EVALUATION OF A SETSCREW CONNECTOR FOR ALUMINUM WIRE

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Abstract - **A new setscrew connector for residential aluminum wiring repair is evaluated by means of a static zero-current test, a high-current "heat cycle" test, an environmental test, and a wire disturbance test. Additionally, the current partitioning between the two paths between the wire and the connector body is determined. After a short time in service, the resistance of the direct contact between the wire and the connector body increases to the extent that most of the current flows from the wire to the connector body through the setscrew. Further connection resistance increase then occurs at an insignificant rate, resulting in a satisfactory long life projection. The connector resists contact deterioration from the wire disturbances that occur during installation, provided that the setscrews are fully tightened as specified. The connector must be tool-held to reliably achieve the required degree of tightening, however. The connector's corrosion inhibitor is found to be involved in the initial connection resistance increase. This connector is considered to be a satisfactory candidate for residential aluminum wire repair.**

Keywords: aluminum wire, setscrew connectors, inhibitor, pigtailing, environmental test, heat cycle test.

I. INTRODUCTION

Potentially hazardous overheating of aluminum wire terminations in homes can be prevented by splicing short copper wire extensions ("pigtails") to the aluminum circuit wires wherever they are terminated. The success of the method depends on the predictable long-term safe performance of the particular type of splicing connector employed. Not all splicing connectors that have been rated and marketed for that application are actually suitable. Twist-on connectors, for instance, have been troublesome in this regard even though specifically rated ("labeled", "listed", or "certified") for the required aluminum and copper wire combinations used in residential wiring.[1][2][3][4][5]

The United States Consumer Product Safety Commission (CPSC), on the basis of extensive testing, recommended the use of a specific tool-applied compression connector for permanent aluminum wiring repair, and considers twist-on connectors to be suitable only for temporary repairs.[6] The compression connector recommended by CPSC is not widely available, however. Where available, repair with the CPSC recommended connector is likely to be more expensive than alternatives proposed by local electricians and electrical inspectors, whose recommendations are most often simply based on the labeled rating for the application.

The practical need - and market potential - for a widely available alternative to CPSC's recommended full compression connector has attracted the attention of several manufacturers. Creating such a connector, one having predictable long-term safe performance essentially equivalent to the full compression connector, is not a trivial task, however. Recently, a new setscrew splicing connector has been marketed for the application. The objective of the work described in this paper is to determine if the setscrew connector performs well enough to be considered as a candidate for recommendation as a permanent repair for residential aluminum wiring. This work is intended to serve as an initial screening to determine if more extensive life testing and field installation tests are justified.

II. DESCRIPTION OF THE SETSCREW CONNECTOR

The subject connector is shown in Figure 1.

FIGURE 1 - SETSCREW CONNECTOR (wired, prior to closing cover)

Within the plastic insulating enclosure is an aluminum body with three conductor openings and three corresponding setscrews. The conductor openings are pre-filled on the wire-entry side with a corrosion inhibitor compound. Figure 2 shows the connector assembly complete with its plastic insulator and, alongside, the inner current-carrying connector body (inhibitor compound removed).

FIGURE 2 - CONNECTOR BODY (left, inhibitor compound removed) AND CONNECTOR ASSEMBLY

The connector body is tin-plated aluminum, while the setscrew is nickel-plated aluminum. The end of the setscrew that bears against the inserted wire is spherical. A cross section of the connector with the setscrew tightened down onto an aluminum conductor is shown in Figure 3. Note that there are two paths for current to flow from the conductor to the connector body. One is a direct path where the conductor is pressed against the connector body and the other is through the setscrew.

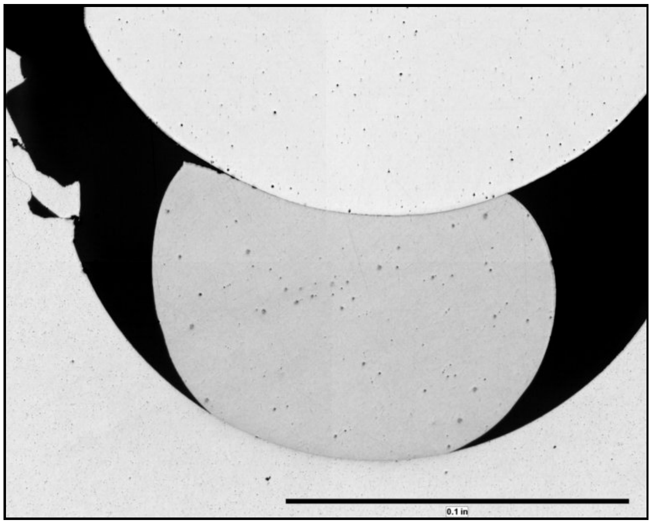

FIGURE 3 - CROSS SECTION OF #10 ALUMINUM CONDUCTOR INSTALLED IN CONNECTOR

The current-carrying connector body resembles a section of small busbar of the type utilized in residential service entrance panels for the branch circuit "neutral" and ground wire terminations. Among the field reports of aluminum wire failures, burnouts or other problems involving setscrew neutral busbar terminations are relatively rare. Successful use of the same general design as a pigtail splicing connector requires attention to several important differences in the application.

For instance, in a service entrance panel, the busbar is rigidly mounted, making it easy to tighten the setscrews, while the connector is intended to be hand held while tightening. It is not generally possible to achieve the specified tightening torque while holding the connector by hand, however. The need for full tightening of each and every termination is greater for the pigtail connector than for the busbar, in order to prevent contact interface disturbance due to installation stresses. The busbar wire termination is subjected to minimal - if any - wire disturbance after being tightened. In contrast, the forces on the completed pigtailing connector wire terminations are high when it is manipulated into a junction or outlet box.

Another fundamental difference is the higher heat dissipation capability of the busbar relative to the connector. The busbar is long, relative to the connector, and it does not have a plastic electrical insulator. The connector is thermally isolated and has a plastic insulator around it, separated by an air gap. For a given power dissipation at the terminations, the connector would be expected to run at a higher temperature.

The connector being evaluated differs from the typical busbar in that its setscrew is aluminum (as opposed to steel in the typical busbar). This reduces both corrosion potential and differential thermal expansion/contraction effects. Another difference is that the connector is precharged with corrosion inhibitor, which helps assure a gas-tight contact interface.

The inhibitor compound also serves to lubricate the setscrew threads. This occurs because the screws are fully threaded into the connector body when the compound is injected into the wire hole, so that the lower screw threads are partially coated with compound. When a screw is backed out to allow insertion of a wire, compound is spread into threads of the connector body. The resulting lubrication helps maximize the compression force on the wire that is developed from the tightening torque applied to the setscrew.

III. TEST METHODS AND RESULTS

A. Test Conductor

Tests with aluminum wire only are considered satisfactory to qualify this connector for the pigtailing application. The conductors are isolated from one another (only one conductor is inserted in each opening), and there is no reason to question the life of the copper conductor termination.

The aluminum conductor utilized for all tests is solid #10 AWG that was produced by a major manufacturer in the early to mid-1970's. This particular aluminum conductor was initially produced as an "EC" type (sometimes called "old technology") and then later also marketed as an "alloy" aluminum conductor (so-called "new technology"). Analysis indicates no significant difference in composition between samples of the original brand designation and the later brand designation. (By weight, 99.8% Al minimum, 0.2% Fe maximum.)

Both the new and the old versions of this manufacturer's aluminum conductor have a relatively tough insulating surface film, as indicated by crossed-wire tests.[5] The test conductor is representative of that installed in the majority of aluminum-wired homes in the United States.

B. Connector Installation

The manufacturer's installation instructions call for the screw to be tightened to either of the following criteria; torqued to 1.7Nm (15 in-lb), or one full turn of the screw after it first contacts the conductor. The method employed for each of the tests described below is appropriately indicated.

C. Connection Resistance Measurement

1) Significance Connection resistance reflects the extent to which metallic contact is established through the insulating aluminum oxide and then maintained with the passage of time. Low resistance, consistent from sample to sample, is the first indicator of a potentially long-lived connector for aluminum. Low rate of change is the second.

2) Determining Connection Resistance Connection potential drop is measured at 15A current, using A Fluke Model 8842A Digital Multimeter, with resolution to one microvolt. Connection resistance is then calculated using Ohm's Law (E=IR). Figure 4 shows measurement of the potential drop of terminations "A" and "B", with current flowing through their respective conductors.. The current path is then changed to "B" and "C" for measurement of the potential drop of termination "C". Current flows only during the time (less than 5 sec.) required to obtain a stable reading.

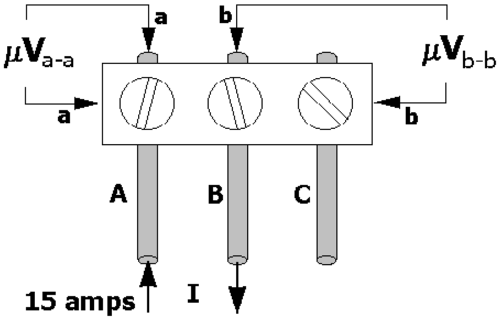

FIGURE 4 - MEASUREMENT OF POTENTIAL DROP

A machined slot across the back of the connector's insulating shell provides measuring probe access to the stub ends of the conductors, while a small hole drilled through the shell on each side allows probe contact to the sides of the connector body. This is essentially a "four-wire" method, and it provides consistent and reproducible measurements.

3) Experimental Results - Standard Installation

A set of 10 connectors (30 terminations) was prepared with the conductors installed and the setscrews torqued to the manufacturer's recommendation. Connection resistance results for this set are shown in Figure 5.

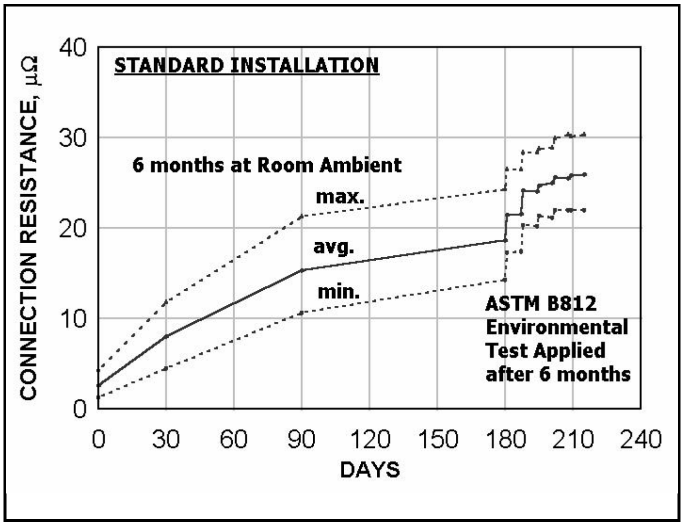

FIGURE 5 - CONNECTION RESISTANCE WITH STANDARD INSTALLATION

Exposed to a mild room ambient environment for six months, with no current flow except when making measurements, connection resistance increases with time but remains relatively low. (At 15A and 25μΩ, for instance, power dissipation at the connection is an insignificant 6mW.) The trend in the data is consistent from sample to sample.

A more aggressive environmental exposure was then applied. The ASTM B812 method, developed for testing resistance to environmental degradation of residential wiring connections, was employed.[7] Exposure consists of repeated weekly sequences of 5 thermal cycles (75 C temperature excursion) and then, for the remainder of the week, a static exposure to high humidity (100% non-condensing) at room temperature. The step increases seen in Figure 5 result from the thermal cycling. The humidity exposure produced little change, as expected for a connection utilizing corrosion inhibitor compound.

4) Experimental Results - Effect of Abrasion

Abrasion of the aluminum conductor is commonly employed to help assure adequate metallic contact through the native insulating oxide film on the aluminum wire. Whether or not conductor abrasion makes a significant difference in initial resistance and/or performance can be a useful measure of how effective the connector is in establishing metallic contact. For this set of specimens, the conductors were abraded with #220 grit abrasive under a film of inhibitor immediately prior to insertion into the connector, and then the setscrew was immediately torqued to specification. Results for this test set are shown in Figure 6.

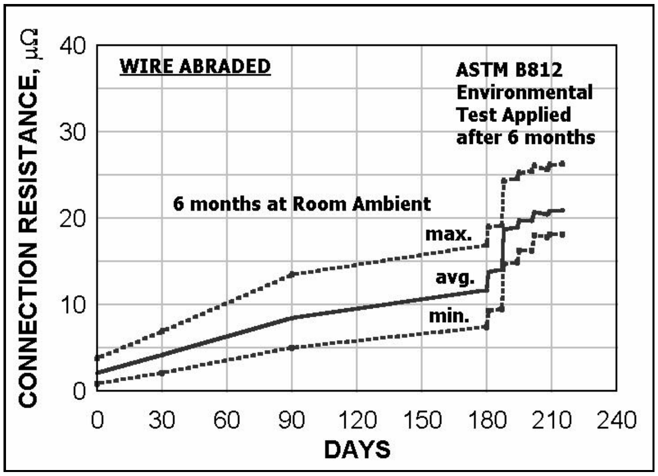

FIGURE 6 - CONNECTION RESISTANCE, WITH CONDUCTOR ABRASION

Conductor abrasion does not substantially lower the initial resistance, indicating that adequate penetration of the insulating aluminum oxide is achieved by normal tightening of the setscrew. Additionally, conductor abrasion is not effective in arresting the connection resistance increase that occurs with time and thermal cycling.

5) Experimental Results - Current Path Isolation

In order to estimate the useful (safe) life of these teminations, a further understanding needs to be developed as to why the connection resistance increases. A first step toward that objective is taken by analysis of the current flow through the connector.

There are two separate contact interface paths in this connection, and they are quite different with respect to interface mechanics as the setscrew is being tightened. A relatively massive disruption of the oxide film is expected at the wire-to-setscrew interface due to the combined effects of the rotating screw and the indenting (and stretching) of the surface. That should result in a substantially lower resistance at that interface relative to the wire-to-body contact.

The current division between the two paths is determined by insulating the contact between the wire and the connector body. All of the current then passes through the wire-to-setscrew path. For this purpose, a .025mm (0.001") Kapton$^{(TM)}$ polyimide film is inserted at the wire-to-body contact interface prior to tightening the setscrew. The results are shown in Figure 7.

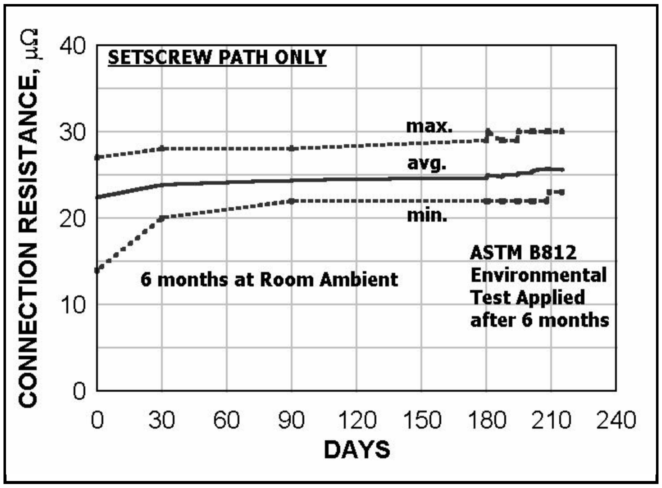

FIGURE 7 - CONNECTION RESISTANCE, SETSCREW CURRENT PATH ONLY

With the direct path between the wire and the connector body completely insulated, all of the current flows from the wire to the body through the setscrew. There are two contact interfaces in that path, both of which are subjected to a large amount of wipe as the setscrew is tightened, resulting in relatively low contact resistance at those interfaces. The resistance that is measured for this current path consists primarily of the bulk resistance of the setscrew. For the purpose of discussion, it is now helpful to put the three previous results (averages) side by side, as shown in Figure 8.

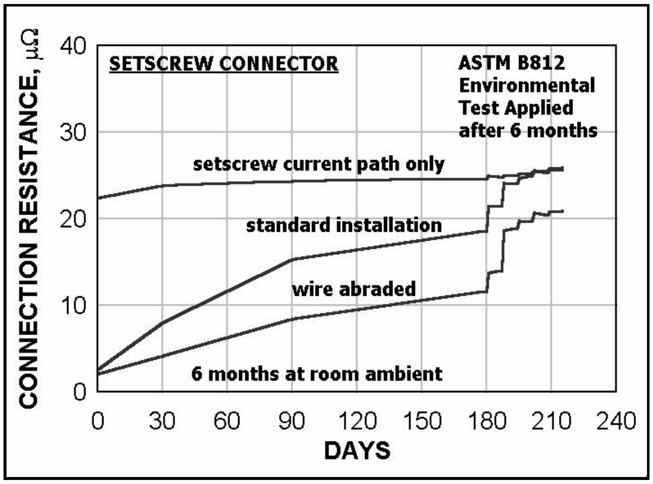

FIGURE 8 - CONNECTION RESISTANCE, AVERAGE, UNDER PREVIOUSLY SHOWN CONDITIONS

These results show that there is relatively little resistance increase with time and environmental test exposure at the contact interfaces in the setscrew path. As the wire-to-body path resistance increases, the long term resistance increase of the overall connection will approach that of the setscrew path only, resulting in an extrapolated increase of the order of 2 μΩ/yr, which would be quite satisfactory.

6) Experimental Results - Alternate Inhibitor The accuracy of future performance projections for electrical connections depends to a great extent on a proper understanding of the deteriorating factors. In that context, the fast degradation of the wire-to-body contact interface is unexpected and needs to be understood. For a connection of this robust construction, it should not occur so quickly under such mild applied conditions. One possible cause is the inhibitor, whose lubricating and chemical properties may have an adverse effect.[8]

As a preliminary evaluation of the role of the inhibitor, three additional (smaller) sets of connections were made and subjected to thermal cycling only. One set was made utilizing the connector manufacturers' standard inhibitor, the second set was dry (no inhibitor), and the third utilized an alternate commercially-available inhibitor. The results for these test sets are shown in Figure 9.

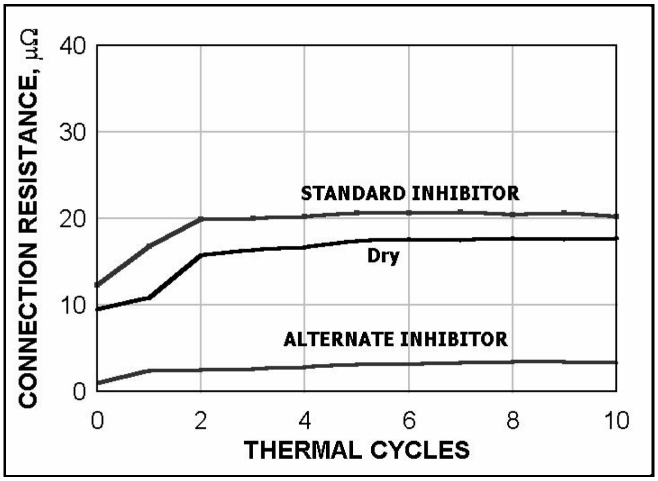

FIGURE 9 - ALTERNATE TREATMENT

Because of the differences in connector assembly method and test sequence, the results shown in Figure 9 cannot be compared directly with those previously shown. A strong influence of the inhibitor is apparent, however. The alternate inhibitor clearly improves the connection, and so the influence of the inhibitor is worthy of further study. If the life of the wire-to-body contact interface - which should be the primary current path - can be substantially improved, then the connector would have an additional safety factor.

D. Heat Cycle Tests

Heat cycle (actually high current cycle) testing is useful as a side-by-side measure of performance of different connectors. In this instance, the setscrew connector is tested with the same aluminum conductor and under the same conditions as two alternate connectors marketed for the same purpose.

Applied current for the heat cycle tests is 60A (UL486C standard value for testing #10 AWG aluminum wire splices). Current is applied for one hour on and 1/2 hour off. The test is conducted in a temperature-controlled room at 20 C. Temperature as reported in the figures below is taken at 3/4 hour into the current-on portion of the cycle.

The full compression crimp connector recommended by CPSC serves as the benchmark of performance for this application. Originally subjected to extensive testing by CPSC in the mid-1970's, there is now a 30+ year history of its use without reports of failures (burnouts). That stands in marked contrast to other connectors that have been marketed and promoted to be suitable for aluminum wire.

Figure 10 shows the heat-cycle test results on a newly-made set of these connectors, utilizing two #10 AWG aluminum conductors and one #12 copper conductor. The current (60A) in this test flows into the splice through one of the aluminum conductors and out through the other aluminum conductor.

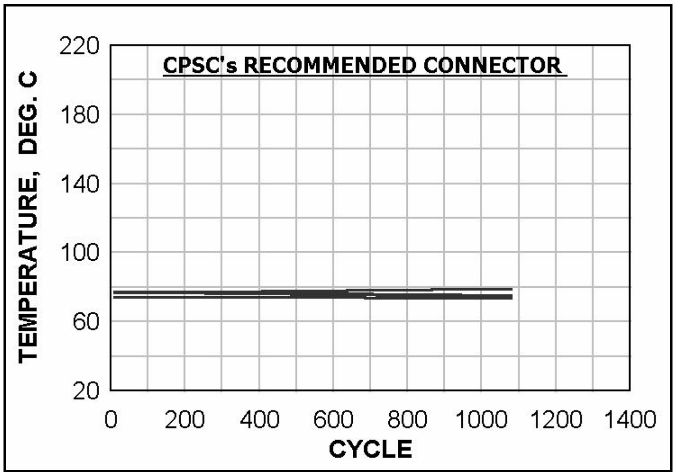

FIGURE 10 - HEAT CYCLE TEST @60A, COMPRESSION CONNECTOR

The four specimens tested are tightly grouped and show no upward trend of temperature with increasing number of cycles. That is the hallmark of a sound connector for this application. In contrast are the results shown in Figure 11 for a twist-on connector that is presently rated for the pigtailing repair application. The wire combination in the tested splices is two #10 AWG aluminum with one #18 AWG solid copper, which is a rated combination for this connector. The twist-on connector performance is inconsistent and somewhat erratic. One of the four fails the "stability" requirement of the industry standard heat cycle test prior to 500 cycles. After 500 cycles the connectors were subjected to a wire disturbance, consisting of a 90° bend upward and return, with the bend in the wire centered about 2.5cm from the connector. All four test samples went to thermal runaway (burnout) condition shortly afterward. The performance of this connector has previously been evaluated.[4][5] Long term safe operation of this twist-on connector is not predicted from the test results, and field failures have been reported.

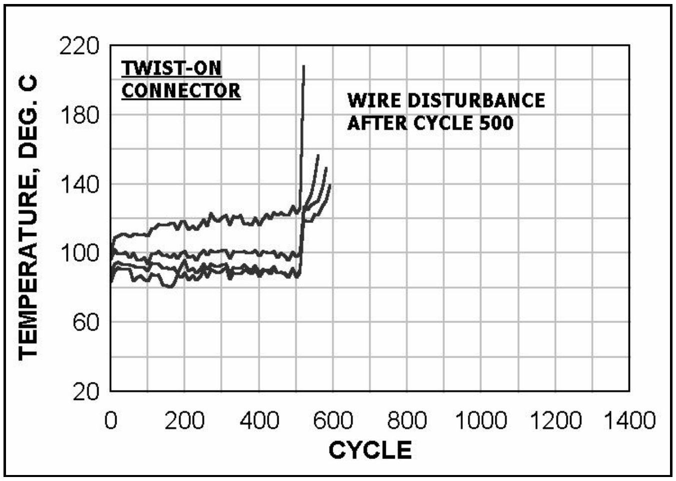

FIGURE 11 - HEAT CYCLE TEST @ 60A, TWIST-ON CONNECTOR

Resistance to degradation from wire disturbance is a fundamental requirement for the aluminum wire pigtailing application, since the completed splices must be manipulated into the existing outlet or junction boxes. The setscrew connector has been heat cycle tested with an applied wire disturbance, and the results are shown in Figure 12.

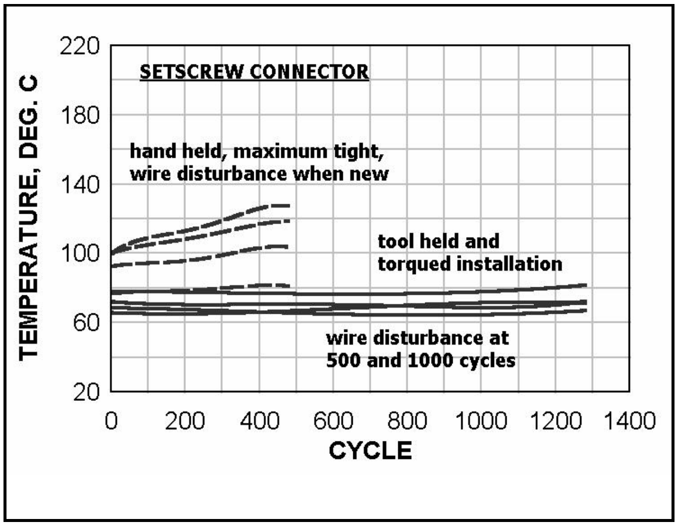

FIGURE 12 - HEAT CYCLE TEST @ 60A, SETSCREW CONNECTOR

For the heat-cycle test, one group of setscrew connectors was tool held and tightened to the recommended torque when made. That group showed reasonably close sample-to-sample results, and no significant upward trend of temperature with increasing number of cycles. After 500 cycles, and again at 1000 cycles, a wire disturbance was applied. There was no apparent degradation due to the wire disturbance.

A second group of these connectors was installed hand-held and screwed as tightly as possible. It is difficult to hold the connector tightly enough by hand to achieve the recommended degree of tightening by either of the recommended methods (on the connector's instruction sheet), and this group was tested to determine if that represents possible exposure. Connectors in this group were subjected to a wire disturbance after initial installation. The performance is degraded by the combination of hand-held tightening in combination with the wire disturbance.

IV. CONCLUSIONS

These preliminary tests of the new setscrew splicing connector show it to be a satisfactory candidate for the aluminum wire pigtailing application. Tightened to the manufacturer's recommendation, it yields consistent low-resistance aluminum wire terminations, a projected low rate of resistance increase, and withstands wire disturbance. A recommendation for its use as an alternate to CPSC's approved and well-proven compression connector is justified where that recommended repair is not available. The performance of the setscrew connector is far superior to that of the twist-on connector that is presently marketed for the application.

Long-term tests employing larger sample size are required to increase the level of confidence in this recommendation, however. A quarter of a century ago, CPSC confirmed its recommendation of the full compression connector through tests involving 1000 samples of different wire combinations and wire manufacturers.[9] A sample size of that magnitude would not be required today, as there is a larger experience and knowledge base by which to predict the long-term performance of aluminum wire connections.

The question of sensitivity to setscrew tightening and wire disturbance needs to be explored further. Large-scale general use for this application demands a large safety factor for these variables. Product changes may be justified to increase the certainty of satisfactory performance over a wider range of installation conditions. In particular, these preliminary test results suggest that the safety factor with respect to installation variables could be increased substantially through use of a different inhibitor compound and/or improved design for mechanical wire restraint.

ACKNOWLEDGEMENT

This investigation has been supported in part by the United States Consumer Product Safety Commission.

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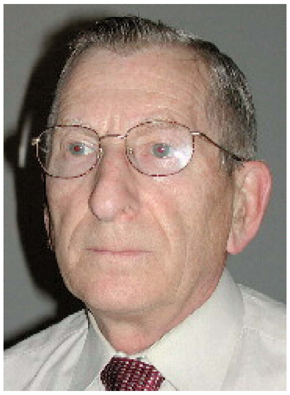

Jesse Aronstein received a B.M.E. from the City College of New York, an M.S. in Mechanical Engineering and a Ph.D. in Materials Science from Rensselaer Polytechnic Institute. At the General Electric Company he was engaged in the development and testing of liquid-propellant rocket engines. Later, with the IBM Corporation, he held engineering and management positions related to the development of advanced testing and manufacturing equipment for semiconductor chips. He was Vice President, Special Engineering Projects with Wright-Malta Corporation, involved in the development of specialized manufacturing and test equipment, and in the investigation of the performance of aluminum wire terminations and the fire hazards which result from overheating connections. Currently he is a consulting engineer, involved primarily with electrical equipment failure and safety analysis. He is also President of Protune Corp., which develops and manufactures specialized electronic instrumentation. Dr. Aronstein is a member of IEEE, ASTM, NFPA, Pi Tau Sigma (the National Mechanical Engineering Honor Fraternity), and Alpha Sigma Mu (the National Materials Engineering Honor Fraternity). He is a licensed Professional Engineer in New York State. He has 15 patents in his name and received several invention and achievement awards for his work at IBM. Dr. Aronstein has authored more than 25 papers relating to electric contact technology, most of which involve studies of the nature of the aluminum contact interface and the behavior of practical aluminum connections.