ANALYSIS OF FIELD FAILURES OF ALUMINUM-COPPER PIGTAIL SPLICES MADE WITH TWIST-ON CONNECTORS

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ABSTRACT

A new type of twist-on splicing connector for use with aluminum and copper wire combinations was utilized to reconnect wire terminations in a group of residential apartment units. The connector differs from conventional twist-on connectors in that it is pre-filled with a corrosion inhibitor compound containing suspended particulates. Burnouts occurring among these splices led to removal and replacement of all of the new connectors. In this study, the connectors removed from 102 apartments were inspected for signs of overheating and for indications of abnormal conditions that might cause connection failure. The failed connectors included samples that were applied to rated wire combinations and showed no sign of abnormal installation or application conditions. Tests of the aluminum conductors from the apartments reveal no abnormalities that could account for the poor performance of the new connector. The inhibitor compound inside the connector was determined to be of limited effectiveness in improving the wire-to-wire contact through the high resistance film on the aluminum wire surface. On the basis of the field failures in combination with previously reported laboratory studies it is concluded that the connector is not suitable for permanent use with aluminum wire residential wiring systems. Keywords: aluminum wire, connectors, pigtailing, twist-on connectors, corrosion inhibitor, failure analysis.

INTRODUCTION

Twist-on connectors consist of an insulating shell inside of which is a spiral metal spring. The connectors are hand-installed by holding the pre-stripped wire ends together, placing the connector onto them, and turning the connector until it is tight. The connector spring threads itself onto the wires during installation. After several complete turns the connector becomes tight, and the splice is complete.

Twist-on connectors of various designs have been rated for aluminum and aluminum-copper wire combinations in the past, and field failures were frequently reported.[1][2][3][4][5] The new type of twist-on connector differs from previous designs in that it is pre-filled with a corrosion inhibitor. The inhibitor is a grease with suspended particles. In other regards, the construction of this connector is similar to previous failure-prone designs. Previous publications report test results and analysis for the common types of twist-on connectors with splices involving aluminum and copper wire combinations.[6][7][8][9][10]

This new twist-on connector was introduced in about 1995. It is rated for use with aluminum-to-copper wire combinations. Figures 1 and 2 show the subject connector.

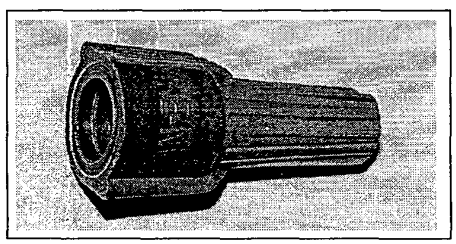

FIGURE 1 - TWIST-ON CONNECTOR FOR ALUMINUM-COPPER SPLICES

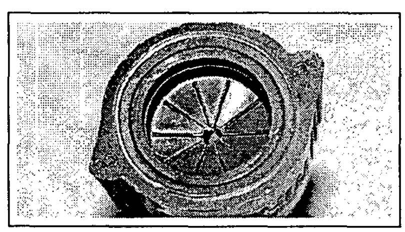

FIGURE 2 - TWIST-ON CONNECTOR, END VIEW SHOWING INSERT

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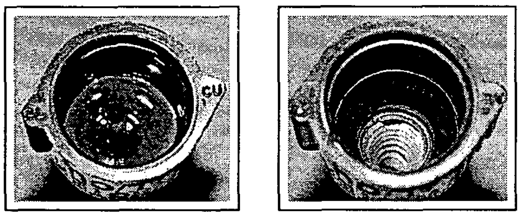
The connector's insulating shell is a thermoplastic. In the open end of the connector shell is an insert that helps prevent escape of the corrosion inhibitor compound from inside the connector. Removing the plastic insert reveals the inhibitor filling, as seen in Figure 3A. With the inhibitor removed, the zinc-plated steel connector spring can be seen, as shown in Figure 3B.



A B

FIGURE 3 - INSERT REMOVED, SHOWING INHIBITOR (A) AND SPRING (B)

The new twist-on connector was listed for use with aluminum-to-copper wire combinations on the basis of the applicable standard.[11] Qualification testing under the standard consisted of "heat-cycle" (actually current cycle) tests on relatively few samples, using an alloy aluminum wire. The qualification testing did not include environmental tests, long-term life tests, or testing of the ability of the finished splices to withstand the wire bending disturbance applied due to insertion into the electrical enclosure.

Independent testing of the new twist-on connector demonstrated significant weaknesses.[12] Splices made with this connector utilizing an aluminum wire of the type most common in existing aluminum-wired homes failed the heat-cycle test. Connection resistance of newly-made splices with this new twist-on connector varied substantially from sample to sample. Progressive increase of connection resistance was evident in a basic environmental test. It was also determined that splices made with this connector did not have the ability to reliably withstand a wire bending disturbance without substantial deterioration.

The laboratory testing indicated that the fundamental deficiencies of the twist-on connector for aluminum wire combinations had not been successfully overcome by the new connector. Prefilling the connector shell with inhibitor compound did not overcome the fundamental deficiencies of this type of connector for aluminum wire applications.

In twist-on connector splices involving aluminum wire, the actual wire-to-wire contact resistance was previously found to be relatively high and variable (sample to sample) because of lack of penetration of the insulating oxide on the aluminum wire surface.[7][12] Contact at the wire-to-wire interface is essentially line contact. Little or no shearing of the insulating aluminum oxide occurs from the action of threading the connector onto the wires. A substantial portion of the current carried by the spliced conductors then passes from one conductor to another through sections of the spring. In this regard, the new twist-on connector is the same as previous failure-prone types.

The spring in the new connector is constructed of zinc-plated steel, which is generally considered to be incompatible with aluminum as a current-carrying component in a termination or splice. Additionally, the spring is flimsy relative to the stiffness of the wires that it is intended to splice, and it is unable to maintain a fixed wire-to-wire contact interface against forces applied during insertion of the completed splice into the electrical enclosure, and against thermal expansion/contraction motions.

Considering the above-noted deficiencies, the poor laboratory test results, and the well-known field failure history of similar connectors with aluminum wire, it was concluded that the new twist-on connector could not be considered suitable for use in making pigtailing splices that become a permanent part of residential aluminum wire systems.[12] Field failures would be expected.

Field failures of splices made with the new connector have now been reported. The purpose of the present investigation is to determine whether the reported field failures resulted from intrinsic deficiencies of the connection system (aluminum wire and twist-on connectors) or are attributable to unique installation or application factors.

BACKGROUND

The subject aluminum-wired residential units were constructed in 1968. In 1997, a licensed electrician was contracted to replace all aluminum-wired branch-circuit switches and receptacles with newer "CO/ALR" type devices (the type presently rated for direct connection to aluminum wire) and to reconnect or "pigtail" certain (most heavily loaded) branch circuit splices using a recently- introduced twist-on connector rated for the purpose.

"Pigtailing" involves splicing a copper conductor to the aluminum conductor(s) and then attaching the copper conductor to a device that is not suitable for direct connection to aluminum wire. Other splices made with the new twist-on connector involved connection of the aluminum branch circuit conductors to copper wire leads of lighting fixtures, heating and air conditioning equipment, and appliances. Failures were noted within the first year, and continued into the second year. These failures were detected by the occupants due to smell and/or electrical malfunction. Severity of the failures varied from mild (deformed/melted connector shell) to severe (charring/burning of connector shell and burn-back of wire insulation).

Abnormal heating of additional splices was demonstrated by infra-red temperature measurement with the connections carrying their normal current. Because of the failures already experienced, along with the projection of additional failures (based on the infra-red measurements and available published data), all of the newly-made twist-on connector splices were replaced by the end of 1998. Where applicable, the splices were re-made using a particular type of compression crimp connector that is recommended by the U.S. Consumer Product Safety Commission for aluminum wire pigtailing repair.[13] More than 4,500 of the new type twist-on connectors were removed from 102 apartments after less than two years in service.

During the replacement process, additional overheating failures of the new twist-on connectors were found. Including those previously detected, 14 of the new connectors showed visible indication of overheating failure. All of the twist-on conectors that had been removed from the apartments were provided for examination. Samples of aluminum cable from the buildings were also provided.

EXAMINATION OF FAILED SPLICES

A total of 4,531 of the new type twist-on connector were examined. No additional visually-identified failures were noted beyond those previously found by on-site personnel. The 14 failures involved splices in 10 separate apartments. The electrician who removed the connectors identified the application of each failure, as summarized below.

(2) Pigtail (Bathroom GFCI)
(5) Dishwasher
(7) Heat strips, air conditioning

The focus of this evaluation is the failure of splices that conform to criteria for correct application and installation. One of the heat damaged connectors was a questionable failure, in that the visible heat damage to the connector shell did not appear to have come from internal heat generation within the splice. Six of the heat-damaged connectors were non-conforming, in that they contained wire combinations beyond those listed for the connector. All six had been installed in air conditioning and heating equipment.

No abnormalities of application or installation were found among the remaining seven failed splices. The application of the various failed splices in this group is summarized below.

(2) Pigtail (Bathroom GFCI)
(4) Dishwasher
(1) Heat strips, air conditioning

Figures 4, 5, and 6 show failures of varying degrees of severity. All of these examples are from the dishwasher applications.

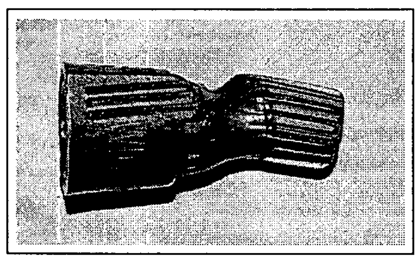


FIGURE 4 - EARLY STAGE OF OVERHEATING

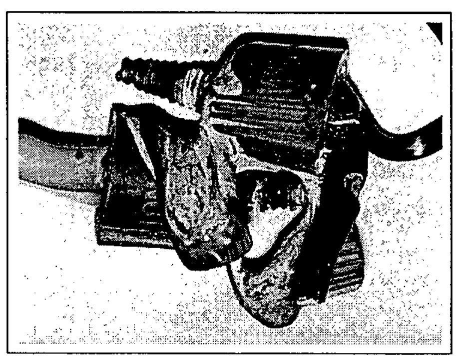


FIGURE 5 - TWO FAILED SPLICES ADHERED TOGETHER BY MELTED PLASTIC SHELLS

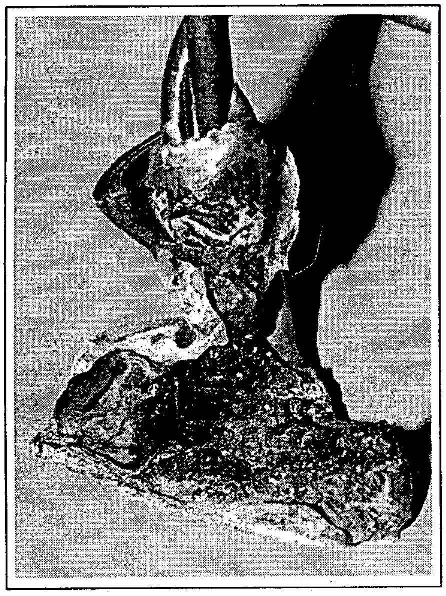


FIGURE 6 - SEVERE FAILURE, PLASTIC SHELL MELTED AND CHARRED

The failures shown in Figures 4 and 5 show heat damage around the plastic shell corresponding to the portion of the connector spring that is in contact with the spliced wires. This heating pattern is characteristic of failing twist-on connector splices made with aluminum and aluminum-copper wire combinations. As the failure progresses with time, higher temperatures are developed at the splice and at the connector shell, leading to melting and charring of the plastic.

The hot plastic flows downward due to gravity, and the final appearance of the failing connectors therefore varies according to the physical orientation in addition to the level of heat generation. The connector shown in Figure 6 shows the downward flow of the plastic. The severe charring of the plastic from this connector indicates that the plastic shell may have actually ignited. Both the insulating plastic shell of these connectors and the inhibitor compound inside are easily ignited and burn readily.

Some of the failed samples were removed along with short lengths of the wires. The insulation on those wires showed no indication of heating due to overcurrent. Heat damage to the wire insulation was localized to the insulation closest to the overheating splice. Overcurrent is therefore ruled out as a contributor to the failure of those splices.

The two failures that were associated with GFI-receptacles were wired with (2) #10 AWG solid aluminum wires and (1) #12 AWG copper wire. This is the typical "pigtailing" configuration. A short copper "pigtail" is spliced to the aluminum branch circuit wires, and the copper wire is connected to the screw terminal of the GFI-receptacle. Current up to full circuit capacity may flow through the pigtail splice to loads downstream in the circuit wiring.

Pigtailing was necessary because the terminals on the GFI-receptacle were not rated for direct connection to aluminum wire. Physically, the GFI is larger than a conventional receptacle, and there is very little room in the electrical enclosure ("receptacle box") for the pigtail splices. Installation in this instance normally requires considerable bending and manipulation of the wires and the connectors inside the enclosure in order to mount the GFI-type receptacle.

Previous testing demonstrated that this new type of twist-on connector cannot reliably withstand a wire bending disturbance without deteriorating.[12] It is likely that the wire bending disturbance during installation of the GFI-receptacles contributed to the early failure of these splices. Bending of the wires to position the completed splice is a normal and necessary part of the installation process, however.

THE ALUMINUM WIRE

The aluminum wire itself is a variable in the twist-on connector system. Some types of aluminum wire perform better than others in this type of splice. The surface film on the aluminum wire is a key determinant of the performance of aluminum-wired twist-on connectors.[14]

In order to determine if there was anything abnormal about the aluminum conductors used in the wiring of the apartments, samples were obtained for examination and testing. Two types of branch circuit aluminum wire were noted to be in the buildings. Both are principally iron-bearing alloys.

One, with slightly more than 99.5% aluminum, is considered to be an "EC" (Electrical Conductor) grade material. Essentially the same material was later marketed in the solid branch circuit sizes until the mid-1970's as an Aluminum Conductor Material (ACM) that had qualified under standardized testing introduced in the early 1970's. The ACM version of this wire is the same aluminum conductor that was used in previous testing of the new twist-on connector.[12]

The other sample type of aluminum wire from these apartments is defined as an alloy aluminum conductor, having less than 99.5% aluminum.. This is the same brand and type of aluminum conductor material originally used for the qualification testing of the new twist-on connector. There is, therefore, some previous test data available for the new twist-on connector in combination with the aluminum conductors used in these apartments.

Previous investigations determined that a primary reason for failure of twist-on connector splices involving aluminum wire is high contact resistance at the wire-to-wire interface. As the connector is tightened on the wire ends, the resistance of the wire-to-wire contact interfaces depends on the nature of the film on the aluminum wire surface and on the highly variable mechanical stresses and motions that occur at that interface.

In the subject connector, the particles in the inhibitor are intended to aid the formation of metallic contacts through the tenacious aluminum oxide film. Previous testing has demonstrated, however, that these connectors do not reliably establish low resistance contact at the wire-to-wire interface, resulting in substantial current flow through sections of the connectors' steel spring.[7][12]

Two types of tests were conducted to determine whether a unique characteristic of the aluminum wire used in the subject apartments, such as an abnormally thick oxide film, contributed to the failures. Additionally the testing evaluated the relative connectability of several wire samples and the ability of the inhibitor to reliably achieve low resistance contacts at the wire-to-wire interface.

Initial Resistance Test

A single strand of EC grade aluminum wire from the apartments was utilized to create a set of 20 splices with the subject twist-on connector. The splice in each connector consists of (2) #10 AWG solid aluminum conductors with (1) #18 AWG solid copper conductor. This is among the rated wire combinations for this connector. Typically, the #10 AWG aluminum would be used in branch circuits rated at 20 A.

The splices were made according to the connector manufacturer's printed instructions, and are the same as one of the groups previously tested.[12] The only difference is that the new group was made using the EC grade aluminum from the subject apartments while the previously tested group was made using a sample of the same brand and type of wire produced after the ACM designation was applied.

The connection resistance of the newly-made splices is evaluated by measuring the potential drop at current loading of 18 A, which is 90% of the circuit rating for a #10 AWG aluminum wire residential branch circuit. The potential drop attributable to the bulk resistance of the length of aluminum wire that is included in the measurement is then subtracted and the result is converted to resistance (microOhms) using Ohm's law. Table 1 provides the connection resistance results for the two groups of splices.

		CONNECTION RESISTANCE (micro-ohms)			
TEST GROUP	No. of Samples	Avg.	Min.	Max.	σ_{n-1}
PREVIOUS STUDY[12]	10	71	5	189	56
PRESENT STUDY	20	225	33	528	151

TABLE 1 - INITIAL CONNECTION RESISTANCE (micro-ohms) OF HAND-INSTALLED TWIST-ON CONNECTOR SPLICES (2) #10 AWG solid Al, (1) #18 AWG Cu

Connection resistance of the splices made with the EC wire sample from the apartments in this present study is consistently higher than the equivalent splices made with the later (ACM) version of the same wire.

The overall connection resistance results from the combination of two parallel conduction paths, the direct wire-to-wire path and a path consisting of current flowing from wire to wire through segments of the connector spring. The spring path resistance for this connector was previously determined to be about 350 uΩ.[12] This is primarily due to the bulk resistance of the spring wire segments in the current path. Contact resistance between the spring and the aluminum conductor is initially very low, due to the severe scraping action that occurs as the spiral connector spring is threaded onto the wires. When the initial overall connection resistance (combination of the two parallel paths) exceeds about 175 uΩ, then more than 1/2 of the current is being carried through sections of the steel connector spring. Based on the measured values, in the connection group of this study the majority of the load current was carried in sections of the connector spring for 50% of the specimens.

Crossed-Rod Tests

These tests provide a controlled method by which the influence of surface films on wire conductors can be evaluated.[15] The conductors used in this study are all #10 AWG aluminum, with contacting pairs cut from the same continuous length of wire. The wires were freshly stripped of insulation just prior to installation in the fixture, taking care not to scratch or abrade the aluminum surface while removing the insualtion.

Specimens are brought into contact gradually, without impact. After initial contact is made, the load is gradually increased to 3 kg. Current applied in these tests is 10 A, provided by a constant-current DC power supply with maximum open-circuit potential set to 0.150 V.

For each type of aluminum wire tested, three conditions of surface preparation were evaluated. The results are shown in Table 2 and Figure 7.

CONTACT RESISTANCE (micro-ohms)

WIRE & (PREPARATION)	# of tests	Avg.	Min.	Max.	σ_{n-1}
EC (as stripped)	10	5,940	1,680	12,810	3,950
EC (with inhibitor)	10	936	66	1,720	367
EC (coat/abrade)	10	167	70	240	49
ACM (as stripped)	10	9,450	2,620	15,230	4,230
ACM (w/inhibitor)	10	4,890	370	11,100	3,960
ACM (coat/abrade)	10	186	110	290	636
ALLOY (as stripped)	10	7,480	1,720	11,490	3,410
ALLOY (w/inhibitor)	10	1,280	520	2,410	639
ALLOY (coat/abrade)	10	131	100	170	20

TABLE 2 - CROSSED ROD CONTACT RESISTANCE AT 3kg LOAD

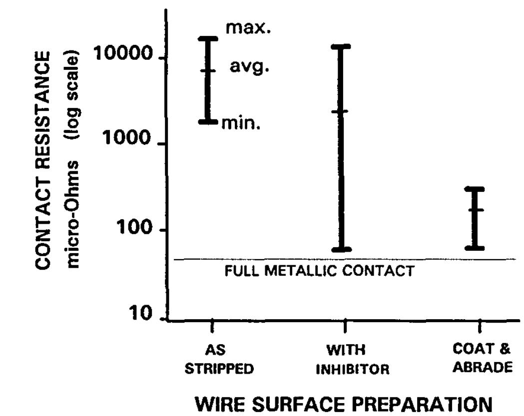


FIGURE 7 - CROSSED-ROD CONTACT RESISTANCE AT 3 kg AS A FUNCTION OF SURFACE PREPARATION
(Composite including all three wire types)

Without surface preparation, just as the aluminum wire surface exists after the electrical insulation is stripped off, all three aluminum conductor samples demonstrate high resistance in the 3 kg crossed wire contact tests. The apparent area of contact is a circle measured to be about 0.6 mm diameter. The contact resistance of a fully-metallic circular aluminum contact of that diameter is approximately 50 uΩ, calculated as per Holm.[15] Without any surface preparation, contacts with these aluminum conductors average more than two orders of magnitude higher resistance than a fully-metallic contact under the same conditions. In the as-stripped condition, the results are essentially the same for the three types of aluminum conductor.

Application of inhibitor compound (taken from inside one of the new twist-on connectors) to the wire surface prior to contact engagement results in some reduction of contact resistance, on average. There is a significant difference in the effectiveness of the inhibitor from one conductor sample to another. The overall average contact resistance for samples treated with the inhibitor is almost two orders of magnitude greater than for a fully-metallic contact.

Average contact resistance was minimized when the aluminum wire was coated with petrolatum and then abraded using a #400 grit abrasive paper. With this surface, average contact resistance is about an order of magnitude lower than with the inhibitor treatment, and only three times that of a fully-metallic contact. The effect was consistent for all of the wire types.

CONCLUSION

Six of the field failures from the subject apartments were correctly applied, and no abnormal conditions are noted that could have contributed to their premature failure. The failures were intrinsically hazardous, due to insulation melting off the metallic parts, and, in at least one instance, probable flaming ignition.

The aluminum conductors from the apartments are among the most common aluminum wire types used for residential construction in the late 1960's through the mid-1970's. The samples of the conductor from the subject apartments that were tested are normal for this type of product.

The failure of the six properly-applied connectors is attributed to inherent weaknesses of the twist-on connector type for aluminum wire applications, as had previously been determined. The addition of corrosion inhibitor does not overcome the fundamental deficiencies. The corrosion inhibitor is found to be inconsistent in its ability to assure low resistance wire-to-wire contact

The field failures confirm the previous evaluation, that this new type of twist-on connector is not suitable for use as part of the permanent aluminum branch circuit wiring system in buildings.

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