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L O G O F M E E T I N G

SUBJECT: Connectors for Use with Existing Installations of Solid Aluminum Branch Circuit Conductors

DATE: October 21, 1997 **PLACE:** Room 612
East West Towers

DATE OF LOG ENTRY: October 21, 1997

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SUMMARY:

Dr. Jesse Aronstein provided a synopsis his technical paper presented at the IEEE Holm Conference on Electrical Contacts on October 20, 1997. A copy of the paper is attached. Dr. Aronstein responded to individual questions from attendees. In addition, Dr. Aronstein expressed a willingness to cooperate with the manufacturer of twist-on connectors and CPSC staff in conducting further tests.

EVALUATION OF A TWIST-ON CONNECTOR FOR ALUMINUM WIRE

2.2

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ABSTRACT

A new type of twist-on splicing connector for use with aluminum and copper wire combinations is tested to determine initial resistance, performance in a zero-current environmental test, performance in a heat-cycle test, and portion of current carried by the connector's steel spring. The splices tested consist of two aluminum wires and one copper wire. The aluminum wire samples used for the test are of the types actually installed in aluminum-wired homes. Initial resistance is found to be relatively high, and there is a significant sample-to-sample variation. This reflects failure to consistentlty establish low-resistance wire-to-wire contact through the insulating oxide film on the wire. Results of the environmental and heat-cycle tests show deterioration of a significant portion of the samples. The splices made with this connector are also found to be sensitive to mechanical disturbance, such as applied in normal installation when the completed splice is pushed back into the junction box. Based on the test results, it is concluded that this connector has not overcome the fundamental deficiency of twist-on connectors for use with aluminum wire, and is not considered to be suitable for permanent splices in residential aluminum wire applications. Keywords: aluminum wire, connectors, pigtailing, twist-on connectors, environmental test, heat-cycle test.

I. INTRODUCTION

Twist-on connectors are the most common splicing connectors employed in residential branch circuit wiring. The connector typically consists of an insulating shell enclosing a spiral metal spring. The connectors are installed by hand, being pushed over the wire ends and turned while holding the pre-stripped wire ends together. The connector spring threads itself onto the wires during installation. After several complete turns the connector becomes tight, and the splice is complete. The mechanical action that occurs at the wire-to-wire interface in these splices varies considerably according to the number and sizes of wires being spliced, the stiffness of the wires, the type of spring within the connector, and the tightening torque.
Twist-on splicing connectors of various designs were utilized for aluminum wire from its earliest use in residential applications. Field failures of twist-on connector splices with aluminum wire have been frequently reported.[1][2][3][4][5]

Laboratory tests demonstrate relatively rapid deterioration of splices made with this type of connector, with both aluminum-aluminum and aluminum-copper combinations.[6][7][8][9][10] The worst-case failures degenerate to a condition where all of the current passing through the splice is conducted through sections of the connector spring, causing the spring sections to become red-hot at less than rated current.[6][7] Special installation techniques involving use of corrosion inhibitor, abrasion of the aluminum wire surface, and pretwisting of the wires, are demonstrated to improve the performance substantially.[11][12]

This type of connector continued to be rated for use with aluminum wire until the mid-1980's, when the applicable qualification standards were made more rigorous. In the United States, twist-on connectors manufactured for almost the next decade after that time were rated for use only with copper wire.

Recently, a twist-on connector rated for splicing aluminum-copper (but not aluminum-aluminum) wire combinations has been introduced. The connector incorporates a zinc-plated steel spring utilizing wire of a diamond-shaped cross section. The connector is of the "live-spring" type, meaning

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that the spring is not diametrically constrained by the plastic shell, so that it expands and rides over the wire ends when the connector is installed. The essential difference between this connector and previous similar twist-on connectors for aluminum wire is that it is pre-filled with a corrosion inhibitor. The inhibitor is a grease with suspended particles. The inhibitor serves to supress oxidation and corrosion by excluding atmospheric gasses and moisture.

The major application of these connectors in aluminum wired homes is for "pigtailing". This consists of splicing a length of copper conductor onto the aluminum circuit conductors in order to safely connect the circuit to receptacles, fixtures and other devices that do not have terminals suitable for direct connection to the aluminum wire. Most pigtailing splices consist of two aluminum wires and one copper wire. The copper wire serves as a tap in a continuous circuit feeder. The splice may carry substantial current to downstream loads, with little or no current flowing in the copper wire pigtail. A representative splice of this type, made with the twist-on connector being evaluated, is shown in Figure 1.

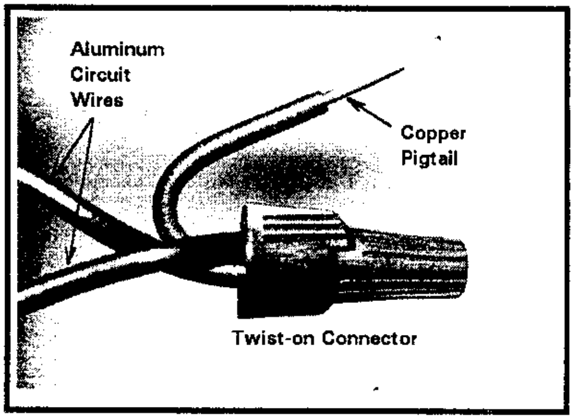

FIGURE 1 - "PIGTAIL" SPLICE OF ALUMINUM AND COPPER WIRES.

Based on the previous testing and field experience, there is reason to thoroughly examine whether this new twist-on connector is suitable for permanent pigtail splices in an aluminum-wired home. Qualification testing consists principally of relatively few samples subjected to a current cycling (so-called "heat-cycle") test. Passing the standard heat-cycle test has not provided a total basis on which to predict successful and safe long-term performance in large-scale use, however.[8]

There are several major reasons for this, including small sample size, lack of environmental testing, and liberal pass/fail criteria.[13] Most important for this application, however, is that; 1) the qualification tests do not require testing of the splices through the aluminum-to-aluminum current path, 2) the splices are not mechanically stressed during the qualification testing as they are in actual installations (by the action of inserting completed splices into junction boxes), and 3) the aluminum wire used for the qualification testing is an alloy conductor rather than the EC aluminum that exists in most residential installations. (The alloy aluminum conductors were developed to have improved performance relative to the EC grade aluminum conductor in a heat-cycle test using binding-head screw terminals.)

The present tests have been conducted to evaluate the suitability of the new connector as a permanent splicing connector for use with EC aluminum wire of the types actually in use. The evaluation is based on heat-cycle test performance as well as tests for sensitivity to environmental conditions and mechanical disturbance.

II. EXPERIMENTAL

A. Initial Potential Drop

1) **Significance**. The initial resistance of a twist-on connector splice reflects the extent to which metallic contact has been established through the insulating aluminum oxide at the wire-to-wire interfaces. Contact resistance at that interface in a newly-made aluminum wire splice varies widely, depending on the oxide thickness, the sizes and properties of the wires, and the mechanical distortion imparted during connector installation.

The overall resistance of a twist-on connector splice is the combined resistance of two current path sets in parallel. The intended primary conductive paths are at the wire-to-wire interfaces. Secondary paths exist through sections of the connector spring. The spring threads itself onto the conductors during installation, indenting and cutting grooves in the conductors at each contact point. Resistance at points of contact to the connector spring is extremely low when the connector is first installed. This is due to the relatively massive scraping action that occurs between the spring and the wire surface. The secondary path resistance initially consists mainly of the bulk resistance of a set of parallel sections of the steel spring that connect the current-carrying wires.

Connection resistance is determined by measuring potential drop across a section of the current-carrying conductors going into and out of the splice. The measured potential drop is a function of several components, namely: 1) bulk resistance of the wire going into and out of the splice, 2) contact resistance at a set of wire-to-wire interfaces, 3) contact resistance at a set of wire-to-spring interfaces, and 4) bulk resistance of the sections of connector spring in the current path. In newly-made twist-on connector splices involving aluminum wire, the wire-to-wire contact resistance is the major sample-to-sample variable in the measured potential drop.

The low limit for the measured potential drop approaches that of the bulk resistance of the conductors alone. This occurs when the wire-to-wire contact resistance is very low relative to the bulk resistance of the sections of spring wire that are in the parrallel conducting path. The upper limit for the initial measured potential drop occurs when there is no conduction directly from wire-to-wire.

Extensive test data for aluminum-wired twist-on connector splices has conclusively demonstrated a correlation between initial resistance and time to failure.[6][7][8][10][11][12] Splices of this type that exhibit initially low resistance, indistiguishable from a length of solid wire, demonstrate long life and resist deterioration under a variety of applied electrical and environmental conditions. Aluminum-wired twist-on connector splices with initially high resistance demonstrate short life and substantial deterioration under even the mildest applied test conditions. In general, it has been found that the higher the initial resistance, the shorter the life under the conditions tested.

Evaluation of initial connection resistance is therefore considered to be a fundamental predictor of life test performance and field performance of a twist-on splicing connector for aluminum wire applications. Low and consistent initial potential drop, with a narrow sample-to-sample distribution, with any of the aluminum wire types that it may actually be applied to in service, would have to be demonstrated to generate confidence in the connector's potential for long and safe service in large scale application.

2) **Experimental Method**. The aluminum wire used for this test was manufactured in the early 1970's. It is of a brand and type that was installed in a major portion of the aluminum wired homes in the United States. Sections of the wire are precision cut to length out of a single long piece. A short section of insulation is stripped from the center of each piece for the purpose of making potential drop measurements. A carefully measured length of insulation is then removed from each end without any scraping of the aluminum wire surface.

Each aluminum wire is anchored near its center to a supporting mount. Connectors are then hand installed per the manufacturer's instructions, by positioning the ends of the wires together and screwing the connector on by hand as tightly as possible. Each splice consists of three wires, two aluminum and one copper. The copper wire in the splice is not connected in the circuit. Current through the group of test splices passes in and out of the splices through the aluminum wires. The potential drop is measured at 18 A, which is 90% of circuit rating for the #10 AWG aluminum conductor, after allowing one hour to achieve thermal equilibrium.

3) **Experimental Results**. Initial potential drop of two groups of splices, after subtracting the bulk resistance of the wire that is included in the measurement, is shown in Table 1. The results are equivalent to those previously obtained for similar aluminum-wired twist-on connector splices.[7][8][10][11][12]

		POTENTIAL DROP mV AC @18 A		
WIRES SPLICED	No. of Samples	Avg.	Min.	Max.
(2) #10 AWG Al (1) #12 AWG Cu	10	2.16	0.8	4.6
(2) #10 AWG Al (1) #18 AWG Cu	10	1.28	0.1	3.4

TABLE 1 - INITIAL POTENTIAL DROP OF HAND-INSTALLED "PIGTAIL" SPLICES

The potential drop measurements reflect overall connection resistance ranging from about 10 to 250uΩ. Based on estimation of the resistance of the parallel current path through sections of the spring (350uΩ, Section II.F.3, below) this corresponds to an effective wire-to-wire contact resistance of the ranges approximately from 10 to almost 1000uΩ. These results demonstrate that this connector design does not consistently establish low-resistance wire-to-wire metallic contact through the insulating aluminum oxide.

B. Zero-current Environmental Test

1) Significance. Actual installation of the tested connector in aluminum-wired homes involves long-term exposure in environments that may include high levels of atmospheric moisture, condensation, atmospheric contaminants, and wide temperature variations. Environmental deterioration is generally recognized as a significant contributor to contact and connection failure. More specifically, environmental deterioration of aluminum-wired twist-on connector splices has previously been demonstrated.[11]

The presence of inhibitor compound inside the connector (prefilled) is likely to supress deterioration due to oxidation and corrosion. The inhibitor does not alleviate the mechanical deficiencies of the connector type, however. In this type of splice, the contact interfaces are not sufficiently fixed to preclude relative motions that destroy conducting metallic areas on the wire surface. The motions are a natural consequence of thermal expansion and contraction due to environental temperature variations.

Whether or not environmental deterioration will be significant must be determined by testing. A basic environmental test involves exposing the subject splices to the environment of use and periodically measuring connection resistance. A connector suitable for permanent use in a residential wiring system should not show any progressive resistance increase.

The applied conditions of an environmental test must at least reflect the more stressful end of the applications spectrum. For these tests, the connectors are exposed to sheltered outoor conditions, whereby temperature and relative humidity change with outdoor conditions but the samples are protected from direct exposure to precipitation. The environment of actual use in residential electrical systems spans a wide range, from climate-conditioned interior applications to essentially outdoor conditions. The applied conditions of this test are close to the latter end of the range, being similar to that in a junction box on the underside of a mobile home, in unoccupied or seasonal residences, in attic spaces, and other common residential junction box locations.

This exposure does not accelerate deterioration, but simply applies the most stressful application environment. Satisfactory resistance to environmental deterioration would be indicated by indefinite maintenance of stable and low connection resistance. Any progressive increase of resistance during exposure to conditions that are within the range of actual application environments indicates that the connector is not suitable for making permanent splices in residential aluminum wiring systems.

2) Experimental Method. The two sets of pigtail splices previously described were subjected to sheltered outdoor exposure for 18 months (September 1995 through March 1997) at Poughkeepsie, NY. Except for taking 12 sets of potential drop measurements, no current flowed through the test specimens. Potential drop measurements were made at 18 amps after allowing one hour to establish thermal equilibrium.

3) Experimental Results. The potential drop results (measured at 18A) for the zero-current environmental exposure test for the two pigtail splice groups (combined) are shown in Figure 2.

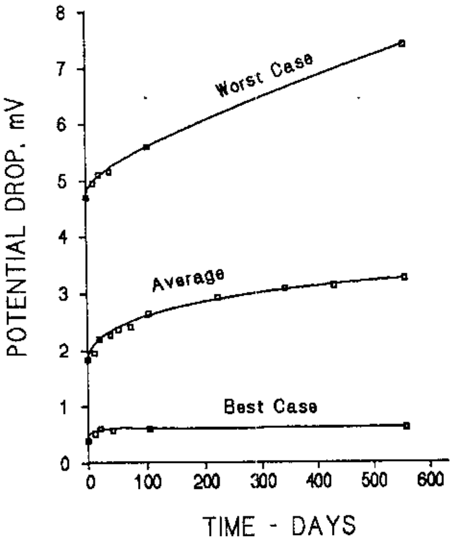

FIGURE 2 - ZERO CURRENT ENVIRONMENTAL EXPOSURE, PIGTAIL SPLICE POTENTIAL DROP @18 A (bulk wire potential drop subtracted).

All but one splice of the 20 samples (2 groups combined) showed progressive increasing potential drop. The one exception is the splice with the lowest initial reading, which showed an early increase but was then stable for the balance of the test. On any particular sample, the increase during the test exposure is seen to correlate well to the initial measurement. The largest change occurs in splices that have high initial readings. Splices that start out with low potential drop show the least change. A profile of the results is shown in Table 2.

		POTENTIAL DROP mV AC @18 A		
WIRES SPLICED	No. of Samples	Avg.	Min.	Max.
(2) #10 AWG Al (1) #12 AWG Cu	10	3.87	1.7	7.4
CHANGE.....		+ 1.71	+ 0.9	+ 2.8
(2) #10 AWG Al (1) #18 AWG Cu	10	2.49	0.6	6.3
CHANGE.......		+ 1.21	+ 0.5	+ 2.9

TABLE 2 - POTENTIAL DROP OF HAND-INSTALLED "PIGTAIL" SPLICES AFTER ZERO-CURRENT ENVIRONMENTAL EXPOSURE.

Table 2 also indicates the changes relative to the initial values previously shown in Table 1. The changes are all positive, reflecting the general nature of the progressive deterioration of the splices.

The data demonstrates that the aluminum wire pigtail splices made with this twist-on connector deteriorate under environmental conditions that are within the expected application range. This result is another indicator that the splices made with this connector cannot be considered for permanent use in aluminum wire -wired homes. If it is assumed that the inhibitor prevents ingress of moisture and atmospheric contaminants, then it is likely that the deterioration shown in this test is due primarily to the effect of temperature variations resulting in relative motion at the contact surfaces.

C. Effect of Current at Constant Temperature.

1) **Significance**. Relatively High resistance at the aluminum wire-to-wire contact interfaces in splices of this type is due to failure to establish substantial metallic conducting areas ("a-spots") through the insulating aluminum oxide.[7] As a result, the current density in the a-spots at that interface may be high enough to make the splice susceptible to deterioration due to bulk electromigration.

Bulk electromigration is solid-state atomic diffusion that is enhanced by the effect of high current density. Practical implications were first recognized in semiconductor integrated circuit aluminum "wiring" applications. More recently, an understanding of electromigration as a cause of failure of aluminum pressure contacts has been developed.[14][15][16]

Current density in a-spots at aluminum contact interfaces is expected to exceed the threshold for electromigration deterioration in many practical types of connections, including twist-on connector splices.[17] When significant electromigration of aluminum atoms out of a conducting a-spot occurs, it results in the formation of voids and the eventual distruction (to open circuit) of the a-spot. In a contact interface consisting of a number of a-spots spanning a range of size, the smallest a-spots (with respect to conducting metallic cross section area) have the highest current density and will fail first.[17] Bulk electromigration has been shown to be an operative deterioration process in aluminum with either AC or DC current flow.

A basic test for the possible sensitivity of an aluminum connection to deterioration by electromigration is to pass current through the connection while keeping all other conditions constant. If the connection resistance increases under continuous current flow, at constant ambient temperature and without the influence of corrosion or oxidation effects, then electromigration must be considered as a possible cause of the deterioration. If the connection remains stable under continuous current flow, then it may be considered to be resistant to electromigration deterioration at that current.

2) **Experimental Method**. The pigtail splice groups previously described are subjected (after the environmental exposure test) to continuous operation at 40 A DC at room ambient temperature (20°C). The applied current is double the rated current for the #10 aluminum wire. This is therefore an accelerated test relative to normal rated conditions.

Power is fed from a regulated constant-current supply. Direct current is utilized to avoid the possible influence of alternating current vibrations and temperature cycling (at the a-spots) on the results.

3) **Experimental Results**. The potential drop results of the 40 amp DC continuous current test for the two pigtail splice groups (combined) are shown in Figure 2. In this test, most of the splices remained relatively stable. The worst case samples (highest potential drop at the start of this test) deteriotated. The unique feature of these results relative to the environmental exposure test is that

there was essentially no deterioration among the half of the sample set having the lowest potential drop.

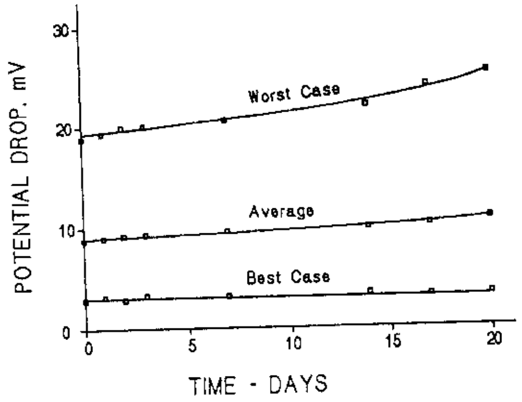

FIGURE 3 - CONTINUOUS CURRENT TEST, 40A DC, CONNECTION POTENTIAL DROP (bulk wire potential drop subtracted).

Although the test current is double the rated for the wire size in a residential circuit, the temperature is still well within rated conditions, since the specimens are in open air. Connection temperature is measured by inserting a thermocouple into a splice (alongside the wires) until its reading peaks. At the end of this test, the worst-case splice measured 67°C, while the best-case splice measured 56°C (at 40A in 20°C ambient). These temperatures are below the rated temperature for both the wire and the connector, and are within the range expected in actual installations due to the combination of ambient temperature and self-heating under normal current loading.

The observed deterioration in the higher-resistance splices under constant current conditions is considered to be due to electromigration causing disintegration of a-spots at the aluminum wire-to-wire contacts. While the current of this test was high relative to the actual expected application, the threshold current at which electromigration deterioration becomes significant in actual long-term use is not a fixed value.

When the splices are first made, the threshold current for electromigration failure is substantially higher than rated current. Given deterioration from other factors, however, electromigration will start to accelerate the failure process when the remaining metallic conducting area becomes inadequate for the actual current loading. Given the demonstrated rate of resistance increase due to environmental degradation, the threshold for current-related deterioration effects is likely to be reduced to less than the rated current for a significant portion of installed connections of this type in a short number of years relative to the required service life.

D. **Heat-Cycle Test**.

1) **Significance**. A high-current heat-cycle test is used to qualify these connectors according to the applicable standard.[18] The wire used for the qualification test is an aluminum alloy conductor. The wire actually installed in most aluminum-wired homes in this country, however, is "EC" grade. Also, the heat-cycle test as prescribed in the standard does not require the test to be run with current flowing in the aluminum wire to aluminum wire current path for a connector rated only for aluminum-to-copper. Nor does the standard heat cycle test procedure precondition the splices by simulating the mechanical disturbance that occurs in actual installations when the spliced wires are pushed into junction boxes. Because of these important factors, the qualifying heat-cycle test is performed on connections that are quite different from those of the intended application.

A heat-cycle test is useful as a benchmark test with which to compare the performance of different types of connectors under standardized conditions. The heat-cycle test is not a life test by which one can accurately predict successful field performance. Twist-on connectors for aluminum wire that were qualified by heat-cycle testing have failed in a hazardous manner in tests conducted within rated conditions of actual use.[8]

To the extent that the standard heat-cycle test serves as a performance benchmark, it is logical to test the connector in pigtail splices made with aluminum wires representative of the types it will actually be applied to, and in the aluminum wire to aluminum wire current path. Failure to perform well in such testing would be a signal that the connection type is not suitable for the intended application.

2) **Experimental Method**. Except for the use of aluminum wire samples representative of the types actually installed, and the passage of current through the aluminum wire to aluminum wire path, the test is conducted according to the procedure prescribed in the applicable standard.[18] Wire ends are stripped of insulation to the length prescribed by the installation instructions. The insulation is removed without scraping the wire surface.

The heat-cycle specimens are pigtail splices consisting of two #10 AWG solid aluminum wires and one #18 AWG solid copper wire. All of the samples of aluminum wire used were manufactured prior to 1974 for residential application. Current flows through the two aluminum conductors. The copper conductor is not connected in the test circuit. Connectors are tightened to a torque of 0.83 N-m (7.4 lb-in).

The applied tightening torque (5% higher than that calculated according to the standard, to allow for torque-wrench tolerance) is greater than can be imparted when holding the wires by hand. The limit becomes the ability to hold the wires in the fingers without having them slip. Accordingly, the wires are fixtured in a clamping device when tightening the connector. The test is conducted using groups of four splices. All splices in a group are made from the same piece of aluminum wire.

For the #10 AWG aluminum wire, the standard test current is 60 A (RMS) AC. A PC-based data and control system regulates the current by means of a feedback control loop, and also serves to record current, time, and temperature data. Thermocouples are used for temperature measurement, for local ambient, control conductor, and specimens.

The thermocouple for each specimen is inserted alongside the wires into the connector. During the first current-on cycle, the thermocouple is inserted into the connector to the point where it is indicating the highest temperature. This installation is in keeping with the requirement in the standard to sense the highest temperatures generated by the connector.

The test is 500 cycles of one hour current applied and one-half hour current off. Go/no-go criteria based on temperature rise and temperature "stability" are applied to determine a pass/fail rating for each splice being tested.[18] Essentially, to pass the test, a connector may not exceed 125°C above ambient, and it must operate within +/-10°C of its own average temperature relative to the reference conductor.

3) **Experimental Results**. A summary of the heat cycle test results is shown in Table 3. Each test group is made using a different sample of aluminum wire, from a different manufacturer. In all other respects the test groups are identical.

Test Group #	Number of Samples	Number of Failures, >125°C above Amb.	Number of Failures, Stability Criterion
1	4	1	1
2	4	2	0
3	4	0	0
4	4	0	0
5	4	1	0

TABLE 3 - HEAT CYCLE PERFORMANCE, TWIST-ON CONNECTOR PIGTAIL SPLICES, (2) #10 Aluminum with (1) #18 Copper, at 60 A flowing from aluminum wire to aluminum wire.

The overall failure rate is 25%. The sample size for each group is too small to attach any significance to the variation in the number of failures from one brand of wire to another. As in the previous tests, the deterioration correlated to the initial conditions. To a great extent, failures could be predicted from the initial temperature readings. The best-case samples operated at temperature at or below that of the reference conductor, and remained essentially constant for the duration of the test.

The worst-case samples demonstrated progressive increase in temperature, until the failure limit was crossed. Continuing on test beyond the failure limit, the temperature continued to increase, damaging the insulating shell of some samples, as shown, for example, in Figure 4.

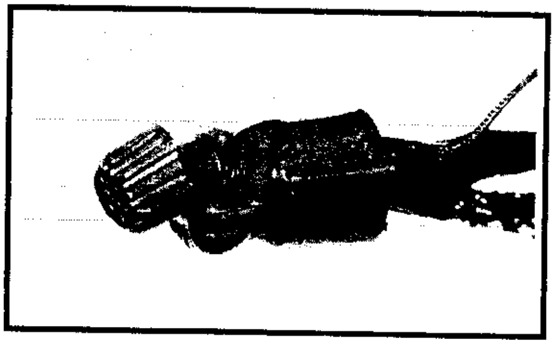

FIGURE 4 - HEAT CYCLE TEST FAILURE
(test continued beyond initial failure cycle)

The pigtail splice connection shown in Figure 4 was continued through the prescribed 500 cycles even though it had reached the temperature rise failure limit at 375 cycles. The melted portion of the connector's thermoplastic insulating shell, where the spring is exposed, indicates the highest temperature region of the overheating connector.

This is the same damage pattern previously observed in field failures and laboratory test failures of aluminum-wired twist-on connector splices, suggesting that the new type of twist-on connector being evaluated is subject to the same type of failure as previous designs. The damage pattern is attributed to heat generated by current flow in segments of the connector's steel spring.

E. Effect of Mechanical Disturbance

1) **Significance**. The standard qualification test procedures do not evaluate the possible effect of mechanical disturbance on performance of a connector. In actual installations, however, residential wiring splices are subjected to severe mechanical disturbance and stresses when the spliced wires are bent around and the connectors are pushed into junction boxes. A connector rated for such service must be able to resist degradation due to that type of handling.

2) **Experimental Method**. Test splices that successfully passed the heat cycle test were subjected to a mechanical disturbance consisting of making a right angle bend in the wires 51mm (2.0 in.) from the connector. The bend was made around a 25mm (1.0 in.) diameter mandrel. The heat cycle test was then continued for an additional 100 cycles.

3) **Experimental Results**. This test was performed on the surviving samples of heat cycle test groups #2 through #5 (Table 3). Of the 13 splices in these groups that had passed the heat cycle test at 500 cycles, 8 were substantially degraded by the mechanical disturbance, and there were 3 additional overtemperature failures within the next 100 cycles. One of the new failures was a splice that had previously remained at a relatively low temperature (lower than the reference conductor) for the previous 500 cycles. The results demonstrate that this twist-on connector does not hold the contact interfaces securely enough to avoid degradation due to normal handling during installation.

F. Portion of Current Flowing in Steel Spring

1) **Significance**. Previous testing and failure analysis of aluminum-wired twist-on connector splices indicated that the primary deficiency of this type of connection is the failure to establish and maintain low resistance wire-to-wire contact through the insulating aluminum oxide.[7] A significant portion of the circuit current is passing from wire to wire through sections of the connector spring. The overall failure process involves deterioration of both the wire-to wire (Al-Al and Al-Cu) contact interface as well as eventual degradation of the the wire-to-spring interfaces.

The zinc-plated steel spring is not suited to be a substantive part of the current path inside the connector. The zinc plating itself is generally considered to be incompatible with aluminum for electrical contact applications. It is important, therefore, to understand the actual current paths that are active in these connections.

2) **Experimental Method**. Pigtail splices consisting of (1) #12 AWG copper and (2) #10 AWG aluminum wires are prepared by first stripping a 13mm (0.5 in.) length of insulation without scraping the wire surface. At a distance of 25mm (1.0 in.), from the bare stripped end, the three wires are fixtured together by being passed through a hole in a solid block and being cemented in the hole with epoxy. Prior to applying the expoxy in the hole, the stripped wire ends are positioned so that they lined up and are touching, as they as they might be held in the best case when making a splice of this type by hand. Behind the block, the wires are bent 90° and fastened to the back surface to prevent rotation of the wire within the insulation.

The aluminum wires are connected into a circuit powered by a constant-current DC supply. The copper wire is not connected in the circuit. At a distance of 102mm (4.0 in.) from the spliced wire ends, instrumentation wires are soldered to the aluminum conductors for the purpose of making potential drop measurements.

The connector is applied and then tightened to a torque of 0.73 N-m (6.5 lb-in), which is considered to be the maximum that likely to be applied in field installation (limited by the ability to finger-hold the wires against the tightening torque). After making a splice and allowing one-half hour to establish equilibrium with room ambient temperature, its potential drop is measured at 18 A current. The measurement is made upon initial application of current, allowing only enough time (about two seconds) for the digital meter to register a stable value. Potential drop measurements are therefore taken with the connector and the wires essentially at room ambient temperature.

The connector is then removed, and strips of thin insulating plastic film are inserted between the wires at the wire-to-wire interfaces. After installing a new connector and allowing one-half hour to to establish equilibrium at room ambient temperature, the potential drop is again measured. The potential drop measured at this step reflects 100% of the current passing through the connector spring path, which is the only active conducting path in the splice.

The connector is then removed, the wire-to-wire contact surfaces are cleaned of inhibitor compound, and the wires are soldered together for a length equal to the length of actual wire-to-wire contact. Potential drop is again measured. The resulting data permits calculation of the portion of the current that is flowing though the steel spring.

3) <u>Experimental Results</u>. A total of 10 pigtail splices were measured by this method. The potential drop data are converted into resistance values by conventional Ohm's Law calculations. The bulk resistance of the wire that is included in the potential drop measurements, taken as equal to the resistance of the soldered splice without the connector, is subtracted.

The spring.path resistance is determined to be in the range of about 350 +/- 50 uΩ. The relatively narrow range serves to confirm that the major portion of the spring path resistance in a new splice of this type is due to bulk resistance of the sections of the spring in the current path. Most of the sample to sample variation is due to differences in the exact number of spring coils actually in contact with the wires.

Knowing the spring path resistance, and assuming that the wire-to-spring contact resistances are negligible in these relatively new splices, the the current division between the two parallel paths within the splice can be calculated. When the direct wire-to-wire path resistance equals the spring path resistance, 50% of the current is flowing through the steel spring. The overall connection resistance in this case would be about 175 uΩ. For pigtail splice connections of the type previously discussed, measured at 18 amps, those that are operating with a potential drop in excess of 3.2 mV (measured value less potential drop due to length of wire) have more than 50% of the current passing through the steel spring sections.

Based on the same assumption, that the wire-to-spring contact resistances can be neglected in relatively new splices of this type, a simple relationship is developed for determining the division of current as a function of potential drop. The potential drop across the two parallel current paths is the same. The current in the spring is (from Ohm's Law) simply the potential drop divided by the spring resistance, or $I_s=E/R_s$. The portion of the total current in the splice that passes throught the steel spring path is then: $I_s/I_{total} = E/(I_{total}R_s)$. Using this relationship, the pigtail splice data of Tables 1 and 2 are presented in Table 4 in terms of the percent of the circuit current being carried by the steel spring.

		% CURRENT CARRIED BY STEEL SPRING		
WIRES SPLICED	STATE	Avg.	Min.	Max.
(2) #10 AWG Al (1) #12 AWG Cu	new	34	13	73
	after environmental exposure	61	27	100*
(2) #10 AWG Al (1) #18 AWG Cu	new	20	2	54
	after environmental exposure	39	10	100

<u>TABLE 4</u> - % OF CURRENT CARRIED BY STEEL SPRING FOR PIGTAIL SPLICES OF TABLES 1 & 2. (* calculates as over 100%, implying deterioration of wire-to-spring contacts.)

The minimum current density at the aluminum wire-to-wire interfaces can also be estimated.[17] At 18 A circuit current, one of these splices operating with 50% of the current passing through the spring has a wire-to-wire contact resistance of about 350 uΩ,, operates at about 3mV potential drop, and 9 A current flows through that interface. For this condition, the current density at the a-spots of the aluminum wire-to-wire interface is estimated to be in the range of 0.2×10^6 to 2×10^6 A/cm^2 (corresponding to a range of from one to ten a-spots).[17, see Fig.6]. This is in the range for electromigration deterioration to become significant.

III. DISCUSSION

As a general summary, there are two pivotal weaknesses of this connector that underly its poor performance in these tests. First is the inability to consistently establish adequate metallic contact through the insulating aluminum oxide at the wire-to-wire contact interfaces on samples of the wire with which it is likely to be used. Second is the inability to hold the wire-to-wire interface fixed against stresses normally applied by handling during installation and by thermal expansion and contraction. These are fundamental deficiencies of the twist-on connector type when applied to aluminum wire, and are not alleviated in the tested connector simply by the addition of inhibitor compound.

The combined result of these deficiencies is that a significant portion of splices of this type deteriorate at the wire-to-wire interface in a short time relative to expected service life, under relatively mild conditions. The safe useable life of the connections then hinges on the longevity of the wire-to-spring contacts. The wire-to-spring contact interface of this connector is aluminum to zinc-plated steel, and it is poorly suited to be part of the current path. Zinc plating is well known to be detrimental in aluminum contact interfaces, and some standards prohibit its use with connectors intended for aluminum wire applications.[18][19]20]. Poor long-term field experience with this connector in the aluminum wire pigtailing application is anticipated based on its poor performance in every one of the tests conducted in this evaluation, including the industry standard heat-cycle test.

IV. CONCLUSION

On the basis of the results of this evaluation, together with fundamental considerations, the tested twist-on connector cannot be considerd as suitable for use in making pigtailing splices that become a permanent part of residential aluminum wire systems.

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