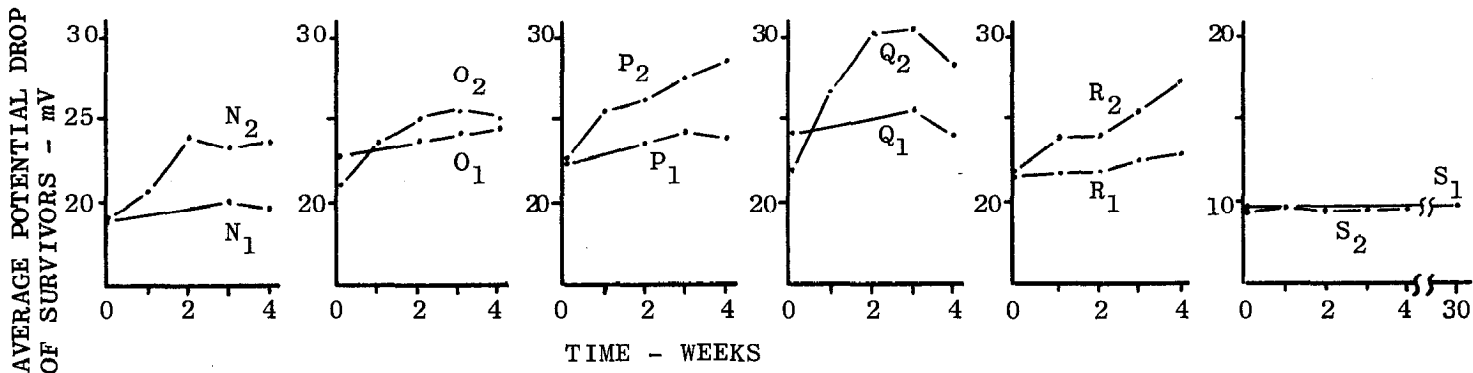


FIGURE 2 - POTENTIAL DROP OF SURVIVORS, GROUPS N_1 THROUGH S_2

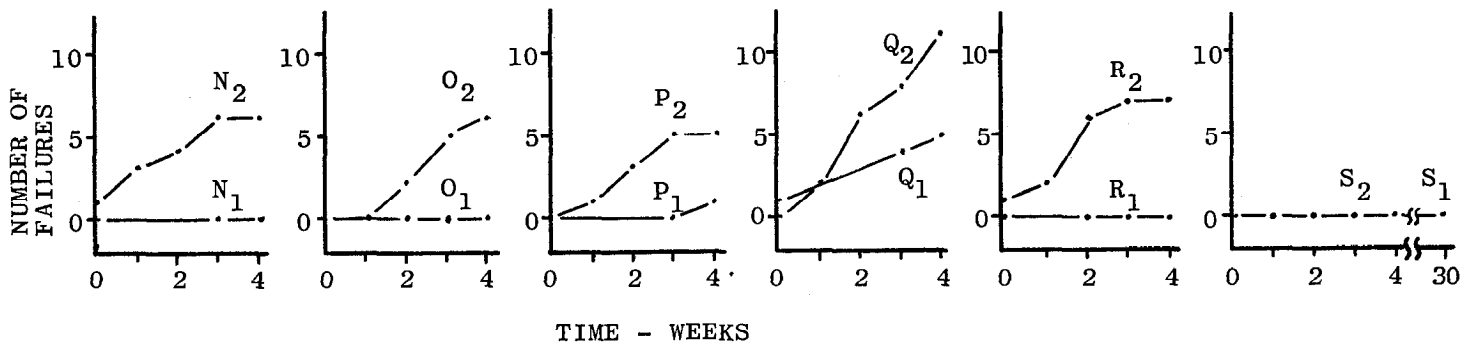


FIGURE 3 - NUMBER OF FAILURES, GROUPS N_1 THROUGH S_2

Figures 2 and 3 are subdivided to show clearly the difference in results obtained with identical connection groups subjected to different environments. In all cases with aluminum-wired connection groups, N through R, the group exposed to the constant high humidity environment (subscript "2") has a faster increase of potential drop and a higher failure rate than the group exposed to the normal environment (subscript "1"). In interpreting the potential drop results, it should be kept in mind that the population on which the average potential drop is based is decreasing as some of the connections with high readings cross the failure threshold.

Among the aluminum-wired groups in the high humidity environment, 84 of the 100 connections have shown significant (greater than 2 mV) increase in potential drop. Among the groups in the normal (varying) environment, 25 of the 100 connections have increased significantly in potential drop.

The copper-wired groups are stable in both environments. Of the 40 connections in the groups S_1 and S_2 , none have shown a significant change in potential drop. Note that one of the copper-wired control groups (S_1) of this environmental comparison experiment was installed six months

prior to the other groups. None of the specimen groups have been removed from the test system in these continuing experiments.

Vibrations

Vibrations are detected in some overheating special service connections. When previously detected in steel spring connectors, the vibrations were attributed to the electromagnetic forces caused by current flow in the spring.¹ Since the spring in the special service connectors is normally a copper alloy material, non-magnetic, the vibrations detected would have to be due to electrostatic forces in these cases. That the springs were non-magnetic was confirmed (using an external permanent magnet) for several cases in which vibrations were detected.

Other Special Service Connections

Some special service connectors are used for interconnections in the test system, and so are subjected to the same environmental and electrical conditions as the test groups. One severe failure has occurred among these connections, and this is shown in Figure 4.

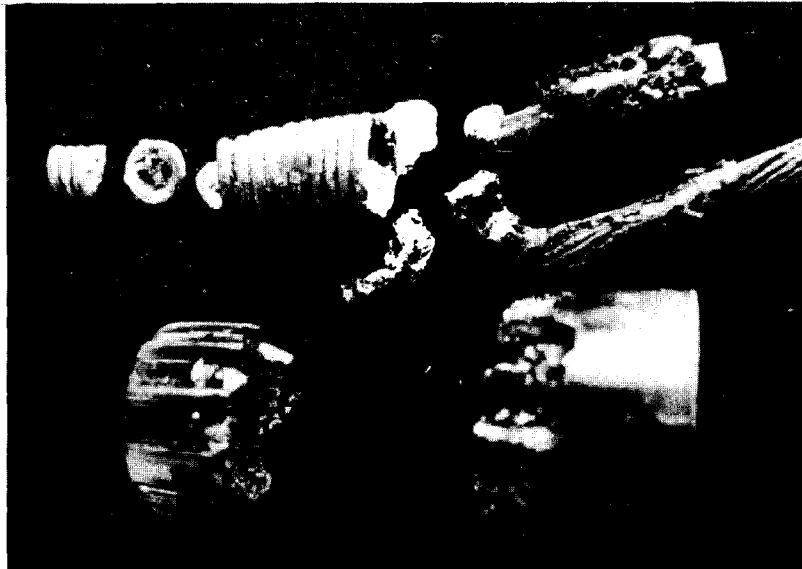


FIGURE 4 - REMAINS OF SPECIAL SERVICE CONNECTOR
USED TO SPLICE SOLID #12 ALUMINUM
(ALLOY) TO STRANDED #12 COPPER. TIME
TO FAILURE: LESS THAN ONE YEAR,
13.5 A, 13.5% DUTY CYCLE, NORMAL ENV.

DISCUSSION

General

The results show that there is a substantial difference in performance between copper-wired and aluminum-wired connections of the type tested. The copper-wired twist-on connections perform well. The aluminum-wired twist-on connections do not, whether made with standard or special service connectors.

There is little difference in the initial performance of the aluminum-wired connections made with special service connectors compared with those investigated previously made with the conventional connectors.¹ In both cases the initial resistance is high compared to that achieved in copper-wired connections. With both types of connectors, aluminum-wired, there are initial failures and a significant number of additional failures with time. Whether or not there is a meaningful statistical difference in the failure rates cannot be determined by these small-scale tests, and any such difference as may exist is insignificant considering that in both cases the failure rates are many orders of magnitude too high for the intended application conditions and quantities.

That the deterioration processes which take place in these aluminum-wired special service connections can lead to hazardous levels of overheating has also been demon-

strated. Here again, the difference between connector types, in performance, is small compared to the improvement necessary to assure safe field performance in long-term use.

As with the connections previously studied (Reference 1), the poor performance is primarily due to failure to achieve and sustain low conductor-to-conductor contact resistance when these connections are made with aluminum wire in accordance with the manufacturers' instructions. The mechanical conditions at the conductor-to-conductor interface are the same in both types of connectors, and therefore the performance at that contact interface is expected to be the same. The larger portion of the current, in the aluminum-wired connections, flows from conductor to conductor through sections of the connector spring. The spring in the special service connectors is considered to be more suitable for contacts with aluminum than that of the conventional connectors, it is clear that deterioration nevertheless occurs at the conductor-to-spring contacts in the connections.

It was previously determined that the initial conductor-to-conductor resistance of these aluminum-wired twist-on connections is approximately 1×10^{-3} ohm, while the combined resistance of the current paths through the (steel) connector spring

is approximately 0.5×10^{-3} ohm.¹ The connector spring path resistance of the special service connectors would be lower due to the change in spring material. If the conductor-to-conductor contact alone deteriorated, to an open circuit condition, the connection resistance would increase to that of the spring path resistance, and the potential drop would not exceed the failure threshold. Similarly, if the conductor-to-spring contacts alone were deteriorating, the limiting resistance would be that of the conductor-to-conductor contact. The potential drop increases of the failed connections indicate connection resistances of the order of 10×10^{-3} ohm. The degradation processes in these connections therefore involve both the conductor-to-conductor and the conductor-to-spring contacts.

There is no outstanding difference in the performance of these connections as a function of the type of aluminum wire. Failures occur in connections wired with Canadian and U.S. aluminum wires, both EC and alloy types. Tests by Ontario Hydro also found that there is no significant difference in the performance of alloy aluminum wire compared with EC aluminum wire in this type of connection.⁴ Additionally, the Ontario Hydro tests indicate that special service connectors joining #12 solid aluminum to #14 stranded copper have a "median test life" only 1/6 that of the equivalent copper-to-copper combination using the conventional twist-on connectors. The tests were performed at 27.5 A with a duty cycle of 88%, the high current and duty cycle having been chosen to "accelerate the failure processes".

The failure processes are not all accelerated by high current, however. In these present tests humidity is seen to be a more significant factor than current or duty cycle in the failure processes for aluminum-wired twist-on connections. The application of high current with almost continuous loading has long been known to inhibit the accumulation of atmospheric moisture in electrical equipment, thereby actually inhibiting, rather than accelerating, failure modes which are moisture related.⁵

Failure Mechanisms

There are a number of reasons for aluminum-wired twist-on connections to increase in resistance. Loss of normal force due to creep of the aluminum, fretting corrosion due to vibrations, and thermal expansion mismatch are important factors, and their relationship to failure of aluminum-wired twist-on connections has been previously discussed.¹ Except for the el-

ectrostatic origin of the vibrations detected in some overheating special service connections, the factors previously discussed apply to the special service connections as they do to the conventional aluminum-wired twist-on connectors.

The strong effect of humidity points to corrosion as a factor which deserves special discussion. For the groups which are subjected to the constant environment, with essentially no application of current, corrosion processes are the cause of the resistance increases. The corrosion processes are accelerated by the high humidity, while the other degradation processes known to apply to these aluminum-wired twist-on connections are diminished or eliminated by the conditions of the test.

At least four types of corrosion are possible in twist-on connections: fretting, galvanic, general, and crevice corrosion. Fretting corrosion does not apply to the constant environment, zero-current tests, since the sources of microscopic motions are not present.

Aluminum corrodes relatively slowly in pure dry air because of the very thin protective film of aluminum oxide which develops rapidly on its surface, but it is a very active metal which has a high tendency to corrode in an aqueous environment. This can be seen from its position in the electromotive force series, where it is highly anodic to all the base metals with which it may come in contact in a twist-on connection. Standard potential differences are: 2.18 V, 1.52 V, 1.22 V, and 0.9 V for Al to Cu, Sn, Fe, and Zn respectively.⁶

The electrolyte for the aqueous corrosion is a thin film on the surface. It has been shown that a film of water as thick as 100 Å can build up rapidly even on a platinum surface, as it becomes contaminated by dust.⁹ On an active metal like aluminum, much thicker electrolyte films can form as aluminum reaction products accumulate. These products are, for example, hydrated alumina, aluminum chloride, and aluminum sulfate. In atmospheric corrosion tests on a number of telephone contact materials, it has been shown that all the base metals tested increased in corrosion rate in going from a low to a high relative humidity.⁷

Galvanic corrosion occurs when aluminum is in metallic contact with most base metals. It is a probable cause of the deterioration of the conductor-to-spring contacts in the high humidity environment.

General corrosion is believed to occur in an aqueous environment by the presence of spots on the surface having different

solution potential. These spots are caused by inhomogeneities in the surface such as scratch marks and points at which impurities are compacted or alloying elements are segregated. Crevice corrosion takes place at a joint between adjoining surfaces of the same metal or at a pit in a metal surface. It is characterized by the development of anodic areas at the bottom of the crevice. Corrosion is therefore concentrated there. A twist-on connection provides a continuous crevice at the junction of the conductors. Both general corrosion and crevice corrosion are probably involved in the deterioration of the aluminum conductor-to-conductor contacts in the high humidity environment.

Thus, the conditions required to activate corrosion-related failure mechanisms in these connections exist, and this is the most probable explanation for the strong sensitivity to humidity that is observed experimentally.

Qualification Standards

The qualification standards for connectors for use with aluminum wire, and for the wire itself, must be stringent enough to ensure safe and reliable long-term operation over the reasonably predictable circumstances of use. The test conditions for special service connections in this study are well within that range in all respects. Overheating failures of the aluminum-wired special service connectors must therefore be considered as failures of the standards under which the connectors and conductors are approved.

The qualification standard for the special service connectors is one of several relatively new standards issued in Canada and the United States which apply to connectors for use with branch circuit sizes of aluminum wire. These standards have in common the use of a so-called "heat cycle" test as the only life test of contact performance.

The "heat cycle" test is a cyclic current test by which elevated temperatures are imposed on a connection by use of higher-than-rated current. The test is performed in open air in a laboratory ambient environment. Standards for connectors for #12 aluminum wire specify heat cycle current ranging from 22 A to 40 A, and 35 A is applied in the case of the special service connectors.

The current is specified to be applied for a one hour on, one hour off cycle, but under some conditions the off period may be shortened. The tests are completed at the end of 500 cycles. To pass the test, the measured temperatures of the samples must have remained below a specified maximum limit and the samples must exhibit

temperature stability within defined limits.

The number of samples tested varies according to the application range and type of connector. The maximum total number of connections heat cycled to qualify a connector of a specific size intended for a broad range of conductor sizes and materials is of the order of 20 connections, in sample sets of four each of various conductor combinations. Certain types of connectors with narrowly-defined application ranges may be qualified under the heat cycle tests with a sample set consisting of two connectors. A single sample of aluminum conductor is used for the heat cycle tests.

The alloy aluminum conductors are also qualified using a heat cycle test as the only life test in the qualification standards. In this case the heat cycle test is performed on connections to zinc-plated steel binding head screw terminals of receptacles.

The heat cycle tests for both connectors and conductors are principally tests for failures related to creep and to some of the thermal expansion/contraction effects. These have been the most prominent failure mechanisms encountered in connections to aluminum conductors, but by no means are they the only ones which the qualification life testing must consider, as has been demonstrated by the results of this investigation.

Another important consideration is the number of samples used for life testing. It is well known that failures of electrical contacts of these types are probabilistic events, rather than deterministic. This is primarily due to the large number of variables which influence contact behavior. Effective accelerated life testing must be performed with substantially larger sample sets than are prescribed by the present standards.

In contrast to the specifications for connectors for aluminum wire for branch circuits, the communication and electronic industries have stringent life test requirements. For example, one such specification requires life testing of a minimum of 3,000 samples and includes three types of environmental tests.¹⁰

Connection failures in communications applications show up as noise in the signals. Connection failures in branch circuit wiring can lead to severe overheating, which is a matter of fire hazard and life safety. The problem of qualification testing of aluminum-wired connections requires careful re-examination considering the poor performance observed in this investigation.

CONCLUSIONS

Aluminum-wired special service connectors fail and overheat in tests within rated electrical and environmental conditions. Atmospheric humidity is seen to be a major factor in the failure process. There is a very low probability that such connections will give satisfactory and safe long-term service in field applications.

Improvements are required in the qualification standards by which such connectors are approved. Specifically, the following changes should be considered:

1. Addition of environmental life testing for both the wire and the connectors.
2. Increasing substantially the number of samples for each life test.
3. Increasing the sensitivity of the test criteria to small but significant changes in the behavior of the contacts being tested.
4. Use a cross section of aluminum wire samples for the life tests. (Aluminum wire is a highly variable product in several properties important to contact performance.)

Without such improvements the degree of confidence in the long-term safety of future aluminum-wired systems would be low. Considering the practical difficulty of instituting such stringent testing for a broad spectrum of connectors and conductors, alternate solutions for the problem may be more desirable. Such solutions would include changing the nature of the aluminum wire surface, as with copper-clad or plated wires.

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