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RELIABILITY LIFE TESTING AND
EVALUATION OF 3-PHASE MOTORS

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ABSTRACT

This paper describes the tests and analyses used to evaluate and permit improvement of the reliability of three-phase hermetic motors for air-conditioning and refrigeration compressors. The method permits meaningful evaluation of motor design and manufacturing quality in a time short enough to allow meaningful reactions.

The test involves plug reversal testing which is not new, but is dealt in a large scale statistical manner. Modified compressor bodies are used as test enclosures. This subjects the motor to rapid electrical reversals with the stator held at a controlled high temperature. Special features include a gravity flow refrigerant system, a cycle counter, a multi-channel recorder, and a sequencing control to minimize power problems.

Tests are continued until failure after which a detailed teardown and inspection of the failed stator is conducted. A simple Weibull methodology is used to statistically assess the failures and suspend data points and permit correlation with field experience.

INTRODUCTION

Reliability of electric motors has continued to be of prime concern in the design and manufacture of air-conditioning and refrigeration compressors. It has been clearly established that some form of "accelerated" testing is required to establish the life characteristics in the laboratory, since large scale manufacturers cannot wait for the field results to establish the reliability of his products [1].

The motor is an inherent part of the compressor, and its failure rate ranks always in the top five compressor failure modes. It is a significant proportion of the overall compressor failure rate and reaches about 50% in some applications.

Reliability evaluation of motors is not new. There have been several tests developed in the past to evaluate various compressor components under different stress conditions simulating corresponding states of compressor operation [2]. For motors, start/stop, high load, blocked fan, and locked rotor testing have been used successfully. However, these tests have not been designed exclusively for motor life testing; for example, under start/stop testing, the internal suspension and tubing are also stressed, and the tests may be terminated due to the failure of these components prior to adequate exposure of the motor.

Motor Failures

Electric motors have been in service for over eighty years, and the reasons for motor failures have been extensively studied by design engineers and manufacturers. Generally, overheating, mechanical failures, adverse transient conditions have been identified as the major causes [3]. Overheating, which ranks as the first, results in motor failures due chiefly to the deteriorating effect of heat on the motor insulation system. The excessive temperatures, if present, adversely affect the insulation before any other material in the motor. The Arrhenius time-temperature relationship holds valid for the insulation degradation mechanism. The direct effect of heat on the insulation is, however, not as damaging as the interaction of the heat and adverse chemical environment, such as moisture or mechanical stresses in the magnet wire. Overheating and contamination have been identified as the causes for 2/3 to 3/4 of all the motor failures.

Motor design engineers have identified the magnet wire and the insulation system as targets for continued design improvement. It has also been established that the great majority of hermetic motor insulation system failures are associated with the magnet wire in the form of turn-to-turn shorts [4]. Mechanical movement of the magnet wire, caused by differences in thermal expansion and the magnetic forces from winding currents, leads to turn-to-turn shorts.

Plug reversal testing provides a means of mechanically and electrically overstressing the motor windings and the insulation materials while maintaining the stator at a controlled high temperature. Plug reversal testing has been shown to be an effective test method of an electrical insulation system for a hermetic motor in the refrigerant environment of interest [5,6].

Especially from the point of view of a large scale compressor manufacturer, the plug reversal test provides a cost effective means of comparing different designs and manufacture of hermetic motors. The test simulates the desired conditions and the results are amenable for quantitative analyses. The test permits the entire motor to be the system type test sample, and uses the compressor body for the sample enclosure; further, the refrigerant circulates by gravity and the desired motor test temperature is obtained. The plug reversal test enables the design engineer to use a valid end point or failure criterion, which is the failure of the insulation system due to turn-to-turn shorts in the windings. The "cycles to failure" data, together with "suspend" data permits the design engineer to successfully use the Weibull distribution to statistically evaluate the data in comparison with other designs.

Testing Procedure

The plug reversing test is conducted on a motor in a standard compressor body without the suction and discharge valves, piston and rod assemblies, pressure relief valves, check valves, and the oil screens. The stators are equipped with thermocouples inserted at eight different places to establish the motor temperature profile to enable monitoring the motor temperature during the test. A multi-channel recorder records the control temperature of various motors at different test stations. The motor temperature is maintained at 300°F ± 25°F during the test. A typical cycle is 2.25 seconds in each direction with 0.25 seconds pause between reversals.

The test stand has a gravity flow refrigerant system and the suction and discharge pressures are held within 10 psi. The liquid refrigerant is metered through two valves, one each for coarse and fine adjustment, to obtain the desired motor temperature during the test (Figure A). Once the motor temperature, as monitored by a control thermocouple at a pre-chosen slot liner, is stabilized, there are two ways the test is stopped - one by the excess temperature cut-off thermocouple control circuit, and/or by the contactor tripping at a current value well-in-excess of the "plugging" value. The liquid refrigerant, when in contact with the hot stator and compressor, vaporizes and returns to the condenser through a copper tube connected to the discharge side of the compressor. A schematic diagram of the Plug Reversal testing is shown in Figure A.

Plug reversal testing is conducted twenty-four hours a day and seven days a week. The failure of a motor manifests itself as blown fuses/open circuit breaker; the test is also stopped if there is a refrigerant leak, low pressure switch open, or if the motor temperature exceeds 325°F. Hi-pot testing, surge testing, and air-gap measurements are made before and after the tests.

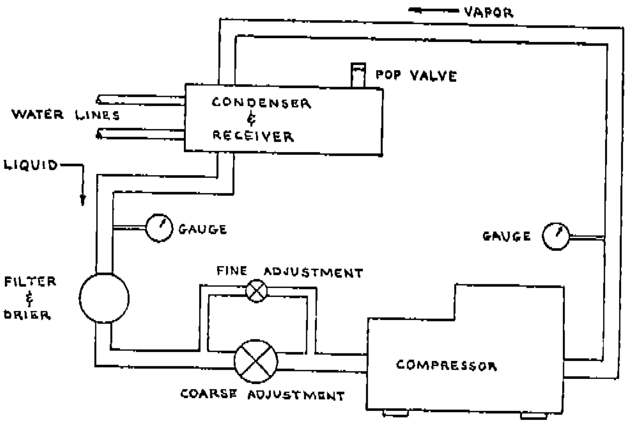

Figure A Schematic Diagram of the Plug Reversal Testing System

Failure Inspections

A detailed teardown and evaluation of a failed motor is conducted. The failure location is documented on a sketch that shows the location of slots with respect to the three phases and the interconnected coils in the 3-phase construction. The physical appearance of the failure and its location is recorded. The hi-pot test of the different coils and the cold (room temperature) resistance values are recorded. If there are more than one coil showing short-to-ground, the hi-pot test is conducted at increasing levels of voltage and the coil showing short-to-ground at the lowest voltage is considered the most likely one to have failed the earliest.

The condition of the lead insulation (normal, abraided, embrittled, melted), magnet wires, phase insulation, slot insulation, tie cords, and wedges (if any) are recorded. Evidence of rotor rub is documented. This condition is not unusual during this test because of the great stresses involved.

Of primary importance is whether the failure is related to the motor design or manufacture. Test stand problems due to poor contactors, or excessively worn bearings in the compressor body may lead to failures, which are invalid. The location of failure and the failure mode details are of greatest importance to the motor designer; to facilitate this, plug reversal test stands can be improved (at a cost) to terminate a test at the earliest signs of failures as opposed to allowing the failure to grow to a gross failure. Neutral shifts monitoring, or detecting a phase current imbalance (under controlled temperature and voltage conditions) are available in today's state-of-the-art.

The teardown evaluation involves cutting the leads off, pushing the slot windings, and inspecting the inside of the slots, evaluating the slot fill and the qualitative "peel test" for the slot windings.

90-Frame Size Qualification

Plug reversal testing has been successfully used in evaluation of 90-frame size (8.77" diameter) motors for semi-hermetic compressors in the 10HP - 40HP ranges. To date, about 200 tests have been conducted of new and rebuilt motors using seven test stands. The test results have gained acceptance by various motor manufacturers and valuable knowledge has been developed toward improving the design and manufacture of these motors.

The plug reversal testing does not detect all possible failure modes by which a motor can fail in its application. However, it is well established that this testing is very effective in discriminating between design and manufacture of motors with respect to the motor windings, the varnish, and the insulation system in general. The effects of the temperature and time are inherently designed into the test, and therefore, the following factors can be evaluated and compared between designs and manufacture.

Design Factors

1. Magnet wire insulation
2. Insulation between phases
3. Insulation to ground
4. Slot fill
5. Varnish (% solids, material) and degree of bonding
6. Thermal gradients (hot spots, etc.)
7. Air gap
8. Rotor fan blades
9. Coil lay in end turn
10. Coining of core

Manufacture/Quality

1. Lamination quality (alignment, freedom from burrs, etc.)
2. Poor bundling of end windings
3. Improper slot insertions & relative maintenance of wire film integrity
4. Incomplete curing of varnish
5. Handling damage
6. Poor connections at lead/magnet wire junctions (eg: at gas welds)

Statistical Analysis of Plug Reversal Data

A. Probabilistic Approach

The "cycles to failure" data from the plug reversal life testing lends itself to a simple but valid method of quantitative analysis. Conceptually, a failure function can be expressed in probabilistic manner in terms of a "stress" function and a "strength" function. Since a failure occurs when stress exceeds strength,

$$\begin{aligned} P\ (\text{Failure}) &= P\ (s > S) \\ &= P\ [s - S > 0] \\ &= P\ \left[\frac{s}{S} > 1\right] \end{aligned}$$

The "stress function" is the "test defined;" for example, the temperature, the reversing cycle, and the plugging amperage. The "strength function" is the design and the manufacture integrity of the motor in question. Thus, the failure data, in cycles to failure which is a mathematical distribution, is a function of the difference between the (test) stresses and the (inherent design) strength of the motor.

Thus, the methodology of comparing two designs (strength functions) keeping the constant test (stress function) is a simple, direct, and valid one. It should be noted that if two laboratories use different test conditions, then the analysis between the laboratories will not be the same since the failure governing (stress-minus-strength) difference distribution has changed.

B. Weibull Distribution

The probability density function of a random variate T having the three-parameter Weibull distribution is given by:

$$f_T(t) = \frac{\beta}{\delta}\left(\frac{t-\mu}{\delta}\right)^{\beta-1} \exp\left[-\left(\frac{t-\mu}{\delta}\right)^{\beta}\right] \qquad \text{①}$$

$$\text{for } t \geq \mu$$

$$= 0 \qquad \text{for } t < \mu\,;\quad \beta, \delta > 0,\quad \mu \geq 0$$

Where μ = threshold (location) parameter

δ = characteristic life

β = shape parameter

To adequately describe the failure function of the plug reversal testing, the author uses a more simplified, two-parameter distribution (where μ is assumed to be zero). Thus, the probability density function becomes:

$$f_T(t) = \frac{\beta}{\delta}\left(\frac{t}{\delta}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\delta}\right)^{\beta}\right] \qquad \text{②}$$

$$\text{for } t \geq 0$$

The cumulative distribution function, CDF, is given as:

$$F_T(t) = \int_0^t f_T(t)\,dt$$

$$= 1 - \exp\left[-\frac{t}{\delta}\right]^{\beta} \qquad \text{③}$$

This leads to:

$$\ln\left\{\ln\left[\frac{1}{1-F(t)}\right]\right\} = \beta \ln t - \beta \ln \delta \qquad ④$$

Equation 4 permits determination of the shape parameter β and the characteristic life δ when the results are plotted on a log-log scale with "$\ln t$" on the x-axis and $\ln\left\{\ln\left[\frac{1}{1-F(t)}\right]\right\}$ on the y-axis. Several textbooks [7,8] illustrate this procedure.

The Weibull distribution and currently available procedures [9] permits use of censored data (suspended/terminated test data) in addition to the failure points.

Example of a 35HP 90-Frame Motor Plug Reversal Data

Sample No.	Cycles	Failed/Terminated
1	96,000	Failed
2	127,000	Failed
3	138,000	Suspended
4	170,000	Failed
5	182,000	Suspended
6	230,000	Failed
7	280,000	Failed
8	390,000	Failed

The Weibull plot is given in Figure B; the computed values of the shape parameter = 2.2, and the characteristic life = 269,300 cycles.

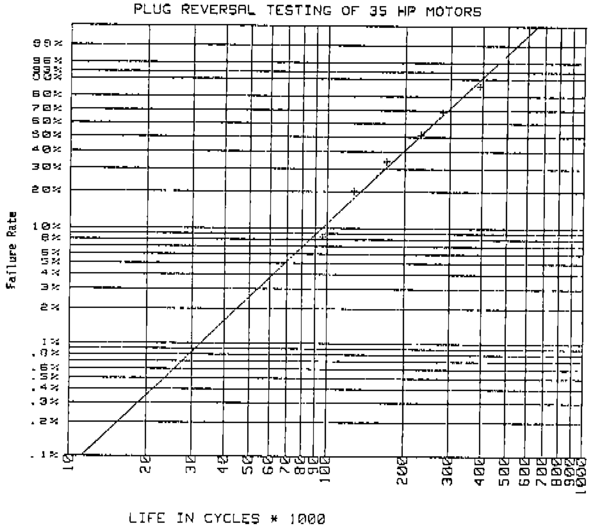

Figure B Weibull Plot of Data

C. Reliability Growth Model

During the qualification testing of various designs of the 90-Frame 35HP motors, two vendors demonstrated significant reliability improvements in three steps (called Phase I, Phase II, and Phase III); the Weibull parameters of slope and characteristic life for these phases quantitatively assesses the failure rate improvements, as shown in Figure C.

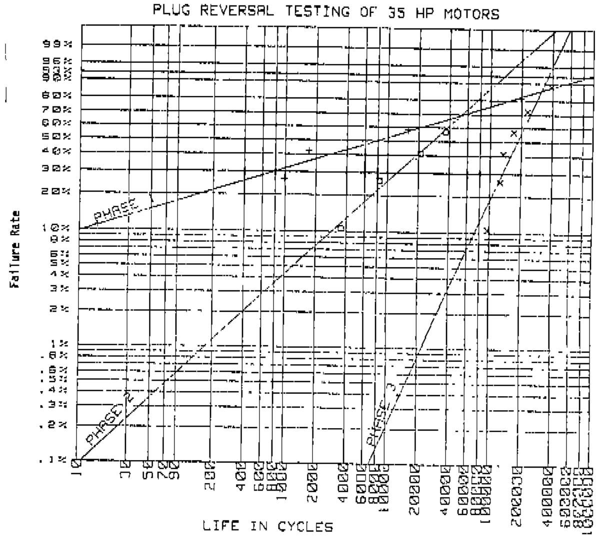

Figure C Weibull Plot of Data from Phases 1 thru 3

	Phase I	Phase II	Phase III
Shape	0.29	0.84	2.0
Characteristic Life	29,800	42,600	222,300

As can be seen, Phase I and Phase II data include infant-mortality (very early) failures, characterized by a Weibull slope (shape) of less than 1 (decreasing failure rate portion of the bath tub curve). There were noticeable quality and workmanship defects. When these were removed and a specific design improvement was introduced, the Phase III motor data showed a Weibull slope greater than 1 (increasing failure rate portion of the Weibull bath tub curve), which supports the wear and/or fatigue failure causes due to magnet wire movement (leading to turn-to-turn shorts).

The reliability growth index M* is given by:

$$M^* = \frac{Rn}{Rn + 1}$$

where Rn = Reliability Index of "n"th phase for a given life period.

The Reliability Index, R, is the numerical value of the in-warranty (or design life) failure rate.

$$M^* = 1.3 \text{ (Phase 1 to 2)}$$
$$= 21.0 \text{ (Phase 2 to 3)}$$

This means that Phase II demonstrated only a 30% reliability growth over Phase I. However, in the given example, there was a 20-fold reliability growth for the Phase III design over that of the Phase II design.

D. Life Testing Audit Criteria

The OC (operating characteristic) curve for an audit test plan based on the acceptable results from the qualified motor design is easily derived. As an example, our audit plan calls for a sample of three compressors to be tested to 50,000 cycles without failure (at the same test conditions).

Probability of lot acceptance = P (zero failures in the lot)

Using the binominal distribution relationships,

$$P\ (\text{acceptance}) = P(0)$$
$$= {}^{n}C_{0}\, p^{0} (1-p)^{n}$$
$$= {}^{3}C_{0}\, x_{1}^{0} (1-x_{1})^{3} \quad (\text{at } 50K)$$
$$= (1-x_{1}^{3}) = y_{1} \quad (\text{at } 50K)$$

where P = probability function
n = sample size = 3
p = fraction failed = x_1 (at 50K)

X2 and Y2 are corresponding values of fraction failed and probability of lot acceptance at test duration of 100K cycles. Continuing this process, the OC (operating characteristic) curve for the audit plan can be derived as illustrated in Figures D and E.

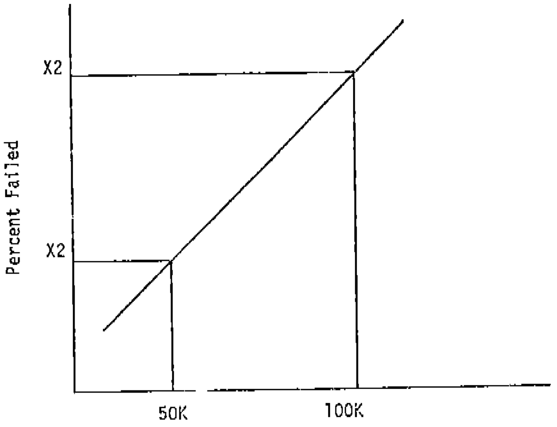

Figure D Weibull Plot of Failure Data

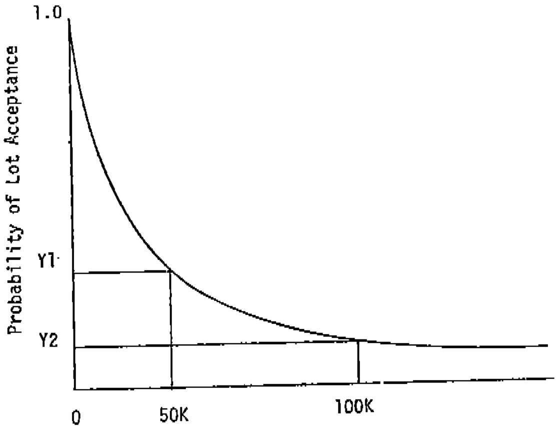

Figure E OC Curve for Audit

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