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## A MECHANISM OF MOTOR FAILURE

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Since the invention of the hermetic system by placing the motor inside the compressor case, motor reliability has been even more important for at least three reasons. First, the motor and its insulation system must resist the chemical effects of the refrigerant and the compressor lubrication oils. Second, the motor became considerably less accessible and therefore, very costly to replace and service. Third, if a failure does occur, the destruction of motor construction materials such as copper, steel, and insulation components can cause large quantities of foreign materials to be deposited within the system. These reasons don't even consider the inconvenience caused to the customer through loss of the system or delays in repair.

Over the years, we have tried to select the proper materials for maximum reliability. To do this required the development of tests which would predict motor reliability in the field. Early efforts relied on chemical tests and constant temperature motor tests to screen materials. These tests sufficed to accomplish our goals until 10 to 15 years ago when new, more chemically and thermally resistant materials started to arrive on the market at an ever increasing pace. Then the tests became unable to show differences between materials or systems and new avenues of motor life testing were explored. Hurtgen (1971) introduced some cyclic stress into small motor tests by accelerating magnetic stress and rate of temperature rise through doubling test voltage at an appropriate time in each test cycle. These tests were developed and applied after study of conditions motors and compressors were subjected to in field service. As a result of these test techniques, and the adoption of the newer materials, small hermetic motors have become very reliable.

Larger hermetic motors (above 3-4 HP) have developed using the same materials and processes. These larger motors and the compressors they power served applications which were usually more demanding than the service seen by a refrigerator motor. In the face of these difficulties they have not quite achieved the reliability of the small ones which power our refrigerators and freezers for tens of years without failure. Obviously further development of tests to predict large motor reliability

was needed.

The plug reversal test has long been one of the important large polyphase motor tests and has been precisely defined by some manufacturers. We have adopted and used it for about seven years, but have found that many stators required 6 to 12 months per test and as a result little data was obtained upon which to compare materials and factory processes. Simultaneously a cyclic locked rotor test was under development for larger single phase motors. This lead us to apply new techniques to study failures and mechanisms from both tests. These techniques ultimately uncovered a common dominant mechanism of failure.

Examination of the data has led to the development of a failure theory which explains the cause of failure for a stator which shows little insulation aging. Our inability to detect aging of materials which were obviously failing initiated a closer look at the failures in order to learn why they occurred. These failures were found between wires where the insulation had been worn away. A hypothesis of wire to wire motion began to develop which was verified through the use of high speed cinematography in our laboratory. A series of movie sequences was taken of stators at various test times and showed the development of winding movements among the coils and to the core. Incidentally, failures due to stuck contactors, shorted capacitors, etc., which we know cause field failures, also occurred on our tests but were considered outside the scope of this investigation as the majority of the failures were associated with wire wear.

Looseness, motion and wear develop as the result of certain stresses applied to the motor windings by the service it sees. Careful analysis revealed the following conditions:

1. Differential Thermal Stresses.
2. Different Coefficients of Expansion.
3. Varnish Weakening at High Temperatures.
4. Magnetic Force due to Winding Currents.

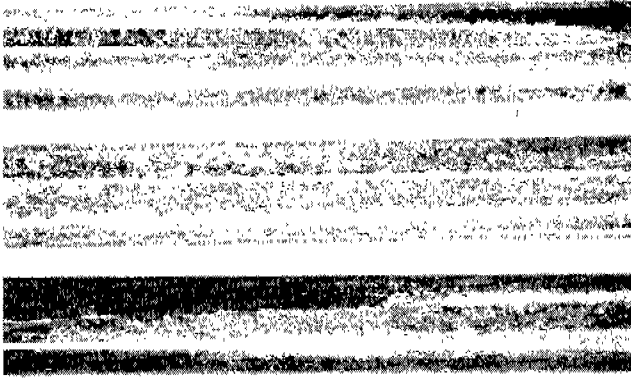


Figure 1: Wire to wire wear. One half to three quarters of the film has been worn off but a continuous film remains. Note end of wear areas on top and bottom wires.

Differential thermal stresses are caused when motor operating conditions demand high outputs and therefore high currents, or under conditions where liquid refrigerants flood back, cooling part of the stator rapidly. Under these conditions portions of the winding heat or cool more rapidly than others and than the core structure. This stresses the bonds between parts of the winding and to the core.

Stators contain many different materials each of which has its own coefficient of expansion. Stress levels are locked in at some temperature level by the treatment applied to the stator and its processing. Any change in temperature from this level will cause additional stress due to the differences in coefficients among the materials. These differences are increased by service conditions which cause temperature differentials between parts of the winding or the core.

Varnishes and insulation materials lose a certain amount of strength as operating temperatures increase. Under severe conditions, bonding between many of the parts may not be strong enough to withstand the stresses applied by temperature differences and coefficients.

Magnetic fields about each conductor are proportional to the electrical current in it. Under heavy loads, such as at starting, motor currents can reach six times normal full load levels. Motors have many conductors per pole so the turns are bundled together in several coils per pole. The magnetic field around each conductor in a bundle will coalesce or gather around the whole group of wires and tend to squeeze the wires together. At times of high current, such as at start or a stall, this squeezing action becomes very strong and places high stress on the stator bonding system in the slots. Strong magnetic

forces also act upon the end turns tending to pull them toward the iron.

In order for any motion to occur in the winding, stresses must be applied which exceed the restraining forces as determined by the strength of the insulations and the varnish. The standard reversal test applied two of the conditions in an accelerated manner quite well. They are the magnetic stress and the high operating temperature. To apply the other two stresses, a new test was developed. The "Cyclic Reversal Test" applied all stresses discussed so that each can be adjusted to achieve the desired stress acceleration for reasonable test life.

Once the restraining forces are exceeded, motion can begin at this point under the influence of the rapidly changing 60 hz power. The magnetic field actually builds up to a peak 120 times per second because a full power cycle includes peak power at both positive and negative parts of the cycle.

Motion continues to increase because the stresses which caused the original break in restraining forces are still effective and an additional vibratory stress is added. It was in this phase of the study that the high speed movies were useful in tracing the development of motion. An accelerometer was also very useful in locating points of maximum motion on various parts of the winding.

Wear between the moving components is a natural consequence of motion and it was found when the likely points were located. This wear leads to baring of conductors and contact probably occurs at 120 times per second under the influence of the squeezing action caused by the magnetic forces. This results in low power intermittent arcing which causes erosion of the conductor until enough power is drawn to weld them. Once welding has occurred, high induced currents in the shorted loops lead to rapid stator failure.



Figure 2: Wire to wire wear. The bare conductor is just visible in the middle of the wear spot. No arcing had occurred yet as mating wire was not exposed.

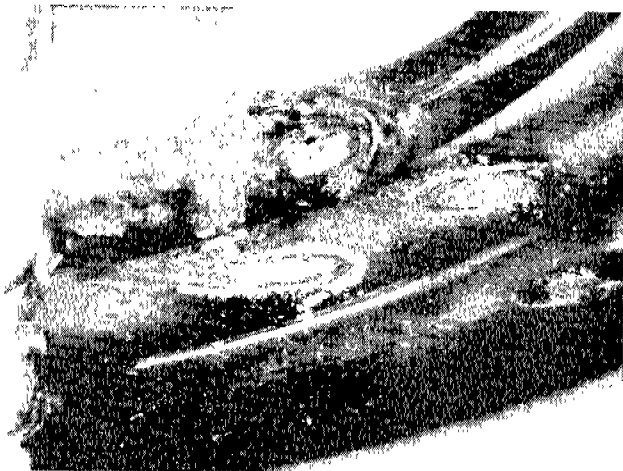


Figure 3: Wire to wire wear. The film was worn through and low power arcing occurred until welding. Note spots on other wires which are ready to fail.

Analysis of these failures reveals three types of looseness and associated wear develop in a stator. They are:

1. Wire to Wire
2. Coil to Coil
3. Wire to Ground Insulation

#### WIRE TO WIRE WEAR - FIGURES 1, 2, AND 3

This situation occurs between wires within a coil or a slot. The looseness and wear usually occur in the largest two coils because they have the most turns and the greatest mean turn length. This outer position also results in the least support for these wires as they leave the slot and join the end turn bundle. The magnetic forces between the wires in these two slots is also greatest and this stresses any bond weaknesses in this area. Failures are further concentrated between a point about one inch inside the slot (in the lamination iron) to a point about one inch beyond the surface of the iron in the end turns. This includes the knee of the end turn coils where the wire makes a relatively sharp bend toward the slot.

#### COIL TO COIL WEAR - FIGURES 5 AND 6

This occurs when two adjacent coils within the same pole become loose and vibrate against one another. The wire to wire wear results in severe failure because the higher voltages between coils cause more severe arcing. This leads to welding sooner along with higher currents in the shorted coils.

The most important parts of this work are the recognition of differential thermal stress as an important accelerating variable and the analysis of failures to develop and support the failure theory. The "Cyclic Reversal Test" was developed to test this theory and to allow us to study materials and process changes. The important change in the reversal test was the incorporation of a temperature swing of 100°C every 45 minutes. In our test the temperature is raised from 50°C to 150°C in 22 1/2 minutes by reversing the motor each 3 seconds after a half second delay. When the stator reaches 150°C the power is removed and it is force cooled with liquid refrigerant (R-22) applied at a rate which will bring the average winding temperature to 50°C in the next 22 1/2 minutes. (See Figure 4). This test procedure has increased our chances of failing a stator within a million cycles by about 10 to 1.

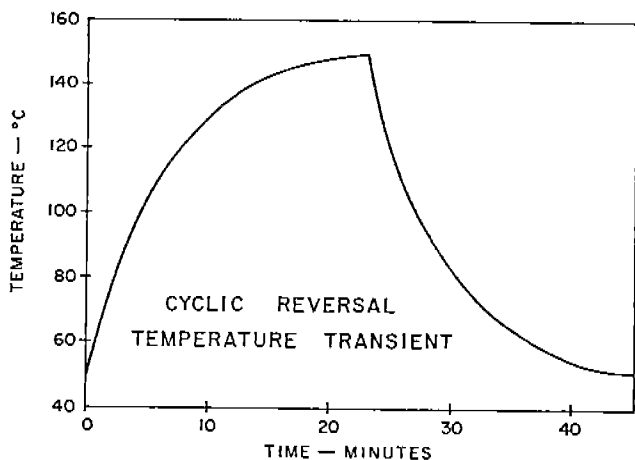


Figure 4: Cyclic reversal test scheme. Temperature rised while reversing on a three second cycle. Liquid R-22 is applied with power off to cool stator.



Figure 5: Coil to coil wear. The failing wires are removed from each coil. The crossover point is in the end turns and the straight wires to the right extend into the slots.



Figure 6: Coil to coil wear. End turn failure due to wear between the coil shown and an inner coil. This is in the knee of the coil where it leaves the slot and joins the end turns.



Figure 8: Surface depressions worn into the film at the end of the lamination stack.

WIRE TO GROUND INSULATION WEAR - FIGURES 7 AND 8

The loosening of bonds between the magnet wires and ground insulation allows wear to occur between them. Considerable wear occurs but this has not been associated with any failures for at least two reasons. First, the ground insulation is thick and the greatest wear seen yet has only worn away less than 16% of the thickness. Second, the wear is concentrated on the film as the wire enamel appears to be more abrasions resistant.



Figure 7: Wire to film wear. View of the wires which have been abraded the polyester film. The white powder is polyester polymer.

The hypothesis of wear and the development of the failure theory has helped us in many ways. Using the new "Cyclic Reversal Test", an experiment was run to explore the relationship between stator size (horsepower) and a number of varnish treatment parameters. The table below shows data obtained

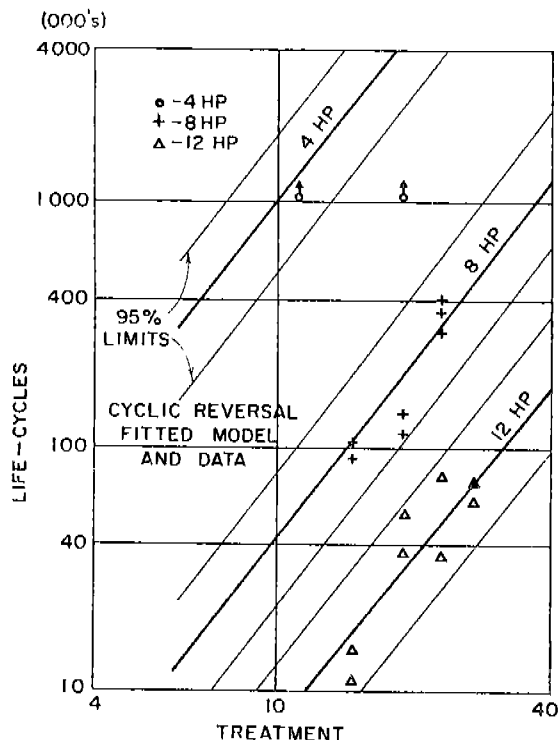
CYCLIC REVERSAL TEST DATA				
MOTOR SIZE				
		SMALLEST	MIDDLE	LARGEST
MOTOR	LOWEST	980,000+	69,216	X
		--	88,100+	X
		--	--	X
TREATMENT LEVEL	LOW	521,841+	92,532	10,839
		--	105,390	15,368
		--	--	61,204
	MIDDLE	1,001,406+	110,000	36,204
		--	135,496	53,084
		--	--	80,918
	HIGH	502,160+	314,320	36,046
		511,100+	359,233	78,433
		--	400,051	--
HIGHEST		X	--	57,074
		X	--	60,082
		X	--	--

-- Indicates stator not tested yet.  
 + Indicates censored data - terminated without failure or still running.  
 X Indicates no tests planned.

from such an experiment. Many of the planned tests have not been started yet and others are still running or have been terminated without failure. Statistical techniques are available to analyze such incomplete and censored data. Nelson (1972 and 1974) and Crawford (1970) have published techniques for analyzing this type of data. Using these techniques a power law model of the form was successfully fitted.

$$\text{Life} = K \frac{(\text{Treatment})^m}{(\text{Size})^n}$$

The graph below shows the above power law model fitted to the data in the "Cyclic Reversal Test Data" table. Study of this graph and model has helped us to understand the significant relationships between motor size, treatment processes and test life.



Further, the critical analysis of test motor failures necessary to develop the theory discussed earlier has given us a better understanding of the pattern of motor failure. As many of you know, the ultimate motor failure on a motor returned from the field may not indicate what initiated the failure. This is where the pattern or route of failure from initiation to final blow out is of interest. By using temperature and ground sensing devices, stators were removed all the way from very early in the failure process to severe burn-outs. These were examined carefully and as they all derived from the same test, the location and severity of the faults could often be correlated to stators removed early in the failure pattern. This has allowed us to make a better analysis of what has caused field failures.

IN SUMMARY, THIS WORK HAS GIVEN US:

1. A failure theory based upon a wear mechanism rather than a material aging mechanism. This theory helps explain the many failures seen where there is no appreciable material degradation.
2. The "Cyclic Reversal Test" as an improved testing method for larger polyphase motors and thereby helped to analyze the relationships of materials and processes to motor size.

3. A much better understanding of the way a stator fails. The initial failure point may be obscured by the massive failure necessary to blow fuses and breakers. By using temperature and ground sensing devices, stators were removed at various stages of failure. Examination of these failures gave a good picture of how failures progress, and therefore improved our ability to examine field failures for initial causes of failure.

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