EVALUATION OF AN ALUMINUM CONDUCTOR MATERIAL FOR BRANCH CIRCUIT APPLICATIONS

J. Aronstein
Consulting Engineer
Poughkeepsie, NY

W. E. Campbell
Consultant
Marco Island, FL

ABSTRACT

An experimental aluminum wire alloy containing Mg was among many tested in the early 1970's in research directed toward solution of aluminum wire connection problems. Unlike other alloys tested at that time, its performance in heat-cycle tests of splices made with twist-on connectors was equivalent to copper wire. Enrichment of Mg at the wire surface appeared to account for the improved connectability of this alloy. Presently, an alloy containing significant concentration of Mg, with Mg enrichment at the surface, is certified for use in Canada. This present investigation evaluates the Canadian alloy aluminum wire using two-wire (Al-Al) splices made with "special service" twist-on connectors installed with controlled tightening torque. No current flows in the test samples except when measurements of potential drop are made. Applied test conditions are within the normal rated application range for connections of this type. After one year of testing, substantial progressive increases of connection resistance are evident among the splices made with the Canadian alloy. No performance improvement is seen with this alloy compared with other aluminum conductors tested. It is doubtful that stable and safe long-term performance will be achieved with this alloy in large-scale field application involving the present types of connections. The reasons are noted, and the weaknesses of the qualification standards testing for aluminum wire are discussed. (Key Words: Aluminum Wire; Aluminum Conductor Material; Alloy Aluminum Wire; Qualification Standards; Corrosion; Environmental Testing; Twist-on Connectors; Special Service Connectors.)

INTRODUCTION

Subsequent to the introduction of aluminum wire for residential applications in the United States and Canada in the mid-1960's, a substantial number of connection overheating failures were reported, some with serious consequences.[1] The failed connections included wiring terminals of receptacles, wire splices, and connections to circuit breakers and fuse blocks. Research efforts centered on the receptacle terminals, since they were most often detected by the occupants and are most numerous in residential installations.

A major factor influencing the failure of aluminum-wired screw terminals on receptacles was believed to be relaxation of the aluminum under the screw head, a consequence of the physical behavior generally measured as creep or stress relaxation. Experimental alloy aluminum wires with improved creep resistance were devised and evaluated. Improvement of the bulk properties of aluminum wire did not alleviate the failures in twist-on connections, since the failure mechanisms in these connections are related to the surface properties of the aluminum. Aluminum alloy wires have been found to perform poorly in twist-on connector splices.[2][3][4]

One particular experimental aluminum alloy conductor material demonstrated performance equivalent to copper in heat-cycle testing of splices made with twist-on connectors.[5] The surface region of the wire had an unusually high concentration of magnesium.

Improvement of the connectability of aluminum by surface property modifications has been attempted through various means. Examples include copper-clad and nickel-plated aluminum wire.[6] Favorable aluminum surface modification resulting from alloying elements, without cladding or plating, is an attractive possibility, as it would generally involve lower cost than cladding or plating. The favorable heat-cycle test results with twist-on connections stimulated further investigation of aluminum alloys containing Magnesium. One such alloy has been certified for use in Canada.

The tests reported on in this paper were initiated to determine if the Canadian Al-Fe-Mg alloy wire is significantly different than other aluminum wires with respect to connectability. Wire splices (Al-Al) made with twist-on connectors are used as the test connections. These have been shown to be failure-prone in the previous tests, and they are a more sensitive indicator of connectability than the binding-head scew terminations used for qualification testing of aluminum wire. The principal differences in these tests compared with those previously reported is the use of controlled applied torque for connector installation, and a lower relative humidity in the constant-environment exposure.

EXPERIMENTAL METHOD

Conductor Tested

The aluminum conductor material tested is reported to be a dispersion-hardened Al-0.77%Fe-0.15%Mg alloy, and the surface region of the wire (at the contact zone studied) has a tenfold enrichment of Mg.[7] This aluminum alloy conductor material is certified for use in Canada. In addition to the Canadian alloy aluminum wire, comparison groups using EC aluminum and another alloy are tested. The wire samples were obtained from non-metallic sheathed cable consisting of two insulated wires and an uninsulated grounding wire.

Test Connections

Failures of aluminum-wired twist-on connections within normal service conditions become evident quickly compared with failures of the binding-head screw terminals used in the qualification standard testing. Therefore, the twist-on connector splices were selected as the test connectors for this study. The connections tested are two-wire Al-Al splices made with solid #12 AWG wire. This size wire is appropriate for 15 A branch circuit applications.

"Special service" twist-on connectors are used to make the test splices. These are certified for use with aluminum wire by a relatively recent Canadian standard. The qualification standard uses "heat-cycle" and "static heating" tests as the principal determinants of connection performance. Both tests involve the passage of current substantially higher than rated. Failures are evident, however, when aluminum-wired splices made with these connectors are tested within normal rated current and environment.[3]

The connectors used were previously identified as type Y1 special service.[3] The connections are made according to the connector manufacturer's printed instructions, with the exception that they are not hand tightened. The wire is stripped to the proper length, the connector is pushed on over the bare wire ends and is then tightened. There is no abrasion of the wire surface, and corrosion inhibitor is not used. The connections are tightened with a torque wrench to 0.4 Nm (3.5 in-lb). This value was determined to be the approximate maximum tightening torque which could be applied by hand to this connector and wire combination.[8] (In field use the connectors are hand applied, but in test connections for evaluation of the performance of the aluminum wire it is desireable to control this variable.)

The connections are arranged 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.

Applied Electrical Conditions

There is no application of electrical current except when potential drop measurements are made. During the year of testing, there were 24 sets of measurements taken. The measurement current is 13.5 A, in a circuit with resistive loads fed from a 115 Vac source, and the time required to take a set of measurements is approximately ten minutes. The total current-on time for these connectors during the year of testing was twenty-four ten minute periods at 13.5 A (90% of the 15 A circuit rating).

Environmental Conditions

One specimen group made using the Canadian alloy is kept in a "normal" environment, with temperature and relative humidity varying in relation to outdoor ambient conditions. This environment is representative of that in a junction box in a perimeter wall of a building. Together with comparison groups, a second set of specimens made with the Canadian alloy is in a "constant" environment at 35°C and 75% RH. Both environments used are within the expected application range for residential wiring applications. Table 1 identifies the test groups and the associated test environment.

Group Number	Aluminum Conductor	Test Environment
1	Alloy, Canadian (Al #6)*	Constant
2	" "	Normal
3	EC, Canadian (Al #4)*	Constant
4	Alloy, U.S. (Al #3)*	Constant

TABLE 1 - TEST GROUP IDENTIFICATION AND ENVIRONMENT

* (See References 2, 3, and 4)

Failure Criterion

As in the previous tests, the failure criterion is 40 mV potential drop for a splice and its associated length of conductor at 13.5 A. This reflects a connection resistance one order of magnitude greater than the average initial resistance for the aluminum-wired twist-on connections, and two orders of magnitude greater than the average for similar splices made with copper wire or abraded aluminum wire.[2][3][4]

The failure criterion is based on the observation that aluminum-wired twist-on connections exceeding that level rapidly progress to erratic behavior at substantially higher potential drop. The heat generated at the connections at a given current is proportional to the potential drop, and the failure criterion chosen is related to the onset of connection behavior that usually results in significant heating of the connection when current is applied. "Severe failure", a term previously applied to connections that heated to the extent of causing noticable deterioration of the wire or connector insulation, is not applicable in these present tests since the duration of current flow is short.

EXPERIMENTAL RESULTS

The results are shown in Table 2. The performance of the Al-Fe-Mg alloy (Group 1) in the constant 75%RH/35°C environment is essentially no different than the comparison EC and alloy aluminum conductors (Groups 3 & 4). In all three test groups there is a general increase in potential drop and approximately 1/3 of the connections in each of the three groups have failed in one year.

Group	Time, mo.	SURVIVORS					FAILURES			
		# of	POTENTIAL DROP, Mv				# of	POTENTIAL DROP, Mv		
			Avg.	Std. Dev.	Min.	Max.		Avg.	Min.	Max.
1	new	17	22.6	2.1	18.7	25.9	0	-	-	-
	3	17	27.1	5.4	18.8	38.1	0	-	-	-
	6	14	27.6	5.8	19.2	38.2	3	59.8	43.4	73.9
	12	12	26.3	5.5	18.3	37.4	5	133.	46.6	345.
2	new	17	22.2	2.2	18.9	28.5	0	-	-	-
	3	17	22.9	2.8	19.4	31.2	0	-	-	-
	6	17	24.1	3.9	19.5	37.2	0	-	-	-
	12	16	24.8	3.9	18.9	33.0	1		218.	
3	new	20	21.5	2.1	18.7	26.3	0	-	-	-
	3	19	25.6	5.1	19.4	38.9	1		40.2	
	6	16	26.5	5.5	18.8	35.0	4	61.0	46.9	78.3
	12	13	26.3	5.9	18.2	37.5	7	100.	44.6	270.
4	new	20	23.2	1.7	20.0	25.9	0	-	-	-
	3	18	28.4	4.9	20.1	38.2	2	41.2	40.6	40.7
	6	14	28.6	4.4	21.7	35.9	6	52.6	42.0	75.5
	12	13	28.3	5.0	20.2	38.0	7	105.	41.3	308.

TABLE 2 - RESULTS: POTENTIAL DROP MEASUREMENTS

With time, the failures increase in severity of heating when current is applied. The maximum heat generation so far observed is approximately 4.5 W at the 13.5 A test current. (Heat generation = current x potential drop.)

The Al-Fe-Mg alloy aluminum test group in the normal environment (Group 2) also shows increasing connection resistance with time, and one failure has occurred in the year of testing. Heat generation at the failed connection was 3 W at 13.5 A. There is a general increasing trend in the average potential drop of the surviving connections. The progressive nature of the potential drop increases, reflecting increasing connection resistance, is shown in Figure 1 for several representative connections.

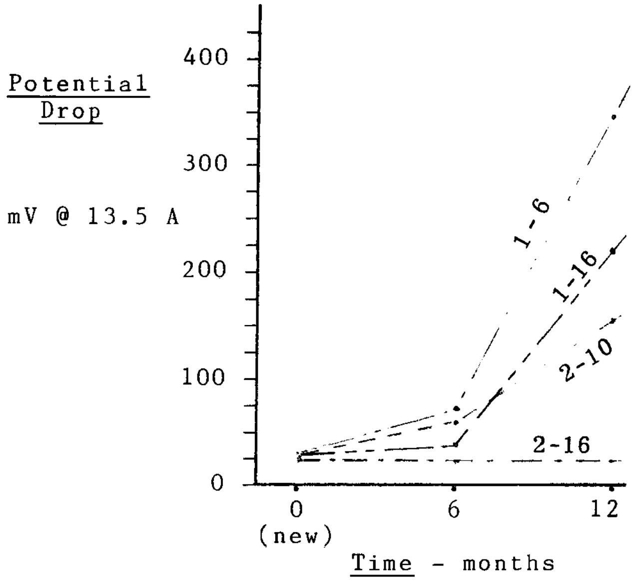

FIGURE 1 - POTENTIAL DROP VS. TIME FOR INDIVIDUAL CONNECTIONS

Table 2 showed the results for the connections made with the insulated Al-Fe-Mg wire of Groups 1 and 2. Additionally, three connections in each of these two groups were made with the uninsulated (#12 AWG Al) grounding conductor from the NM cable. As the results on the connections involving the grounding wire are quite differrent, they are not included in the statistical summary of Table 2. Five of the six connections involving the grounding wire failed, and a maximum potential drop of 429 mV (heating of 6 W @ 13.5 A) has so far been noted.

A copper-wired group ("C") from the previous tests ([2],[3]), made with standard twist-on connections, was installed in the constant environment along with Groups 1, 3, and 4. There has been no change in the copper-wired splices. The copper-wired connections, under the same conditions in which the aluminum-wired connections fail, show low potential drop, tight distribution, and are stable.

DISCUSSION

Connection Failures

The failure data for the Al-Fe-Mg alloy in the constant environment reveals poor connectability, essentially no different than the comparison alloy and EC aluminum wires tested. In all respects, the applied conditions of the test are mild compared to those encountered by these types of connections in actual service. Connection resistance increases and one failure in the normal environment test group demonstrates that the poor connectability manifests itself under conditions of actual installations. The performance difference in the two environments (slower deterioration in the normal environment) is a result of lower average relative humidity in the normal environment.

The aluminum wires in the connections are in direct contact, and the primary current path should be directly from wire to wire. In contrast to similar copper-wired connections, however, the contact resistance between the aluminum wires is initially high, and it then increases as a consequence of corrosive deterioration.[3] The reasons for the failures have been previously discussed, and they are generally related to the surface properties of the aluminum wire.[2][3][4]

The Aluminum Wire Surface

Surface properties and materials play a pivotal role in the initial contact and subsequent deterioration. The aluminum wire surface is quite different from that of clean high-purity aluminum with air-grown oxide. This is to be expected as a consequence of the manufacturing processes, which include wire drawing, annealing, and insulating. These processes involve application of chemicals (lubricants and extruded plastics), elevated temperatures, and a variety of heating and cooling environments. For instance, the annealing atmosphere may be the combustion products of a gas-fired annealing furnace. Post-anneal cooling may be in factory air with a water spray. While the composition of an aluminum conductor material may be specified, its surface characteristics, and therefore its performance in the intended application, may vary drastically according to the manufacturing processes.

Tests of contact resistance vs. force for the Canadian Al-Fe-Mg alloy aluminum wire showed high contact resistance.[7] Of the combinations tested involving the alloy wire, the worst result was obtained in contact with aluminum. Contact resistance of the order of 0.2 ohm was measured at a normal force of 40 N (9 lb.), indicative of substantial insulating films at the contact interface. The wire surface was shown to be contaminated with a significant number of impurities.

The aluminum wire surface is also important with regard to corrosion processes. Practical wire surfaces do not have the corrosion resistance of pure and clean aluminum. There are alloying elements present at the surface as well as contaminants, and both contribute to corrosive deterioration of the Al-Al contacts in the presence of atmospheric moisture. The test results demonstrate that significant deterioration occurs at 75% RH, which is not abnormal in the intended application environments for these connections.

Qualification Standards Testing

The performance of the Canadian aluminum conductor material in combination with the special service connectors is unsatisfactory, as evidenced by high initial connection resistance, wide sample-to-sample distribution, and progressive increases of connection resistance with time in a substantial number of test connections in a mild test environment. The worst-case failures heat significantly when carrying current less than the circuit rating. The probability of achieving long-term satisfactory and safe performance in large-scale field application is low for this type of connection.

Poor performance of the tested connection combination, within rated conditions, demonstrates that the heat-cycle tests of the qualification standards do not serve the required purpose of screening failure-prone and potentially unsafe connection combinations from the market. While the heat-cycle test appears at first glance to be severe, because it applies high current and high duty cycle, there are serious deficiencies. One major weakness in the qualification testing of the wire is that the test connections (binding-head screw terminals) are not the most failure-prone among the connection types with which the wire is intended to be used.

A second major weakness is the lack of environmental testing or environmental preconditioning of the test specimens. The twist-on connections fail due to corrosion-related deterioration processes, while the heat cycle test as presently defined in the qualification standards actually inhibits corrosion-related failures since the high temperature drives off the surface moisture.

CONCLUSIONS

The failures of the aluminum-aluminum wire splices within normal rated conditions reflects poor connectability of the wire surface. High initial contact resistance and subsequent corrosion at the contact interfaces are major factors in the progressive failure behavior. The Mg enrichment of the surface that is reported for this conductor material does not make a significant difference in the performance in the test connections relative to the other aluminum comparison conductors.

REFERENCES

1. R. Newman, "Hazard Analysis of Aluminum Wiring", April 1975, U.S. Consumer Product Safety Comm. NIIC-0600-75-H006

2. J. Aronstein and W.E. Campbell, "Failure and Overheating of Aluminum-Wired Twist-on Connections", IEEE Trans. Components, Hybrids, & Mfg. Tech., V. CHMT-5 No. 1, Mar. 1982, pp. 42-50.

3. J. Aronstein and W.E. Campbell, "Overheating Failures of Aluminum-Wired Special Service Connectors", IEEE Trans. Components, Hybrids, and Mfg. Tech., V. CHMT-6 No. 1, Mar. 1983, pp. 8-15.

4. J. Aronstein and W.E. Campbell, "The Influence of Corrosion Inhibitor and Surface Abrasion on the Failure of Aluminum-Wired Twist-on Connections", <u>Proc. of the Twenty Ninth Annual Mtg. of the Holm Conf. on Electrical Contacts</u>, Ill. Inst. of Tech., Chicago, 1983, pp. 223-229.

5. W. H. Abbott, testimony, CPSC hearings on Aluminum Wire, 1974.

6. V.L.A. da Silveira and W.A. Ma[illegible]imer, "Connecting Aluminum Conductors: Effects of Geometry and Tightening Torque on Contact Performance", <u>Proc. of the Twenty Seventh Annual Mtg. of the Holm Conf. on Electrical Contacts</u>, Ill. Inst. of Tech., Chicago, 1981, pp. 251-258.

7. M. Braunovic, "Research on Aluminum Wire Connections", Canadian Electrical Assoc., Report CEA RP 78-90, June 1983.

8. J. Aronstein, "Twist-on Electrical Wire Splices: Installation Factors, Visual Appearance, and Residual Torque", Wright-Malta Corp., Ballston Spa, NY, Mar. 29, 1983.