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1 INTRODUCTION

The heart of the hermetic compressor is the stator. As with the other components sealed into the hermetic environment, the stator is expected to provide years of reliable service. The motor manufacturer, however, does not look at the hermetic stator as a unit but rather as a selected group of materials and processes that will provide the end user with the reliability and performance desired. One of the processes that has years of proven field reliability is the internal stator connections where copper magnet wire is employed. In the past few years, however, the hermetic motor manufacturers have been designing and producing an increasing number of aluminum wound hermetic stators. Economic considerations notwithstanding, aluminum magnet wire can offer inherent physical advantages. For example, there is evidence of better resistance to long term thermal aging when organic insulations are applied to aluminum wire, as compared with copper. It is common experience that aluminum wire winds easier once proper tensions are adjusted. Springback characteristics in aluminum allow for uniform coil conformation and more efficient use of available space. These advantages partially offset the lower conductivity values of aluminum wire. Historically, however, the primary drawback in using aluminum magnet wire has been associated with the development of reliable connecting techniques. The objective of this paper is to discuss the state of the art in reliability testing of aluminum magnet wire connections for hermetic motors. The paper will also deal with the types of aluminum wire connections available for the industry and a discussion of their relative merits. Comments and data regarding the long term reliability of these connections will also be covered.

2 INTERNAL CONNECTIONS & CONNECTING METHODS

Typically, hermetic stators are random wound coils of either copper or aluminum magnet wire, or in some designs, windings can employ both aluminum and copper wire. Connections include various combinations of magnet wire to magnet wire splices or magnet wire to lead wire joints. Copper connections in hermetic stators are almost always pigtailed together and then fused and brazed. With the advent of high temperature organic wire insulations, an additional step of insulation prestripping was added to the copper wire fuse and braze process. Aluminum magnet wire offered some new challenges. The same insulation could be applied to the aluminum wire and system compatibility was maintained. However, aluminum wire even when properly stripped is not easily fused together, and with copper wire in the connection, dissimilar melting points made heat fusing impossible. Besides heat fusing, other methods of connecting aluminum wire combinations have been explored. For instance, sample connections were made with such advanced techniques as capacitor discharge welding, laser beam fusion, and compression cold fusing. However, the feasibility of these techniques for a production line were soon apparent, and more practical approaches were considered, such as, compression connectors, insulation piercing compression connectors, and soldering. The balance of this paper will present experimental life testing data on connection methods incorporating insulation piercing compression connectors and soldering.

3 TEST CRITERIA AND SAMPLE PREPARATION

The development of these reliability tests did not come about haphazardly. It was known from previous test experience, with non-hermetic type motors, that four inherent characteristics of aluminum were detrimental to a connecting process. These were: aluminum oxide formation, cold flow, coefficient of thermal expansion and susceptibility to corrosion when coupled with a dissimilar material. Since the compressor environment minimizes the effects of oxygen and moisture, efforts were concentrated on evaluating connections from the standpoint of cold flow and thermal expansion. With these considerations in mind, the following test parameters were established:

A. Environment — Saturated vapor of Refrigerant-22, and/or R-12. Refrigeration grade oil.

B. Test Vessels — Modified compressors, compressor shells and stainless steel autoclaves.

C. Test Conditions
- a) Constant current input.
- b) Thermal shock cycling.
- c) Time controlled stress periods.
- d) Millivolt drop & resistance measurements to monitor connection deterioration.

D. Test Samples
- a) Wire combinations representative of actual stator con-

nections.

b) Connection techniques representing proven methods, along with large numbers of samples to statistically test new connection processes.

E. Sample Preparation

a) Mechanical connections prepared with manufacturers' prescribed tooling and procedures. Fuse/braze connections prepared as per established production process specification. Soldered connections were made in accordance to solder manufacturers' recommendations.

b) All samples were insulated with heat-shrink polyester film tubes.

F. Test Criteria

Any condition, such as a radical change in resistance at the joint, overheating, or fluctuating millivolt drop readings alerted the technician as to a possible connection failure. The test could be interrupted and individual connections could be checked for deterioration.

It is important to realize from this point on that test results and recommended practices reflect on the materials and processes used by A. O. Smith, and may not necessarily be true with other materials or manufacturers. The evolution of our test experience is described in the following test programs. It is from these tests and supporting data that we feel confident in the performance and reliability of the method chosen to connect aluminum wire in hermetic stators.

4 MOTORETTE TEST

This test was developed in order to closely simulate the conditions of an actual stator. A motorette was wound with multiple turns of 16 AWG wire. At 15 intervals, the winding was broken and a connection made. Each connection contained, in addition to the 2 - 16 AWG aluminum wires, a 14 AWG stranded lead wire and a 20 AWG copper magnet wire. Each of the 15 connections were thermocouple equipped. A thermocouple was also imbedded in the motorette slot to monitor winding temperature. The 15 connections were prepared as follows:

Legend	All Connections Made With Mechanical Clips
N.S. (3 samples)	16 AWG aluminum magnet wire was not stripped.
C.S. (3 samples)	16 AWG aluminum magnet wire was chemically stripped. No reduction in bare wire diameter.
M.S. 5% (3 sampl)	16 AWG aluminum magnet wire stripped mechanically reducing bare wire diameter 5%.
M.S. 10% (3 samples)	Same as above, except bare wire diameter reduced 10%.
M.S. 15% (3 samples)	Same as above, except bare wire diameter was reduced 15%.

This test was set up in a modified compressor shell in order to introduce a hermetic environment (R-22 & oil). The test was manually controlled with the following parameters:

A. Constantly balanced current - 30 amps.

B. Current off when slot winding temperature reached 350° F. (Observed normal override of 20° F.)

C. Cool down to 100° F. and repeat current on cycle.

We found that the Lab ambient temperature had some influence on the rate of rise, but typical winding temperature rate of rise was 5.5 to 6.0° F. per second.

Basically, we arrived at the following results after 1000 cycles:

1. Connection temperatures ranked in order of lowest to highest:

   A) 5% M.S. - lowest operating temperature.

   B) Chemical stripped.

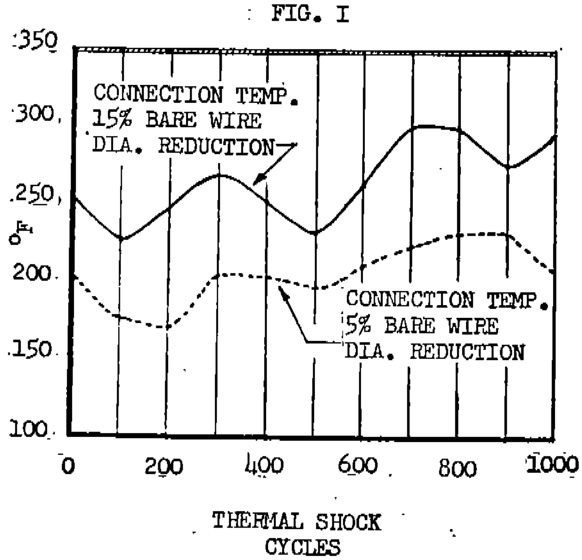
   C) 10% M.S.

   D) N.S.

   E) 15% M.S. - highest operating temperature.

   Figure I illustrates the temperature pattern of the connections at various cycle intervals throughout the test.

FIG. I



2. Resistance and millivolt drop readings were taken on retained samples and on the test samples following the 1000 cycle test. The results of these data also confirmed the optimized condition reached with 5% max. bare diameter reduction plus mechanical clip to achieve a connection.

5 AUTOMATIC CURRENT CYCLING TEST

The motorette test results were limited in scope but provided a direction to go with regards to expanded testing processes. We felt the following items were essential in the expanded program:

A. Constant current self heating.

B. Time on/time off cycle adjustment.

C. Millivolt drop monitoring during the current on portion of the thermal stress cycle.

D. Continuous temperature monitoring.

E. Use of control samples (fused and brazed copper equivalent) in each test group.

F. Increasing the number of samples of each type of connection tested to arrive at a better statistical result.

G. Running parallel tests, R-22 as well as R-12 environments.

With these factors in mind, the initial group of 80 connections were tested under automatic current cycling conditions. Figure II shows schematically the series connections. As of this writing, four (4) groups of connections have been evaluated under automatic constant current cycling conditions. A breakdown of the basic test parameters and results are shown in Figures III(a), (b), (c), and (d). For obvious reasons, tradename descriptions of mechanical connections are deleted in favor of design features.

FIG. II
SERIES CONNECTIONS.

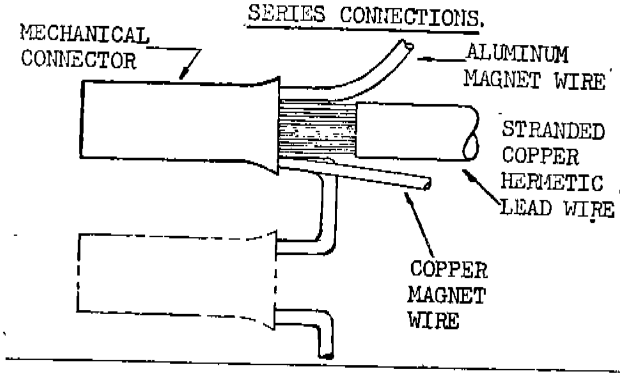


FIG. III (a)

Test Series #1: 20,000 thermal shock cycles in R-22 & oil. 2 min. heating at 40 amps; cool 8 min. & repeat. 16 AWG aluminum wire, total connector CMA = 10230.

Connector Description Each Group 20 Samples	Test Results		
	Failures Noted	Final MV Drop Readings (Avg.)	Max. Connection Temperature
9 Serration Aluminum Wire Pre-stripped	None	3.14	235° F.
7 Serration Aluminum Wire Pre-stripped	None	3.54	240° F.
Soldered 65/35 Zn/Sn Alcoa 68 Flux	None	2.66	172° F.
7 Serration Aluminum Wire Not Stripped	4 Samples Failed	3.53	242° F.

FIG. III (b)

Test Series #2: Essentially the same as Series #1, except 19 AWG Al. wire; total connector CMA = 6180; current density adjusted to give same heating rate.

Description - 20 Samples/ Group	Failures Noted	Final MV Readings (Avg.)	Max. Connection Temp.
9 Serr. Al. Wire Stripped	None	3.6	202° F.
9 Serr. Al. Wire, No Strip	None	3.95	218° F.
7 Serr. Al. Wire Stripped	None	4.7	226° F.
7 Serr. Al. Wire, No Strip	7	4.57	-
65/35 Zn/Sn Soldered	None	2.6	179° F.
Copper Wire Fused & Brazed	None	2.8	191° F.
Copper Wire Banded & Fused	None	2.5	199° F.
Barrel Connector, No Stripping	None	3.15	188° F.

FIG. III (c)

Test Series #3: R-12 & oil. Test modified to produce higher peak temperatures. 19 AWG Al. wire; total CMA = 6180. Test off at 10,019 cycles because of extreme severity.

Description - 20 Samples/ Group	Failures Noted	Final MV Readings (Avg.)	Max. Connection Temp.
7 Serr. Al. Wire, No Strip	9	7.1	315° F.
Soldered 95 Zn/5 Al.	None	4.9	270° F.
Copper Wire Fused & Brazed	None	3.9	265° F.
9 Serr. Al. Wire Stripped	2	5.1	360° F.
9 Serr. Al. Wire, No Strip	7	7.3	345° F.
Barrel Connector, No Stripping	6	6.4	310° F.

FIG. III (d)

Test Series #4: Essentially the same as Series #3. Objective being to determine if MV readings can be correlated to operating temperature. Data below is thru 5000 cycles and test continues.

Description - 20 Samples/ Group Except Where Noted	Failures Noted	5000 Cycle MV Readings (Avg.)	Max. Connection Temp.
7 Serr. Al. Wire, No Strip	14-(Failed Less Than 150 Cyc.)	8.3	457° F.
9 Serr. Al. Wire, No Strip	5	7.1	402° F.
9 Serr. Al. Wire Stripped	1	6.8	376° F.
Soldered 65/35 Zn/Sn	None	4.7	269° F.
Copper Wire Fused & Brazed	None	3.5	272° F.
Barrel Connector, No Strip	1	6.4	334° F.
Barrel Connector, No Strip (Special)	None	6.2	303° F.
Cutting Tooth Flat Clip, No Strip. 4 samples	4-(Failed Less Than 500 Cyc.)	7.9	411° F.

6 RAPID REVERSAL TESTING OF ALUMINUM-WOUND MECHANICALLY-CONNECTED STATORS

Added assurance of reliability for mechanically-connected aluminum-wound stators is being gained through Rapid Reversal Testing. This accelerated test stresses a stator to its fullest, not only from the mechanical forces associated with rapid reversing, but also with elevated winding temperatures and frequent cool-down periods. This test has gained wide acceptance as a recognized method for screening new materials and processes. It was for these reasons that several stators have been tested with the primary purpose of evaluating the connection process. Although the test itself is quite rigorous, the individual connection is not stressed nearly as much as in the component test described in the first part of this paper. Figure IV summarizes the Rapid Reversal Test results in regards to aluminum-wound stators and a particular connection process. Data is currently being obtained on actual connection temperatures while the rapid reversal tests are in progress. To do this, stator connections were thermocouple equipped prior to varnish impregnation. Special fittings were used on the compressor shell to bring up to 10 thermocouples out for direct temperature monitoring. Temperatures being recorded in some initial tests were dampened by the impingement of cold liquid refrigerant returning from the condenser. Modification of internal compressor plumbing provided for uniform stator winding temperatures, thereby enabling comparative temperature studies to be made on various connection processes. Figure V illustrates typical connection operating temperatures under rapid reversal conditions when refrigerant flow is diverted from the connection end turns.

FIG. IV

RAPID REVERSAL STATOR TESTS WITH CONNECTING TECHNIQUES EVALUATED

Stator Size (HP)	Total Reversals	Connection Description and Test Results
3	796757	7 Serr. Al. wire stripped
3	403320	Same as above
3	727088	Same as above
3	690722	65/35 Zn/Sn soldered
5	12207	Barrel connector, Al. wire not stripped, short life from compressor bearing failure
5	503690	Barrel connector, Al. wire not stripped
5	501242	Same as above
5	504211	7 Serr. Al. wire stripped
5	814533	7 Serr. Al. wire not stripped
5	500597	Same as above, 2 of 6 connections overheated
5	534976	7 Serr. Al. wire stripped
5	583103	7 Serr. Al. wire not stripped
5	514760	9 Serr. Al. wire stripped
5	601599	9 Serr. Al. wire not stripped 1 of 6 connections overheated
5	577875	7 Serr. Al. wire stripped
40	252584	Barrel connector copper wire not stripped
15	167877	Barrel connector copper wire not stripped

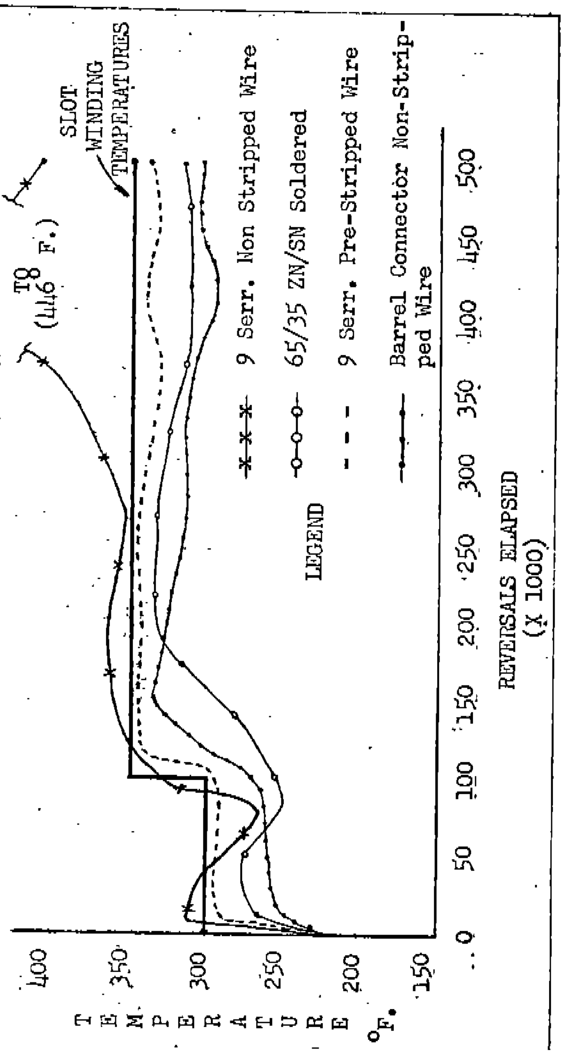


FIG. V
CONNECTION TEMPERATURES - AS TESTED IN ALUMINUM WOUND RAPID REVERSAL STATORS

7 FUTURE PROGRAMS

As with any research activity, answering one question only opens the door to several more. Work is needed in the area of determining connectability of various alloyed aluminum conductors with mechanical connections. Also, a study should be made of various types of film coatings used with aluminum magnet wire in order to determine what influence coatings have on connecting under non-stripping conditions. A solderable aluminum magnet wire insulation with hermetic insulation characteristics would also merit testing.

8 SUMMARY

From our testing, it becomes apparent that aluminum magnet wire will have to be pre-stripped if the conventional and commercially available 7 and 9 serration splice clips are used for mechanical connections. The 9 serration clip appears to be the better of the two. Early test results indicate that barrel connectors with special alloyed perforated liners will perform well even on non-stripped aluminum magnet wire. This connector may be used pending the successful outcome of additional tests.

The reliability of a connection even at operational temperatures as low as 170° F. is questionable if the magnet wire insulation is not removed. Removal of the insulation is a critical operation in two respects:

A. If upon removal of the insulation, the conductor diameter is reduced by more than 5%, the resulting connection may have a higher operating temperature.

B. Removal of the insulation must be carefully controlled in order to prevent undercutting of the aluminum conductor, or other cold work conditions that might lead to a physically weak connection.

Soldering connections appear to be very reliable. The cost and control of an in line high volume production soldering operation appears to be prohibitive at this time. There does not appear to be any correlation between initially high connection millivolt drop readings and operating temperature. Additional testing is required to determine if this is also true with long term connection reliability.

In conclusion, it can be stated that aluminum-wound hermetic stators can be reliably connected providing the techniques of a proven process are incorporated. This conclusion has been verified on many thousands of non-hermetic stators produced by A. O. Smith, and has been demonstrated by countless hours of laboratory component and systems tests for aluminum-wound hermetic motors.

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