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IMPROVING MOTOR RELIABILITY IN NUCLEAR POWER PLANTS

VOLUME 2: FUNCTIONAL INDICATOR TESTS ON A SMALL ELECTRIC MOTOR SUBJECTED TO ACCELERATED AGING

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ABSTRACT

A ten horsepower electric motor was artificially aged by plug reverse cycling for test purposes. The motor was manufactured in 1967 and was in service at a commercial nuclear power plant for twelve years. Various tests were performed on the motor throughout the aging process. The motor failed after 3.79 million reversals (3 seconds per reversal) over seven months of testing. Each test parameter was trended to assess its suitability in monitoring aging and service wear degradation in motors. Results and conclusions are discussed relative to the applicability of the tests performed to nuclear power plant motor maintenance programs.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
LIST OF FIGURES	vii
LIST OF TABLES	x
ACKNOWLEDGMENTS	xi
SUMMARY	S-1
1. INTRODUCTION	1-1
1.1 Background	1-1
1.2 Objective	1-2
1.3 Scope	1-3
2. DESCRIPTION OF THE MOTOR AND TEST EQUIPMENT	2-1
2.1 Test Motor	2-1
2.2 Plug Reverse Cycle Aging Test	2-5
2.3 Test Equipment	2-7
3. TEST PROCEDURE	3-1
3.1 Motor Functional Indicator Tests	3-1
3.1.1 During Reverse Cycling	3-1
3.1.2 During Continuous Running	3-1
3.1.3 During the Stationary Period	3-1
3.2 Test Procedure Changes and Abnormalities	3-3
4. TEST RESULTS	4-1
4.1 Dielectric Insulation Resistance	4-3
4.1.1 Polarization Index (PI)	4-3
4.1.2 Dc Insulation Resistance at 250, 500 and 1000 Volts	4-4
4.2 Surge Testing	4-7
4.3 Dissipation Factor/Capacitance	4-8
4.4 Ac Partial Discharge	4-8
4.5 Ac/Dc Leakage Current	4-10
4.6 Motor Winding Resistance	4-10
4.7 Winding End Turn Movement	4-13
4.8 Bearing Noise and Vibration	4-13
4.9 Bearing Grease Tests	4-16
4.10 No Load Motor Running	4-17
5. POST-MORTEM EXAMINATION OF MOTOR COMPONENT FAILURES	5-1
6. RECOMMENDATION AND CONCLUSIONS	6-1
6.1 Dielectric Insulation Resistance Tests	6-1
6.2 Surge Testing	6-2
6.3 Ac Dissipation Factor/Capacitance Test	6-2
6.4 Ac Partial Discharge Tests	6-3
6.5 Ac/Dc Current Leakage Tests	6-3
6.6 Dc Winding Resistance Tests	6-4

Contents (Cont'd)

		Page
6.7	Winding End Turn Movement	6-4
6.8	Bearing Noise and Vibration	6-4
6.9	Bearing Grease	6-4
6.10	No Load Running Current	6-4
7.	REFERENCES	7-1
APPENDIX A:	Small Motor Test Equipment for Monitoring Motor Integrities	
APPENDIX B:	Analyses of Zeniplex R-2 Grease Used in the Test Motor Bearings	

LIST OF FIGURES

Figure No.	Title	Page
2.1	Random wound stator slot................................	2-2
2.2	Photograph of the motor being tested, along with control panels and test instruments...........................	2-2
2.3	Photograph of the stator (with the rotor removed) showing close-up of accelerometer mounted on the end turn.....	2-3
2.4	Photograph of the stator (with the rotor removed) showing the thermocouples mounted on the end turn..............	2-3
2.5	Programmable plug reverse cycle parel with the door opened to show the components.........................	2-4
2.6	Assembled motor with instruments and test panels......	2-4
2.7	Wiring diagram for the plug reverse assembly, including the programmable controller and switches...............	2-6
4.1	Winding and bearing temperature traces................	4-2
4.2	Polarization index at 500 volts dc....................	4-4
4.3	The effect of temperature on the polarization index...	4-5
4.4	Dc dielectric resistance at 250, 500 and 1,000 volts..	4-6
4.5	Resistance to charging current at 500 volts DC after one minute and ten minutes............................	4-6
4.6	Ac dissipation factor at 500, 750 and 1,000 volts.....	4-9
4.7	Ac capacitance at 500, 750 and 1,000 volts............	4-9
4.8	Variation of peak discharge with increasing ac voltage	4-11
4.9	Partial discharge inception voltage...................	4-12
4.10	Dc phase-to-phase winding resistance..................	4-12
4.11	End turn RMS acceleration for the pulley end and opposite pulley end..................................	4-14

Figures (Cont'd)

Figure No.	Title	Page
4.12	Spectral analysis of the end turn acceleration for the pulley end..	4-14
4.13	Bearing velocity trends..	4-15
4.14	Bearing displacement trends..	4-15
4.15	Current signature of Phase 2 and 3 terminals...........	4-16
5.1	Pulley end bearing after being removed because of noise (bearing came apart during diassembly)..................	5-1
5.2	Opposite pulley end bearing after being removed after test..	5-2
5.3	Traces of surge test signals showing turn short in Phase 2 (test voltage: 1000 volts).....................	5-3
5.4	Time exposure of the stator while being tested with a surge tester..	5-4
5.5	Stator sections for investigating wedge degradations....	5-5
5.6	Failed and good wedges from the failed stator...........	5-6
A.1	Biddle Model RM 2900 Sullivan Megohmmeter..............	A-2
A.2	Biddle Model 670025 capacitance and dissipation factor test set..	A-3
A.3	Schematic of the partial discharge test setup...........	A-4
A.4	Hewlett Packard 7015 X-Y recorder......................	A-4
A.5(a)	Biddle Model 661072 partial discharge tester............	A-5
A.5(b)	Biddle power separation filter........................	A-5
A.6	Baker Instruments Model ST106 surge tester...............	A-6
A.7	Hipotronics Model H303B ac/dc hipot.....................	A-7
A.8	Biddle Model 72-430 Wheatstone Bridge for winding resistance..	A-8
A.9	Brush Instruments high speed recorder for motor running current..	A-8

Figures (Cont'd)

Figure No.	Title	Page
A.10	Omega ten-channel temperature recorded with GenRad Model 2412 spectrum analyzer on top......................	A-9
A.11	IRD Mechanalysis Model 308 vibration-sound meter........	A-10

TABLES

Table No.	Title	Page
S-1	Summary of test results..................................	S-1

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SUMMARY

This report presents the results of a series of tests performed on a small industrial motor. In a previous Phase I study (NUREG/CR-4156), typical motor failures and various functional indicators which could potentially be used to monitor age-related degradation were identified. The tests performed for this Phase II study are an extension of the Phase I work. The objective of the tests discussed herein was to verify the suitability of the previously identified functional indicators. This included an evaluation of their performance feasibility in an actual plant environment, as well as their effectiveness in monitoring aging degradation in electric motors.

The tests were performed on a 10 horsepower motor manufactured in 1967. The motor is a random wound, three phase, 460 volt design, and was used for continuous duty operation in a nuclear power plant for twelve years.

Artificial aging and testing of the motor was performed at NUTECH. The artificial aging consisted of plug reverse cycling (reversing the direction of the electric current every cycle causing a change in rotational direction of the motor). A cycle period of three seconds was chosen to maintain the insulation temperature between 160°C and 180°C. This aging method was chosen for its ability to induce age-related degradation by a combination of thermal, magnetic, electrical and mechanical stresses under accelerated conditions. It was felt this method would best approximate the results of extended service conditions in the field. A total of thirteen tests for monitoring the dielectric and rotational motor integrities were performed during each six hour period of testing. The motor was periodically shutdown, during which time most of the tests were performed.

Failure of the motor occurred after 3.79 million reversals over seven months of testing. The failure was observed as an arcing from a conductor through a stator wedge to the stator iron.

The test program simulated aging and degradation of the winding leading to a wedge failure at the end of the test. The dc insulation resistance and dissipation factor tests showed trends indicating the curing and hardening of the Epoxy resin used in the system, including the Epoxy molded wedge. This was accompanied by cracking and degradation, as noted in the failed wedge, which is consistent with the reduction in partial discharge inception voltage observed. Bearing tests showed excess noise and vibration which preceded a bearing failure at 3.76 million reverse cycles.

Evaluations were made of various test methods leading to recommendations for measurements and surveillance of motors in plant maintenance program. The following table summarizes the conclusions on the various motor functional indicators.

Table S-1 Summary of Test Results

Potential Test Method	Aging Mechanism Detected	Degradation Type [1]		Applications				Remarks
				Preventive Maintenance		Corrective Maintenance	Motor Size	
		Average	Local	Trending	Go/No Go			
Polarization Index [2]	Wetness, environmental contamination	X			X	X	All	May be more useful for trending with improved test equipment
Dc Insulation Resistance [2]	Wetness, envir... ment contamination may detect insulation aging with improved testers.	X			X	X	All	May be more useful for trending with improved test equipment.
Surge	Turn short, phase-unbalance & connection problems.		X		X	X	Small, low voltage motors (<600 V)	Digital storage of wave forms would enhance using this test in condition monitoring and trending
Ac dissipation factor [3]	Cracks and voids	X		X [5]		X	All [4]	For larger high voltage motors power factor test is preferred.
Ac capacitance [3]	Thinning or deterioration	X		X [5]		X	All [4]	Same as dissipation factor test.
Partial Discharge	Cracks, voids and degraded insulations		X	X		X	Large high voltage motors [6]	Present equipment good for large high voltage motors, but must be redesigned for use on low voltage small random wound motors.
Ac Leakage [7]	Cracks, voids, thinning.	X		Not Recommended		X	All	Can be a destructive test if ac voltage is set too high.

Table S-1 (Cont'd)

Potential Test Method	Aging Mechanism Detected	Degradation Type [1]		Applications				Remarks
				Preventive Maintenance		Corrective Maintenance	Motor Size	
		Average	Local	Trending	Go/No Go			
Dc Leakage [7]	Moisture, environmental contamination.	X		Not Recommended		X	All	An alternate to the dc insulation resistance tests. Measurement difficulties at low voltage may detract from usefulness.
Dc Winding Resistance	Unbalanced windings, bad connections & broken wires.		X		X	X	All	Resistance reading must be conver ed to a common base temperature.
End Turn Movement	Loose or underbraced coils which would lead to turn shorts due to coil movement.		X	X [5]			All	Limited to application of sensors on end turns. Specifically useful for insulating system made out of polyester or silicone base.
Bearing Vibration	Damaged or worn bearings.	X	X	X		X	All	
Grease Chemical Analysis	Severe metal wear	X		X		X	All	A good indication of metal wear for the rubbing faces in the bearings. Important for sleeve bearing.
Motor Running Current	Motor electrical design problems & motor loads.		X		X	X	All	Variability of voltage source makes motor running current difficult to apply.

Notes: 1. Average degradation is referred to an overall condition of the insulation. Local degradation includes turn-turn short, hot spot, corona discharges, etc.

2,3,7 Obtained using the same test equipment

4. Dissipation factor/capacitance tests and power factor tests (not included in this program) are similar tests. Depending on the test equipment size, these can be performed on all size motors.

5. Trending of these functional indicators was not verified by this test program but was concluded by evaluation and consultation with experts in the field. These items are included in the table for completeness.

6. Large, high voltage motors are those with form wound coils or rated above 600 volts.

1. INTRODUCTION

A nuclear power plant utilizes hundreds of electric motors of all sizes and types. Failure of these motors, especially those designed for safety operations, could impair plant safety. Although motors are known to be built rugged and have a record of reliable operation, they do fail and disable safety systems in nuclear plants [1]. Operating experience has revealed that stator winding insulation and bearing assembly failures constitute a large percent of motor failures. This is true for both nuclear and non-nuclear applications. It is, therefore, desirable to develop methods of monitoring the condition of these vulnerable motor components.

There exist a number of test methods to evaluate and/or diagnose the condition of stator insulation and bearing assemblies. These procedures are typically used in motor manufacturing facilities to determine the component endurance limits. Some of them are also utilized in motor rewind and repair shops to verify the condition of rebuilt motors [2].

Present industry-wide maintenance tests on motors are primarily limited to insulation resistance (i.e., meggering) and bearing vibration tests. Preventive maintenance activities include periodic lube oil change or regreasing, and cleaning and drying of windings. Seals or gasket changes are made as recommended by the motor manufacturers or as required following maintenance. These maintenance practices, although essential for keeping a motor operationally ready, provide no assurance of acceptable future performance of the motor.

Nuclear power plant motors designed for safety-related operations are required to maintain their operational readiness throughout the life of the plant. Trending of certain test and/or maintenance data is, therefore, needed for predicting the future condition of motor subcomponents which are vulnerable to aging and service wear conditions.

This test program was initiated to evaluate a number of test parameters which could be used to monitor the condition of stator winding insulation and bearing assemblies. Each test parameter was periodically measured and plotted while a motor was subjected to an accelerated aging process within a laboratory environment. It should be noted that the intent of this test program was to determine the trending feasibility of the monitored parameters in a nuclear power plant application. No conclusions with regard to the qualification requirements of a motor for nuclear power plant applications should be drawn from this work.

1.1 Background

As nuclear plants get older it becomes necessary to understand the effects of age on the performance and reliability of safety related electrical equipment. In recognition of this issue, the Nuclear Regulatory Commission has initiated the Nuclear Plant Aging Research (NPAR) Program to evaluate age and service wear related degradation effects on a number of equipment items used in safety-related applications. Electric motors are one of these items. Phase I of the program identified typical motor failures and suggested various functional indicators to monitor age-related degradation. The results of the Phase I work on electric motors are presented in NUREG/CR-4156 [1].

Phase II of the study includes an evaluation of current industry maintenance and monitoring practices, verification of previously identified functional indicators, and evaluation of the effectiveness of current maintenance programs to mitigate age and service wear related motor failures. The motor test program that is the subject of this report is part of the phase II study.

1.2 Objectives

The objectives of this study are:

(1) to determine the effectiveness of condition monitoring and trending of various dielectric and rotational functional indicators, and
(2) to correlate various test parameters with the type of subcomponent failures that might occur during the motor life.

The results of this program will be used in developing effective maintenance program recommendations to predict the condition of motors in a nuclear power plant.

1.3 Scope

To achieve these objectives, a small induction motor was artificially aged. In addition to monitoring the bearing and motor temperatures, various insulation and bearing tests were conducted on the motor. These include the following:

A. Dielectric Insulation Resistance Test (Megger)
B. Surge Test
C. Ac Dissipation Factor/Capacitance Tests
D. Ac Partial Discharge Test
E. Ac/Dc Leakage Current Test
F. Dc Winding Resistance Test (Wheatstone Bridge)
G. Winding End Turn Movement Test
H. Bearing Noise and Vibration Test
I. Bearing Grease Analysis
J. No Load Running Current Test

The Dielectric Insulation Resistance Test was divided into the following two different tests:

Test 1: 500 volt dc 10 minute test to calculate the polarization index, which is the ratio of the 10 minute to 1 minute resistance readings.

Test 2: 250, 500 and 1,000 volt dc tests to determine the change in insulation resistance with age.

All dielectric resistance readings were corrected to the same base temperature.

Section 2 of this report describes the motor and test equipment arrangement. A discussion, supported by photographs of the motor, is provided to show how the test motor was instrumented. The manufacturers, models and principles of operation for the instrumentation used to measure the functional indicators are provided.

The test procedures [3] for periodic testing are summarized in Section 3. The test plan [3] provides a detailed description of the test procedures. The results of the ac and dc tests conducted on the insulation, surge tests, end turn movement and the measurement of the vibration in the bearings are discussed in Section 4. Section 5 discusses the ultimate failure at the end of the test. Also included are the motor post-mortem results and other anomalies observed during the motor testing. Recommendations and conclusions are presented in Section 6.

Appendix A provides a description of lab test equipment used in this test program to monitor the motor insulation and bearing operating conditions. Appendix B provides the results of the chemical tests performed on the bearing grease.

2. DESCRIPTION OF THE MOTOR AND TEST EQUIPMENT

This section describes the test motor design and specifications. Also included are descriptions of the programmable plug reverse cycle controller as well as other test equipment utilized in this test program.

2.1 Test Motor

The test motor is a random wound, 10 horsepower, totally enclosed motor manufactured by Westinghouse Electric Corporation. It is three phase, 460 volt, Class B insulated. The motor was originally varnish treated with a polyester resin. It was manufactured in 1967 and was operated in a nuclear power plant for 12 years of continuous duty. After being removed from service, this naturally aged motor was seismically tested at Brookhaven National Laboratory to investigate aging-seismic correlations.

Upon completion of the seismic tests, the motor was shipped to NUTECH where the tests discussed herein were performed. When the motor was received, it was disassembled, cleaned and inspected. The motor insulation and bearings were found significantly degraded. The stator was subsequently refurbished by vacuum pressure impregnation of an Epoxylite Epoxy Resin varnish [4] and new bearings were installed. The condition of the motor prior to testing was similar to one in a nuclear power plant application subjected to full corrective maintenance or overhaul. Actual plant maintenance records on the motor were not available.

The original insulation system on the received motor is described below[5]. Figure 2.1 shows a sketch of the stator slot.

A. Slot Ground Wall Insulation (Slot Cell) - Composite of glass, mylar and dacron with a polyester binder;

B. Slot Wedge - .030" thick glass reinforced molded epoxy wedge;

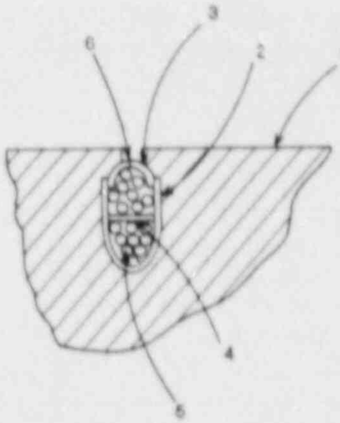
C. Phase Insulation - Natural mat of non-woven polyester fibers saturated with a polyester resin;

D. Treating Varnish - Polyester.

The motor end turns were initially instrumented for the testing with PCB Piezotronics, Inc. Model 303A accelerometers rated for 121°C (250°F). These were destroyed after 3.33 million reversing cycles by the high test temperature (190°C). As a result, they had to be replaced with Endevco Model 7701-50 accelerometers which weigh 25 grams and are rated for applications to 260°C. Two accelerometers were epoxied to each of the end turns.

Two Type K, Chromel-Alumel thermocouples were epoxied to each end turn of the motor to record the winding temperatures. Each bearing was also instrumented with a similar type of temperature measurement device. The temperatures were continuously recorded on a 10-channel Omega recorder.

Photographs of the motor and the test arrangements are shown in Figures 2.2, 2.3, 2.4, and 2.6. Figure 2.3 shows a close-up of the accelerometer which is epoxied to the end turn. In Figure 2.4 the thermocouple junctions are shown mounted to the end turn.



1. STATOR IRON
2. SLOT CELL - Composite of Glass, Mylar and Dacron with a polyester binder
3. WEDGE - .030" Thick Glass Reinforced Molded Epoxy Wedge
4. PHASE INSULATION - Natural Matt of Non-Woven Polyester Fibers Saturated with a poly. resin
5. INSULATED MAGNET WIRE
6. POINT OF WEDGE FAILURE

Figure 2.1 - Random wound stator slot.

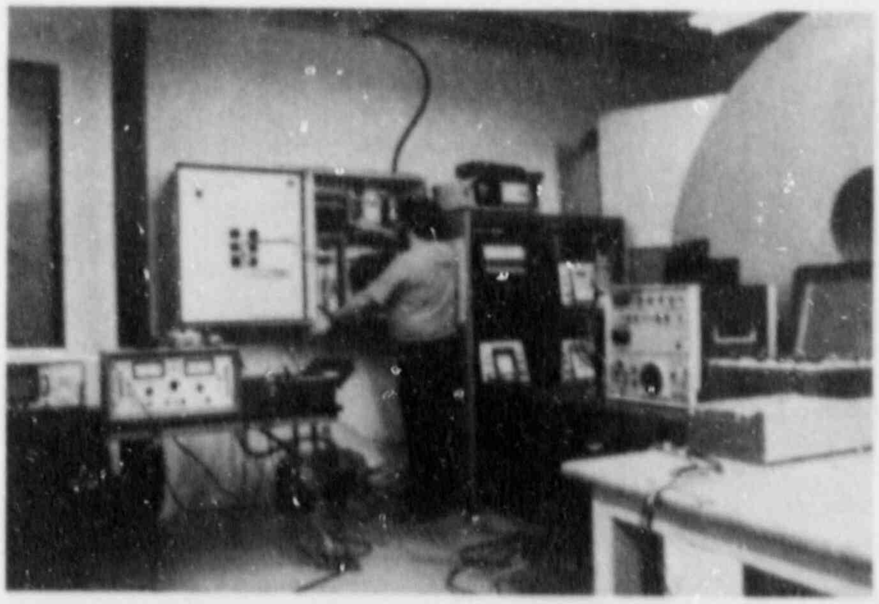


Figure 2.2 - Photograph of the motor being tested along with control panels and test instruments.

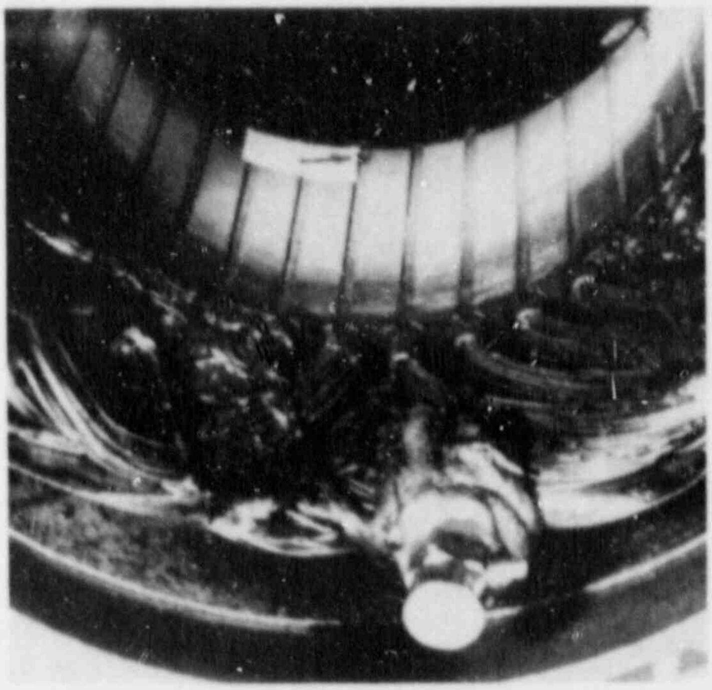


Figure 2.3 - Photograph of the stator (with rotor removed) showing close-up of accelerometer mounted on the end turn.

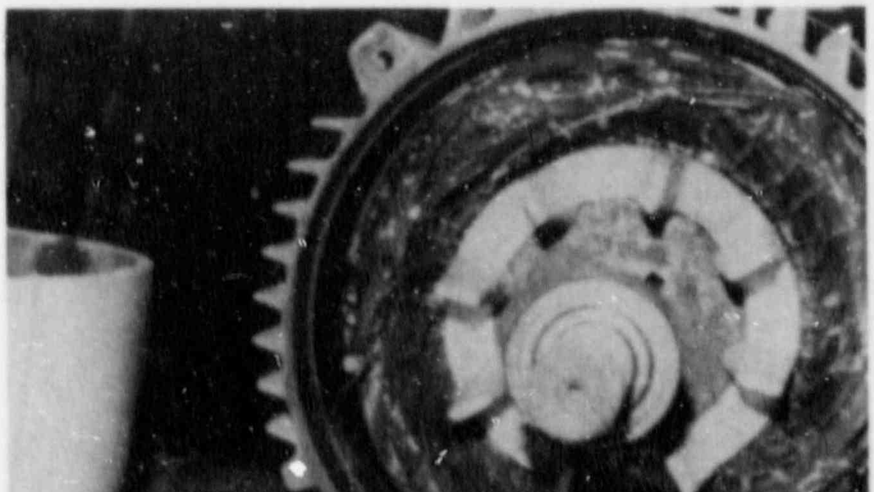


Figure 2.4 - Photograph of the stator (with rotor removed) showing the thermocouples mounted on the end turn.

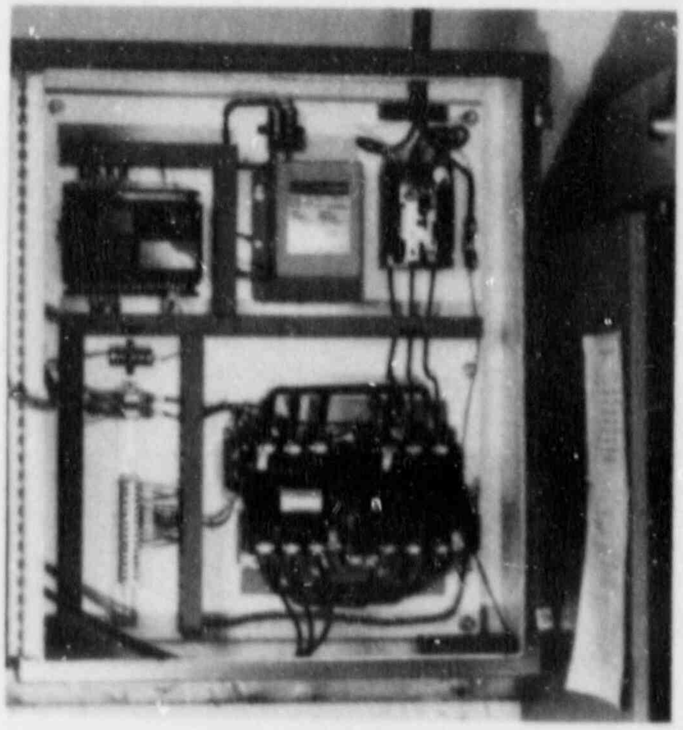


Figure 2.5 - Programmable plug reverse cycle panel with the door opened to show the components.

Figure 2.6 - Assembled motor with instruments and test panels.

2.2 Plug Reverse Cycle Aging Test

The plug reversal test [6] has long been one of the most important means of endurance testing polyphase motors. Interpretation of the results from this test have been precisely defined by manufacturers. Failure patterns of naturally aged stators and stators artificially aged using plug reverse cycling are found to be very similar. Failures induced by this test have been shown to be accompanied by general insulation aging. Looseness, motion, wear and localized hot spots, which normally develop as the result of certain stresses applied to the motor windings and bearings, are properly simulated by the test. The stresses developed by this test method include differential thermal stresses, differential coefficients of expansion, varnish weakening at higher temperatures, magnetic force due to winding currents, and cyclic mechanical stresses on bearings and other fasteners.

The General Electric Programmable Plug Reverse Panel shown in Figures 2.2, 2.5 and 2.6 was used to program the reverse cycling, continuous running and shutdown periods of the test motor. The switch box shown in Figure 2.2 and 2.6 contained a GE series one programmable controller which operate timers for each of the operating phases. The wiring diagram for the programmable controller switches and plug reverse assembly is shown in Figure 2.7. This unit was specifically built by General Electric for this motor test.

The plug reverse tester was operated such that timer 1 controlled the shutdown period of the motor. It was set for five and one-half hours on and thirty minutes off. Timer 2 was used to control the duration of the motor continuous run time. It was also set for five and one-half hours on and thirty minutes off. Timer 3 was used to reverse the motor direction every 3 seconds during the motor reversing period. Each test cycle was planned for 6 hours. The shutdown period was extended as needed to obtain test measurements and to do modifications to the motor and test equipment. The 6-hour sequence of operation was performed as follows:

- Press start button;
- motor starts in clockwise direction and runs 3 seconds;
- timer 3 opens contact G1 and closes contact G2 and motor is plug reversed and runs 3 seconds in the counter clockwise direction;
- timer 3 repeats the 3 second cycles continuously;
- at the end of 5 hours, timer 2 opens contact E1 and closes contact E2 and the motor runs continuously in the counter clockwise (normal) direction for 30 minutes;
- at the end of 5 hours and 30 minutes, timer 1 opens contacts A1 and A3 and the motor stops for 30 minutes. At the same time timer 2 closes contact E1 and opens contact E2;
- at the end of 6 hours, timer 1 closes contacts A1 and A2 and the previous steps are repeated for the entire test time.

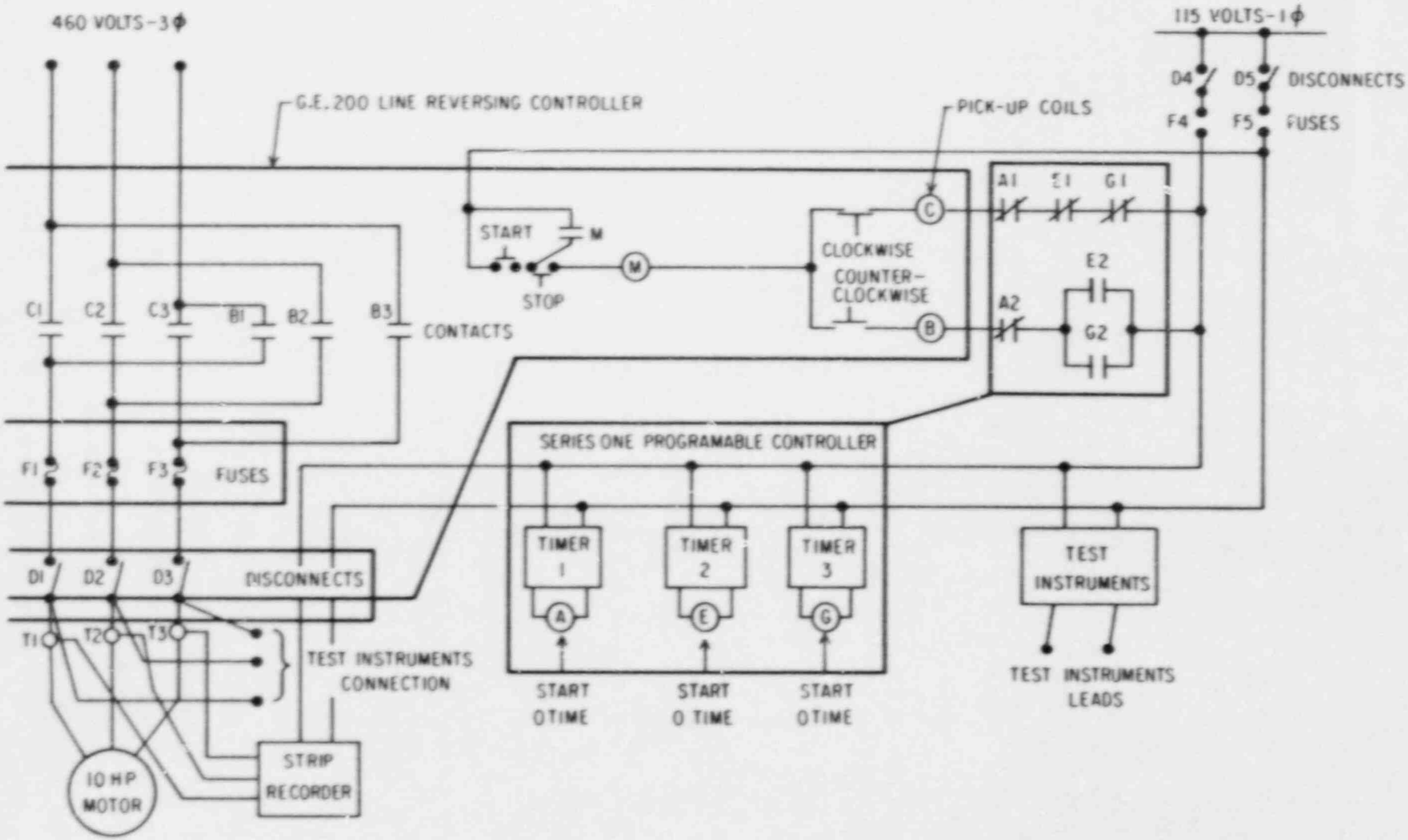


Figure 2.7 - Wiring diagram for the plug reverse assembly, including the programmable controller and switches.

2.3 Test Equipment

The insulation dielectric tests and bearing vibration tests were performed using standard test equipment available for plant maintenance. However, with the exception of the megger, all other test equipment is primarily used for corrective maintenance or repair shops. Appendix A provides detailed descriptions of each piece of test equipment utilized in this test program and also discusses the use and intrusiveness in performing these tests.

The test equipment utilized include:

- Dc Dielectric Insulation Resistance Tester
- Ac Dissipation Factor/Capacitance Test Set
- Ac Partial Discharge Test Set
- Surge Tester
- Ac/Dc Hipot Tester
- Winding Resistance Bridge
- Bearing Vibration Meter
- Other Auxiliary Devices

3. TEST PROCEDURE

The motor was subjected to accelerated aging of the stator insulation and bearing assembly by using the Plug Reverse Cycle Aging Test previously discussed. Each time the motor's rotational direction changed, it allowed an in-rush of starting current on the order of 100 amps into the stator winding. The cycling also imparted a mechanical load on the bearings and motor stator assembly. The starting current remained for about one third of a second inducing resistance heating in the coil insulating system. Thus, the winding temperature was maintained at a constant temperature by heating the insulation at a constant reverse cycle frequency. This method of accelerated aging was preferred over the conventional oven method since both insulation and bearing assemblies could be aged while the motor was in an operating mode.

The motor was aged by automatically reversing the voltage across the leads with a General Electric Programmable Plug Reverse Cycle Panel. The panel was programmed to reverse the voltage every three seconds for five hours (to raise the motor temperature and to simulate accelerated mechanical stresses in the end turns), followed by a half hour of continuous operation during which the motor ran in one direction to permit cooling by the fan. For the last half hour of the six hour cycle, the motor was shut off and dielectric testing was done. Since more than one half hour was usually required to perform all of the dielectric testing, it was necessary to extend the shutdown period until the testing was completed.

The motor winding temperatures were continuously recorded. They were maintained at constant values for a fixed period of testing by initially selecting a fixed cycling time and then adjusting motor cooling air flow. As a result, these indicators were not used to assess the insulation dielectric condition with the reverse cycle aging. The two bearing temperatures, were also continuously monitored.

Test data which were not continuously recorded were obtained from the motor approximately two times each week. Because the testing was begun at different times after the motor began its shutdown period, the temperatures at which the tests were conducted varied. This permitted the investigation of temperature effects on the measurements. All insulation resistance and dissipation factor readings were corrected for temperature.

3.1 <u>Motor Functional Indicator Tests</u>

The following section describes the sequence of motor tests performed for obtaining the motor functional indicators during each of the data collection periods.

3.1.1 Testing During Reverse Cycling Operation

(1) Motor Running Current Tests: Motor running current for each of the three phases was recorded on a Brush recorder for approximately three plug reverse cycles. The speed of the recorder was sufficient to distinguish the variation in current over 1/60 second.

3.1.2 Testing During Continuous Running Operation

(1) Winding End Turn Movement Tests: A plot of RMS acceleration vs. frequency (0 to 5,000 Hz) and the area under this curve was obtained from the accelerometers on each of the two motor end turns. The signals were processed by a GenRad signal process analyzer.

(2) Bearing Noise and Vibration Tests: The velocity and displacement of a point on the motor case above the bearings were measured and recorded using the IRD Mechanalysis Portable Unit. The peak values were noted for trending the data.

3.1.3 Testing During Shutdown Period

(1) Dc Winding Resistance Tests: The motor winding phase-to-phase (lead-to-lead) resistance for each of the three leads was measured with the Wheatstone Bridge. A spray-on electrical contact cleaner was used before the leads from the motor and instrument were connected to assure that the test connection had not impact on the readings.

(2) Dc Dielectric Resistance Test: The insulation resistance was measured with a voltage potential of 250, 500 and 1,000 volts from a motor lead to ground. The first test was conducted at 250 volts. The resistance reading was recorded, then the motor was grounded for one minute to drain the charge. This procedure was repeated for 500 volts and again for 1,000 volts. The temperature corrected readings were then plotted.

(3) Ac/Dc Leakage Tests: The ac leakage current to ground was measured at voltage potentials ranging from 150 to 1,000 volts. The instrument connections were made in the same way as for the dc resistance measurement. The dc leakage current test was initially performed at voltages ranging from 150 volts to 1500 volts. The resulting currents were extremely small and difficult to measure. This test was, therefore, not continued regularly throughout the test program.

(4) Polarization Index Tests: The insulation resistance at 500 volts was measured at one minute intervals over 11 minutes. The instrument leads were connected to the motor the same way as for the dc insulation resistance measurement. The data were used to calculate the polarization index (PI). This test was always taken after the ac leakage was measured to eliminate the measurement uncertainties from residual charge from the previous dc test.

(5) Ac Dissipation Factor/Capacitance Tests: The dissipation factor and capacitance were measured at 250 to 1,000 volts ac in four steps. One instrument lead was connected to a motor lead and the other instrument lead was connected to the ground terminal on the motor. The readings were corrected to 20°C using a correction curve from Reference 7.

(6) Surge Tests: A surge test for inspecting turn shorts in the coil was conducted by continuously increasing the surge voltage to 2,500 volts for each combination of two phases being compared. The instrument compares Phase 3 with Phase 1, Phase 3 with Phase 2, and Phase 1 with Phase 2. The curve on the video display of the instrument can be considered as two superimposed traces; one for each of the phases being compared. When an anomaly in the motor coil exists (e.g., a turn-to-turn or turn-to-ground short), the two traces shown on the instrument are displaced from each other. If no anomaly exists, the two traces will be perfectly matched and will appear as one curve.

(7) Ac Partial Discharge Tests. The last test performed on the motor before resuming the reversing operation was the partial discharge test. The inception voltage for partial discharge was determined by raising the ac voltage (using the power supply for the capacitance and dissipation test set) slowly from zero to approximately 1,100 volts while plotting the amount of partial discharge (in pico Coulombs) with the applied voltage. The inception voltage is a point where a sudden change in slope occurs. An extinction voltage was determined by slowly reducing the voltage. By repeating this test, it was found that the inception voltage would change. Later in the program, the inception and extinction voltages were measured several times to observe how much movement in the voltages was occurring.

(8) Bearing Grease Analysis: The bearings were greased with Keystone Pennwalt Zeniplex R-2 grease periodically while the motor was running. Samples of grease were removed from both bearings at .823, 3.17 and 3.79 million reversals and were sent to Keystone Pennwalt for analysis of the chemistry and the determination of the dropping point.

3.2 Test Procedure Changes and Abnormalities

The motor test program was started on February 13, 1986 and continued to run for over seven months; ending on September 22, 1986. During the initial phase of the test, considerable efforts were made to learn how to use the test equipment for obtaining various test parameters. Therefore, the trending test data presented later in the report might have some outliers or large uncertainties in the first few test results. It was originally anticipated that the motor components would indicate some degradations after 1-2 million reverse cycles. However, motor failure did not occur until 3.79 million reversals. The following discussions describe the sequence of events which occurred in the entire test duration.

On the weekend of April 26, 1986 at about 1.34 million reverse cycles, a spring in the GE programmable controller panel contactor failed. The spring was replaced and the test continued. At the end of June, 1986 a review of the trends of all test parameters revealed no particular sign of insulation deterioration with the exceptions of an increase in insulation dielectric properties due to the curing process and a slight decrease in the partial discharge inception voltages. The bearing vibration indicators started showing large excursions of velocity and displacement values. It was then decided that the aging temperature of the winding insulation should be increased from 160°C to accelerate the aging process.

At 2.42 million reverse cycles on July 2, 1986, the winding temperature was increased to 175°C by placing tape over the motor inlet vents to reduce the cooling efficiency of the fan. The test was continued to July 28, 1986, at which time 3.01 million reverse cycles had been performed. A review of the data at this point indicated that the insulation degradation trend remained unchanged from previous trends. However, the bearing vibration measurements were found to exhibit higher displacements and velocities during the same period. To further accelerate the rate of insulation aging, additional inlet vents were taped to raise the temperature to 190°C.

During the first week of August, 1986, the pulley end accelerometer for measuring the end turn movements was found to be burned out (showed an open circuit) as a result of exposure to a higher winding temperature than its rated value. The test was stopped for couple of weeks and a set of new Endevco accelerometers capable of operating at temperatures up to 260°C were ordered. These were installed on August 22, 1986 at 3.33 million reverse cycles and the test continued.

The data obtained at this point indicated that the aging process was still progressing at an extremely slow rate. In order to obtain a more definitive indication of motor aging within the time constraints of the test program, it was decided to further increase the winding operating temperature. Since the temperature was approaching the operating limit of the insulation, a small temperature increase of approximately 10°C was chosen. This was done to avoid a rapid failure of the insulation from burn-out rather than from aging.

On September 5, at 3.6 million reversals, the motor was shut down for static testing. Before resuming reversing, additional tape was placed over the inlet vents to partially block the cooling air and raise the maximum temperature of the end turns to 200°C. Testing was then resumed.

On September 15, at 3.76 million reversals, the motor was started to resume the reversing after being down for testing. Immediately after starting, a noisy bearing was detected on the pulley end and the motor was shut down. When the rotor was removed from the stator to inspect the bearing, it was found that the pulley end bearing was frozen. A replacement bearing was available in an identical backup motor; however, it was feared that the process of removing the bearing from the shaft of the rotor in the backup motor would damage the bearing. It was therefore decided to substitute the rotor (with its bearings) from the backup motor so that the reversing of the test motor could resume. Since the rotor was not considered a dominant failure mechanism, this change would not affect the test results.

Before reassembling the test motor, the concept of employing moisture to accelerate the aging of the insulation was explored. Water was sprayed on one end and the stator windings were meggered at 250 volts. The insulation resistance immediately dropped from 2.35×10^{10} ohms to less than 28,050 ohms. This test was repeated on the stator end turn of the backup motor with the same results. From this test, it was concluded that using moisture for accelerating the aging or diagnosing the condition of the motor insulation was not feasible because the motor would not start in this condition.

To return the motor insulation to a condition in which the motor could be run without sudden failure, the stator was dried in an oven at 120°C for 3 hours. At the end of the drying period the insulation resistance was tested and found to be 7×10^{11} ohms. This was high enough to begin cycling of the motor.

On September 18 the motor was reassembled with the rotor from the backup motor and the test was restarted. On September 19, at 3.79 million reversals, the motor was stopped and tested. After the stator passed the dc leakage current tests, the surge test revealed a stator failure. Oscilloscope traces of the failure area are discussed in Section 5. On September 22 the rotor was removed from the motor and the failure location was identified in the stator using the surge tester. With the tester, a small arc through the slot wedge to the stator ground wall on the pulley end of the stator was seen. The pinhole created by the arc was approximately one half inch from the end of the stator.

After the motor failed, the stator was sectioned at the failure location to examine the slot insulation in the vicinity of the failure. The post- mortem examination results are presented in Section 5.

4. TEST RESULTS

The 10 HP test motor ran for over seven months and was subjected to 3,789,050 reverse cycles. The six temperature recordings shown in Figure 4.1 indicate typical thermocouple readings from the windings and bearings. The two leftmost traces are for the bearings. The Pulley End (PE) bearing temperature is higher than the Opposite Pulley End (OPE) because of the presence of the cooling fan in the later end. Similar trends also exist in the winding temperature traces. The two bearing temperatures during the five hour plug reverse period were between 95°C and 110°C. The pulley end winding temperatures for the same period were within the band of 160°C to 165°C. The opposite end winding temperatures varied from 140°C to 155°C. These conditions correspond to the initial test period with a three second plug reverse cycle and no obstructions in the cooling air flow from the fan end of the motor.

The stator winding temperatures were periodically increased and maintained constant for the following reverse cycle ranges:

Reversals (millions)	Test Time (10^6 sec)	Winding Temperature (°C)
0-2.42	7.26	160
2.42-3.01	1.77	175
3.01-3.6	1.77	190
3.61-3.79	0.57	195-200

After two million reverse cycles the bearing temperatures began to increase. Prior to the bearing failures, the temperatures for the PE and OPE were 115°C and 120°C, respectively. Although the rate of change in these temperatures was not significant, a deteriorating bearing condition was suggested from the trending. This effect is expected since bearing failure is usually preceded by increased friction in the bearing assembly, which results in higher operating temperatures. However, the effects of increasing winding temperature by reducing cooling air flow must also be considered when evaluating bearing temperatures. The degree to which bearing temperature increase was caused by reduced air flow was not determined. Bearing failure is further discussed in the post-mortem section.

To estimate the age of the motor at the time of failure, thermal aging was assumed to be solely responsible for the insulation degradation. The "ten degree centigrade rule" (in which the accelerated age of the insulation is twice the test time for every 10 degrees centigrade difference between the test and normal operating temperatures) is used to calculate the equivalent time. Based on a normal operating temperature of 120°C for a Class B motor, the estimated age of the test motor insulation was approximately 16 years. This does not include the motor operating time in a nuclear facility prior to the test. As previously mentioned, the motor was refurbished with new insulation using the VPI treatment, and new bearings before the test started and was

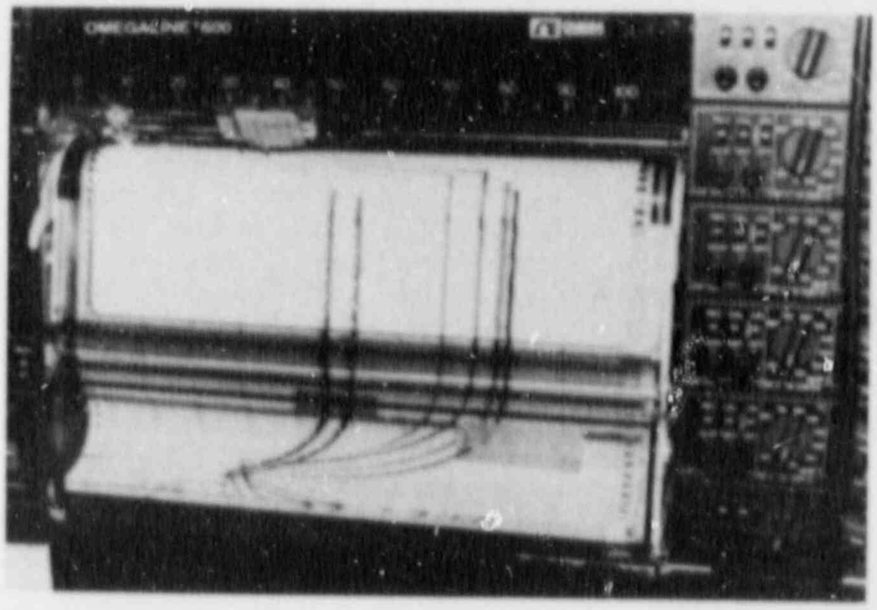


Figure 4.1 - Winding and bearing temperature traces.

considered as a "as good as new" motor. Other aging effects such as mechanical cycling, bearing degradation, laboratory environment, and operating modes were not considered in the above age estimation.

In utilizing the estimated motor age, it must be noted that the main objective of this program was to determine whether there exists any trending of test parameters which could be used to monitor the condition of a motor. The estimated motor age is determined here solely for purposes of this study and should not be used in relation to motor qualification for nuclear facilities.

As a result of this test, the motor was seen to fail in two distinct modes; bearing failure at 3.76 million reversals, and insulation failure at the wedge at 3.79 million reversals. The trends of each of the test results are discussed below relating to these two failure modes.

At the beginning of the test program, a learning period was devoted to performing each functional indicator test using the associated test equipment. As a result, some outliers in the beginning of the plots may be interpreted as anomalies in performing the tests. Outliers also exist outside this period and may be considered as human errors in registering the correct values or in data management after the test was performed. Each plot corresponding to one of the functional indicators is further discussed in detail with relation to the motor component conditions and their future health.

In examining the test results, it should be noted that the findings of this test program are based on the testing of one motor only. Parameter measurements are, therefore, influenced by the characteristics of this motor's component materials and design. Similar testing on other motors could produce different parameter values. The focus of this study, however, is on the trending patterns of these parameters and not their magnitude. The final failure mode(s) of a motor component is expected to be preceded by the same trend in parameter values provided the motor design or materials of construction remains the same. The age-related degradations leading to failure modes inherent to electric motors can then be monitored using the same functional indicators investigated herein. The conclusions drawn from this study are, therefore, applicable to other motor designs.

4.1 Dielectric Insulation Resistance

4.1.1 Polarization Index (PI)

The insulation resistance of a dry motor winding in good condition will increase under a constant test voltage potential until a fairly steady value is reached; typically in 10 to 15 minutes. If the winding is wet or dirty, the steady value will be reached in 1 or 2 minutes after the test potential is applied. The polarization index is the ratio of the 10-minute resistance value to the 1-minute resistance value. Thus, this parameter is useful in appraising windings for dryness and for fitness for overpotential tests.

The polarization index of the test motor was measured as part of this study to determine if results from this test can be trended to monitor aging degradation. Results are shown plotted with reversals in Figure 4.2. The scatter in the results is from several sources. The scatter which occurred during the first few thousand reversals is believed to be due to changes that were continually being made in the measuring techniques to improve reproducibility. Subsequent scatter is believed to be due to inaccuracies inherent to the instrumentation and equipment used to perform the tests. As shown in Figure 4.2, no definitive trend in polarization index was observed during the test period.

IEEE Standard 43 [8], identifies the minimum PI for Class B or F electric motors to be 2.0 and specifies that it should be independent at winding temperatures. As shown in Figure 4.2, the PI for the test motor was found to fluctuate between 2 and 3 throughout the test. This value is very close to the IEEE specified minimum and normally would indicate some degree of contamination. The test motor insulation system, however, was refurbished immediately prior to testing. As previously mentioned, a relatively new vacuum impregnated epoxy type insulation was used. In addition, the tests were performed in a controlled laboratory environment where contamination by dirt and/or moisture is minimal. It is therefore believed that low values of polarization index are characteristic of clean, dry vacuum impregnated epoxy insulation systems. This indicates that the IEEE standard may need to be reviewed and updated to properly address current improvements in insulating materials.

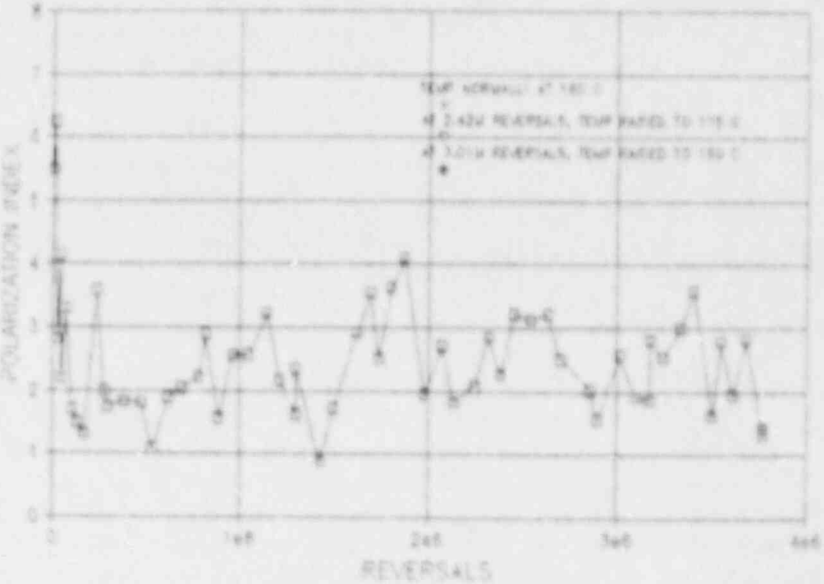


Figure 4.2 - Polarization index at 500 volts dc.

The temperature dependency of the test motor polarization index was also examined. Figure 4.3 shows PI plotted against winding temperature. It should be noted that PI tests were performed during the motor shutdown period after the windings had time to cool down from operating temperature. As shown, the results indicate a very slight increase in PI with temperature. This may be characteristic of the insulation system used, however, the scatter obtained in the data is felt to be too large to draw any firm conclusions regarding temperature dependency.

4.1.2 Dc Insulation Resistance

The dc insulation resistance test measures the electrical resistance of the phase-to-ground insulation in a motor winding at various test voltages. It is typically used in industry to verify insulation dryness prior to starting electric motors. A megger is used to perform this test.

The dc insulation resistance test was performed at three test voltage levels for this study: 250, 500, and 1,000 volts. The megger used in the test program had a resistance measurement range of 10^5 to 10^{12} ohms in 8 ranges. The typical megger units used in plant maintenance programs have a compressed scale in the range above 100,000 megohms. Resistance values above 100,000 megohms are read as infinity. The megger used in this test program was selected to read the resistance value accurately in order to trend the parameter with the reverse cycles.

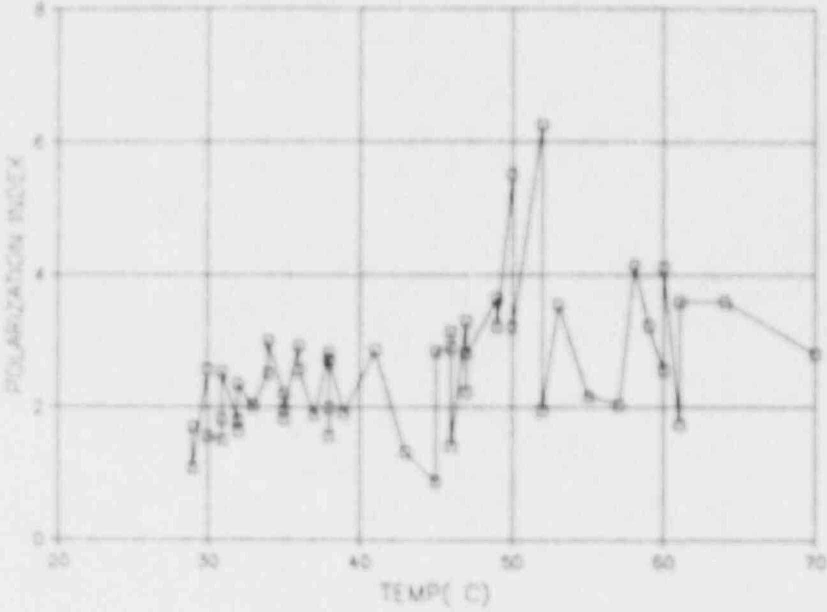


Figure 4.3 - Effect of temperature on polarization index.

Figure 4.4 shows the three test values plotted against the number of reverse cycles. As shown, the dc resistance increased from approximately 26,000 megohms at the beginning of the test to a maximum of over 900,000 megohms. There is a rapid increase in dc resistance at 3 million reversals and an increased scatter prior to the insulation failure. Similar trends are also observed in the resistance to charging current after 1 and 10 minutes, as shown in Figure 4.5. It is also evident that no significant change in the insulation resistance occurred with the increase in applied voltage.

Per IEEE 43 [8], the minimum acceptable insulation resistance (R_{min}) for a 460 volt motor is 1.4 megohms (i.e., R_{min} = Voltage Rating (kV) + 1). As indicated in Figure 4.4, the measured test values were well above 1000 megohms, indicating good insulation condition throughout the test, including the end of life. If a standard megger unit would have been used in the test, all resistance readings would have been represented by a straight horizontal line at a resistance value of infinity. This would have shown no trend in the insulation resistance values as the insulation aged. However, Figure 4.4 illustrates a definite trend at resistance values above 100,000 megohms.

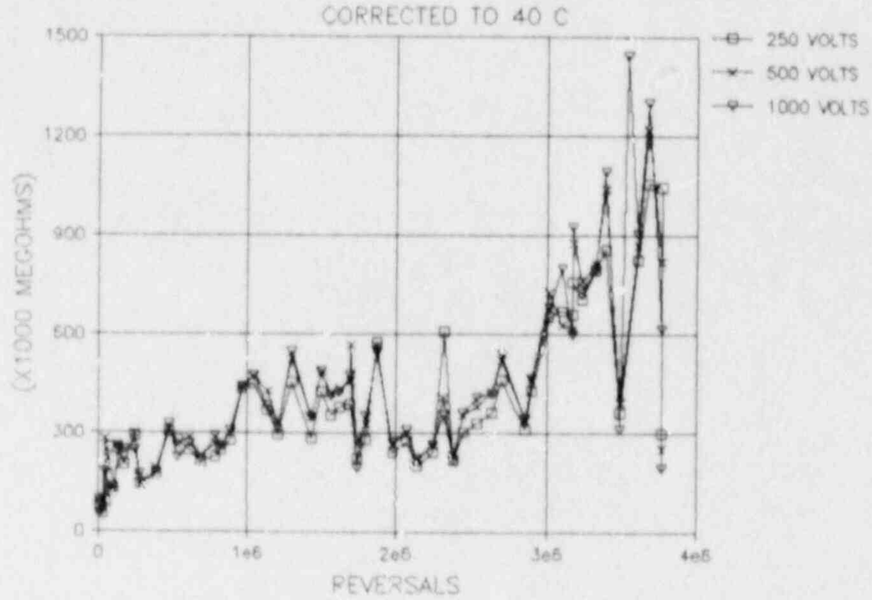


Figure 4.4 - Dc dielectric resistance at 250, 500 and 1,000 volts.

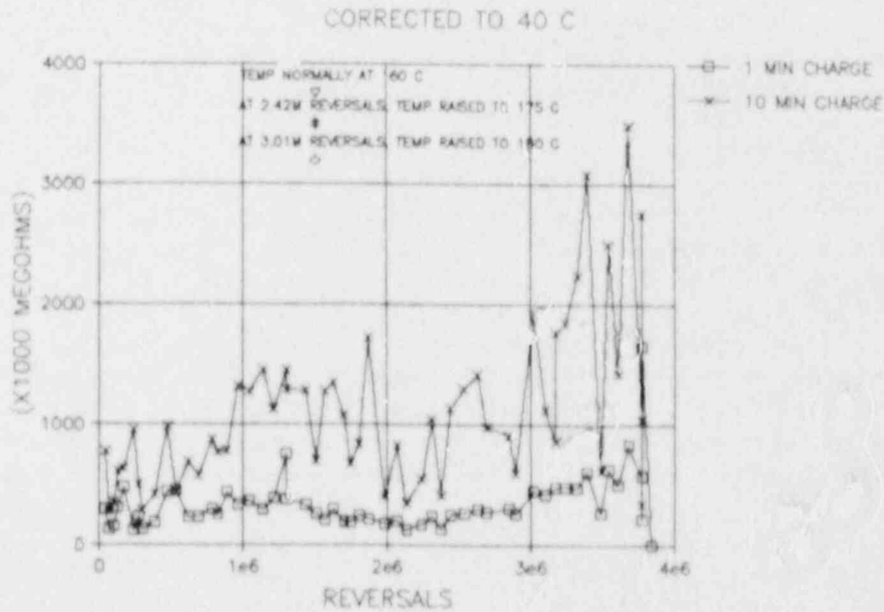


Figure 4.5 - Resistance to charging current at 500 volts dc after one minute and ten minutes.

The increase in resistance shown in Figure 4.4 as the insulation system is aged is believed to be due to the continuous polymerization of the epoxy in the insulation system during the aging. This phenomenon has been observed in other studies [9-15]. As aging occurs in the epoxy insulation, polymerization of the charge carriers occurs, which increases their size. Cross linking between the polymer chains proceeds, which further restricts the movement of the charge carriers. Both of these phenomena contribute to the reduction in the flow of charge carriers and in the dc current through the material.

The materials in the stator insulation include glass, polyester, dacron and epoxy. The epoxy is used in two places in the motor; the end turns, which were vacuum pressure impregnated with an epoxy resin, and the slot wedge which is a .030 inch thick glass reinforced epoxy molded wedge. An increase in dc resistance with aging does not occur in glass. The effect of aging on the electrical properties of dacron and polyester could not be found from a preliminary review of the literature.

The epoxy in the slot wedge is thought to be responsible for the trends observed in the dc insulation resistance, since the electrical path from a conductor through the wedge to ground is the shortest path. The path through the epoxy in the end turns to the ground wall of the stator is considerably longer because the slot tubes extend 1/4 inch beyond the edge of the slots.

It is interesting to note tha[illegible]atter in the dc resistance increased significantly during the last 500,[illegible] reversals, as shown in Figures 4.4 and 4.5. The cause of this trend is no[illegible]ll understood. It might have been an indication of epoxy breakdown or wedge weakening which eventually occurred to fail the motor.

4.2 Surge Testing

Surge testing is a comparison test between two coils or phases. A test voltage is applied to the two phases to be compared. The superimposed voltage oscillations shown on a cathode ray oscilloscope determine the condition of the phase pair depending on the degree to which they match. If the wave patterns diverge, then the two phases are not identical and a fault exists in one or both of the phases. A perfect match indicates that both phases are in good condition.

The surge test can detect localized faults in the insulating material. These include turn/coil shorts, phase shorts, open or loose connections, partial or complete ground, phase imbalance, and reverse connections. Since this test uses a step wavefront high voltage pulse, the application of this test is limited to small low voltage motors that have less copper (large amount of copper will dissipate voltage signals and affect test results). This test can be performed at the motor control center as long as surge arresters or capacitors on the line are properly disconnected.

The surge testing performed for this study compared the following phase combinations; phase 1 vs phase 2, phase 2 vs phase 3, and phase 1 vs phase 3. Test results showed no shorts in the motor until motor failure occurred. This is discussed in more detail in Section 5 of this report. Typical oscilloscope patterns observed are shown in Figure 5.3 for phase 1 vs phase 3. Photographs were not taken of the oscilloscope patterns for each of the surge tests performed.

4.3 Dissipation Factor/Capacitance

Changes in the dissipation factor of an insulation indicate that the insulation has developed cracks and voids which allow a path for current leakage, contamination, and ionization. Similarly, changes in the capacitance indicate insulation degradation due to thinning and presence of moisture, layer short-circuits or open circuits in the capacitance network by the ionization process. These parameters are, therefore, useful in assessing insulation condition.

If the insulation condition is bad enough to cause severe ionization within voids and cracks, both dissipation factor and capacitance will indicate some increase. The voltage level at which this ionization becomes significantly high is known as "tip-up" voltage. This is a widely used maintenance test to evaluate the extent of insulation deterioration caused by ionization. In this test program, the partial discharge test determined the "tip-up" voltage.

Both dissipation factor and capacitance tests were performed at 500, 750 and 1000 volts ac. The test data are plotted against the number of reverse cycles in Figures 4.6 and 4.7. As shown, the curves for the three voltages fall very close to each other. A downward trend is observed in which the dissipation factor fell from approximately 0.7% to approximately 0.35% at the end of the test. The large scatter during initial testing is attributed to changes in measurement techniques, as in the measurement of the polarization index. In general, the dissipation factor remained low during the test indicating a dry, dense insulation system. A similar trend was also observed for capacitance measurements, as shown in Figure 4.7.

The fact that the dissipation factor and capacitance values showed a decrease with reversals is consistent with the findings of the dc resistance test discussed earlier. All three tests indicated that the insulation was still in a curing process, during which its insulating properties were improving.

4.4 Ac Partial Discharge

As an insulating system degrades and develops cracks and voids, ionization (corona) discharge occurs due to the presence of air or contaminants inside these defects. The degree of ionization depends on the number of defects present in the insulating material. Since these electrical discharges are caused by the voltage intensity across the voids breaking down the air or gas molecules inside these voids, these discharges occur at a threshold

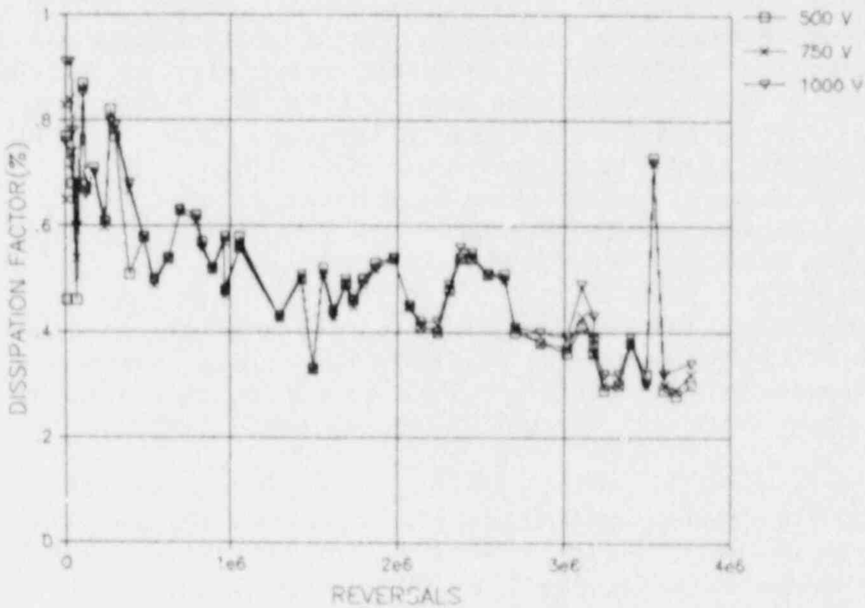


Figure 4.6 - Ac dissipation factor at 500, 750 and 1000 volts.

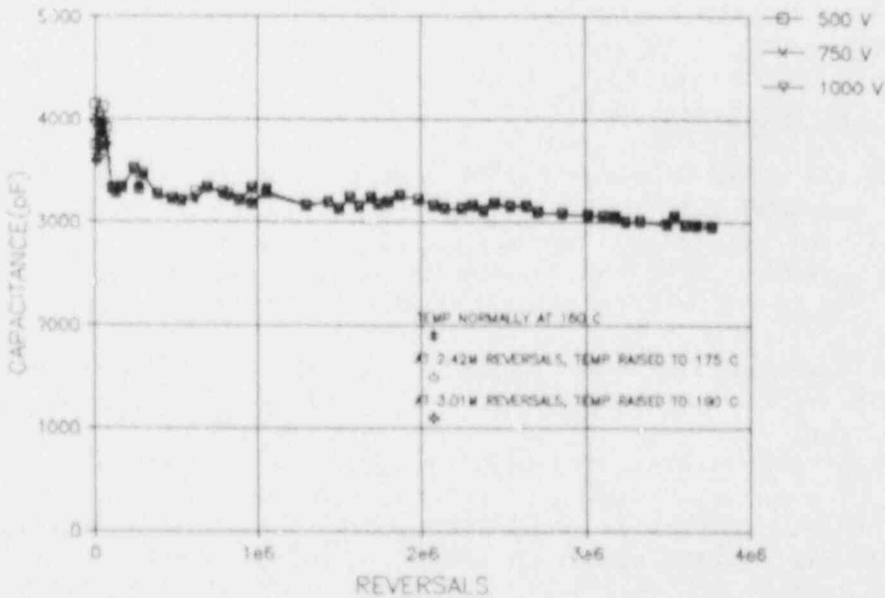


Figure 4.7 - Ac capacitance at 500, 750 and 1000 volts

voltage known as the inception voltage. The partial discharge test[14] determines this inception voltage level at which the electrical discharges become significant.

The high frequency, relatively small discharges inherent to partial discharge testing are difficult to measure, especially at a low voltage level. Therefore, this test is typically reserved for high voltage machines of 6000 V or higher. For smaller motors, as in the case here, a plotter approach was used to determine the discharge inception voltage. Figure 4.8 demonstrates a typical discharge in the winding with an increase in test voltage. At 904 volts the discharge level increased significantly, defining the inception voltage level.

Once discharge has been initiated in a crack, it can be maintained with a voltage lower than the minimum voltage required to produce a discharge initially (25% lower in some cases). This is due to the residual surface charge left from the previous discharge. This minimum voltage is known as extinction voltage.

Both the inception and extinction voltages were measured during the test and were plotted against the number of reverse cycles. The results for the extinction voltage did not yield any particular trend nor provide any information in monitoring the insulation condition with age. The inception voltage plot, however, indicated a definite trend as the motor was aged. Figure 4.9 shows a decline in the partial discharge inception voltage from over 1000 volts initially to 800 volts prior to failure. If the mode of insulation degradation is related to the ionization within voids, this particular parameter indicates the early inception of discharges with an increase in discharge activity as the cracks and voids develop with age. It is believed that this was happening on the subject motor, as is suggested from the test results shown in Figure 4.9.

4.5 Ac/Dc Leakage Currents

Ac leakage current measurements were done with the ac/dc hipot tester at voltages up to 1000 volts with an interval of 150 volts ac. The leakage current values increased proportionally with the increase in applied voltage, as expected. At 1000 volts, the leakage current fluctuated between 1.53 and 1.18 milliamps. No specific trend was observed throughout the test duration.

A dc leakage current test is an alternate to the dc resistance test, and is performed in the same manner. The tests were conducted with a voltage interval of 150 volts dc up to a peak voltage of 1500 volts. The maximum leakage current values read through the test program were of the order of 0.03 milliamps. The extremely small currents obtained were very difficult to measure accurately. This test was, therefore, performed irregularly after the initial few measurements were taken.

4.6 Dc Winding Resistance

Each of the three phase windings were tested for their dc winding resistance values throughout the test program. The results are plotted against

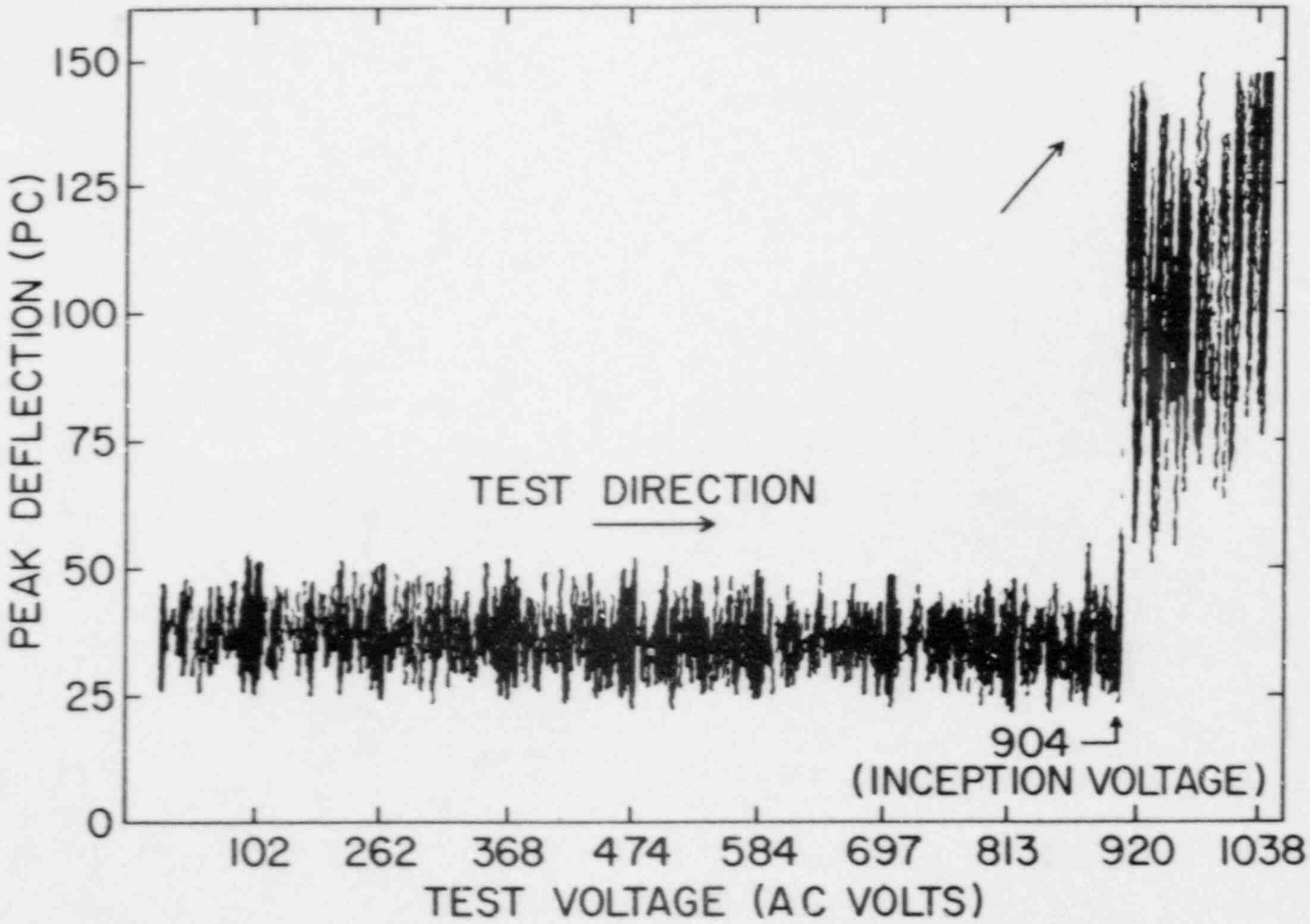


Figure 4 .8 - Variation of peak discharge with increasing ac voltage.

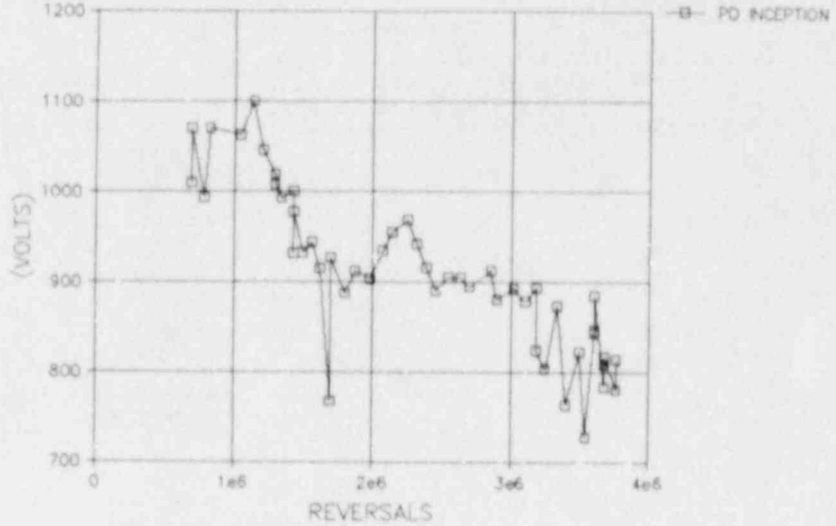


Figure 4.9 - Partial discharge inception voltage.

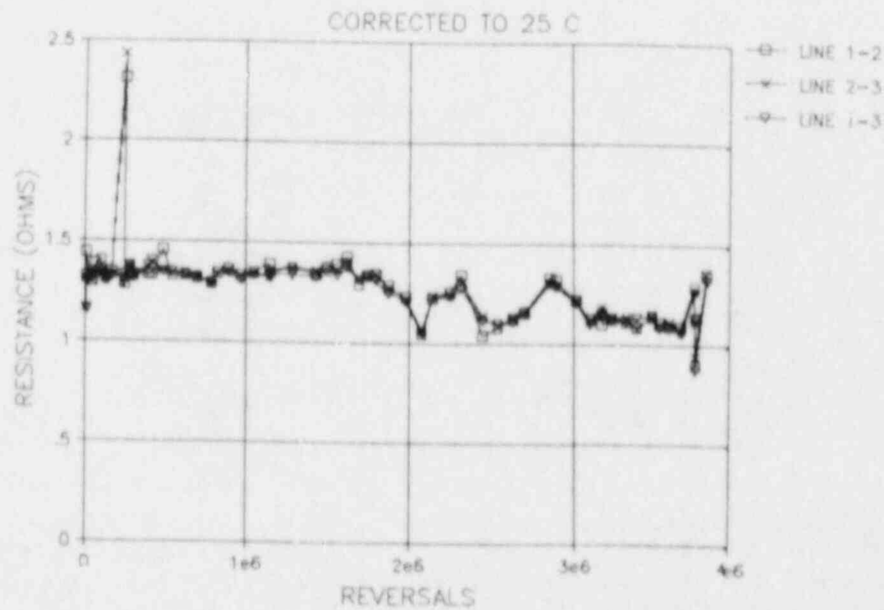


Figure 4.10 - Dc phase-to-phase winding resistance.

the reverse cycles in Figure 4.10. With the exception of one outlier in the beginning of the test, all three resistance values remained relatively constant during the entire test period. Near the end of the test program, the results indicate some wide scattering similar to cases with the insulation resistance test results. The resistance could only change due to a turn short, broken wire, or severely degraded wire connection, however, the exact cause of the scattering is unknown.

4.7 Winding End Turn Movement

The acceleration of the motor end turns from the 60 cycles per second running current was measured during the continuous running of the motor, and is presented in Figure 4.11. Each data point is the area under the curve generated from a spectral analysis on the end turn movement, as shown in Figure 4.12.

Note that in Figure 4.12 there are sharp peaks at integral frequencies of 60 Hz. One volt on the Y axis is equal to 1 g of RMS acceleration. The plot is the average of 4 runs as indicated in the middle, above the graph box. No damping was used, as indicated in the upper right of the figure. On the bottom of the figure, the integrated area under the curve, 203.9 E-03 volts (or g's) is given.

The end turn movement was difficult to measure reliably because of the contribution of bearing noise and vibration to the measurement, and because of the difficulty in maintaining a secure mounting for the accelerometers. Several times during the program the accelerometers came loose from their epoxy mounts and had to be remounted. The epoxy used was a two-part room temperature curing electrical resin.

In general, the movement changed very little during the test. As seen from Figure 4.11, the acceleration results were scattered around 0.2 g. This lack of movement is expected from an epoxy vacuum impregnated stator where the epoxy gets stronger by age, as reflected in the higher dc dielectric insulation test readings. At the end of the test, the end turns appeared to be equal or more rigid than at the start of the test. If the windings had been treated with a polyester or silicone, which soften at higher temperatures, more movement would have been expected. A turn-to-turn failure in the end turn due to conductor movement would also be more likely to occur.

4.8 Bearing Noise and Vibration

The bearing vibration velocity and displacement are shown in Figures 4.13 and 4.14, respectively, for the bearings at both ends of the motor (PE-Pulley End, OPE-Opposite Pulley End). Both of these figures show an increase in vibration at approximately 2 million reversals and a large increase in scatter of the points. Bearing noise also became detectable at this point and more frequent greasing was performed for the remainder of the test to help quiet the bearings.

Bearing noise continued to increase despite the more frequent greasing. At approximately 3.76 million reversals, the noise was excessive and the motor was shut down for inspection. The bearing noise was the determining factor

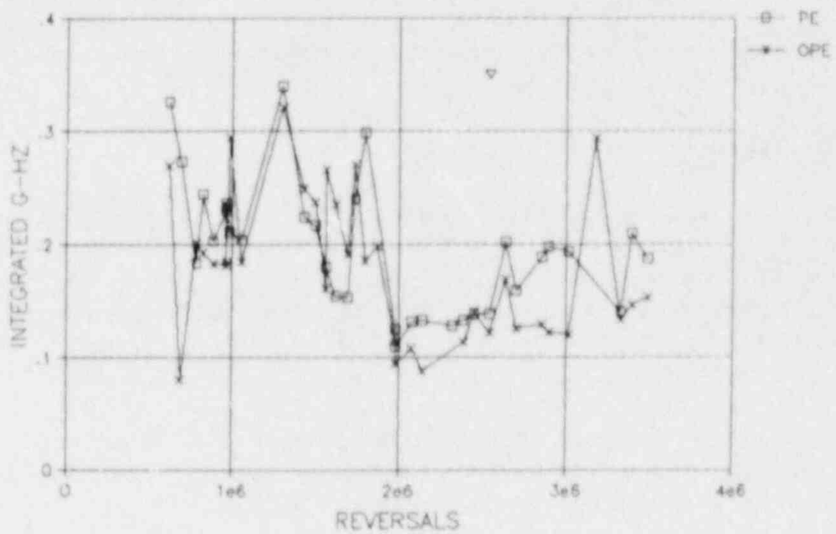


Figure 4.11 - End turn RMS acceleration for the pulley end and opposite pulley end.

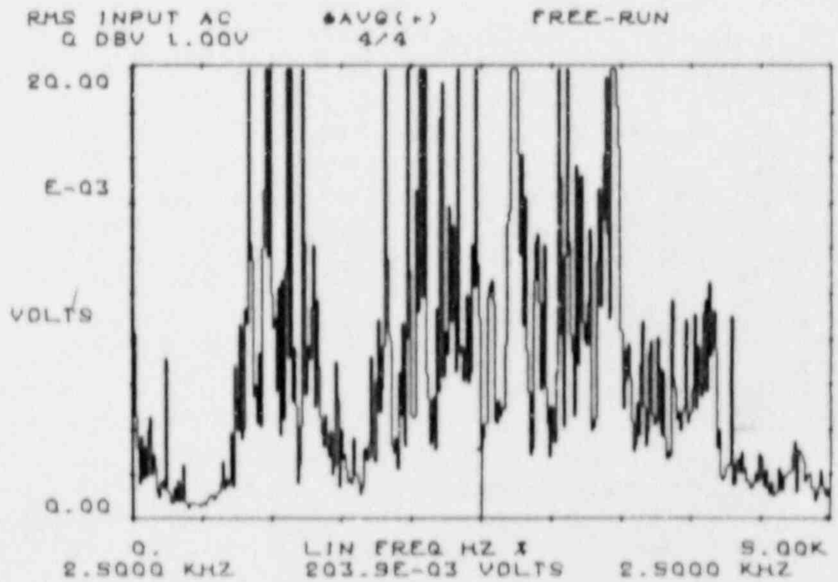


Figure 4.12 - Spectral analysis of the end turn acceleration for the pulley end.

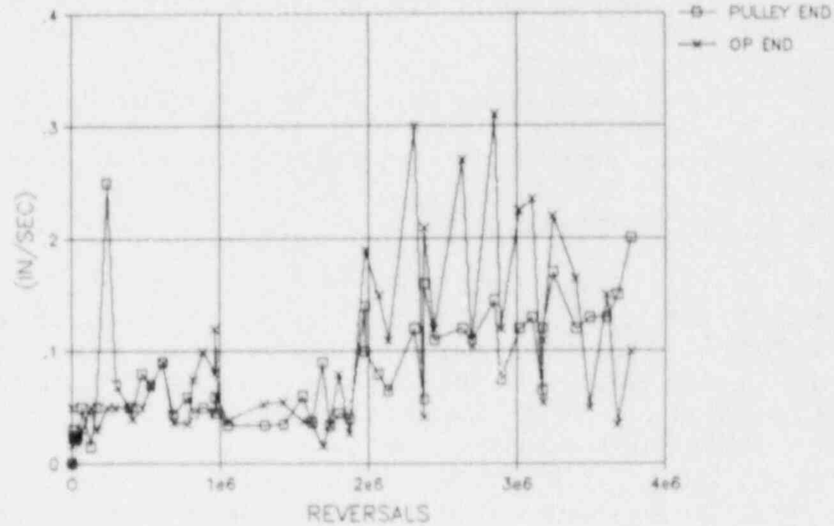


Figure 4.13 - Bearing velocity trends.

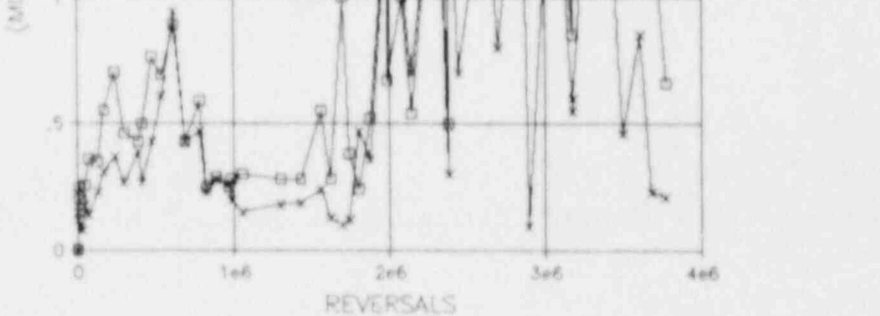


Figure 4.14 - Bearing displacement trends.

for indicating the deteriorated condition of the bearing. Prior to motor shutdown, it could not be determined which bearing had failed or the extent of the bearing damage. Referring to Figures 4.13 and 4.14, the bearing velocity and displacement measurements showed increased vibration for both of the bearings after approximately 2 million reversals. This indicated that both bearings had sustained some degradation.

While removing the bearings from the shaft during the post-mortem analysis, the pulley end bearing was frozen to the rotor shaft. When force was applied to remove the PE bearing, it broke into pieces. It was evident from inspection of the bearings that both were severely degraded and were considered to be failed. This is consistent with the results of the bearing velocity and displacement plots which indicated degradation of both bearings.

4.9 Bearing Grease Analysis

Samples of grease were taken from the bearings after 0.82 million, 3.17 million and 3.79 million reversals (failure). The samples were sent to Keystone Pennwalt for a spectrochemical analysis and a test to determine the dropping point (ASTM D2265). The test reports are included in Appendix B. Because the bearings had to be continually greased while the motor was reversed to prevent them from failing, the grease samples contained mostly fresh grease and very little aged grease. The results of the grease analysis are, therefore, not a true representation of the results which might be obtained from an actual motor in a plant environment. Where aged grease was available, however, the spectrochemical analyses did show the presence of wear metals (iron and nickel) which were not present in the unaged grease.

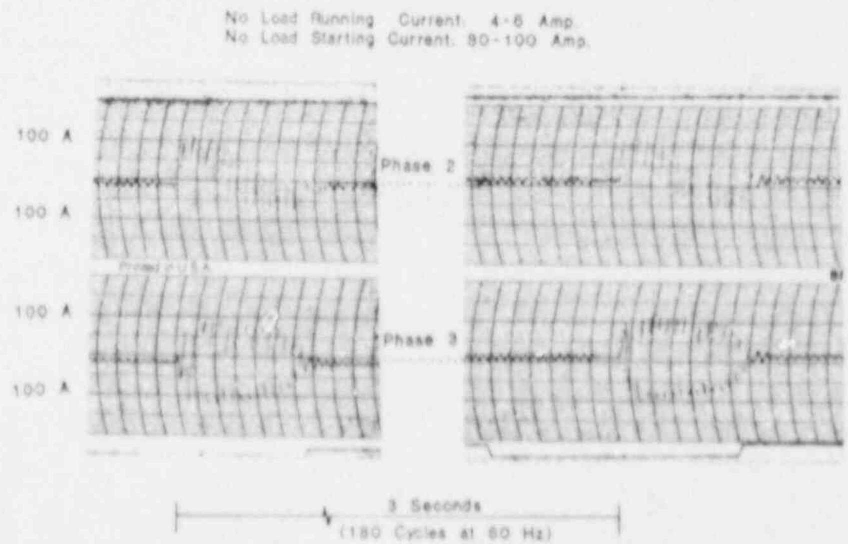


Figure 4.15 - Current signatures for phases 2 and 3 terminals.

4.10 No Load Motor Running Current

Motor running current signatures were periodically recorded, as shown in Figure 4.15. Throughout the test period, this parameter fluctuated between 3.5 and 6.0 amperes. Also recorded along with the no load current was the starting current each time the motor terminals were reversed. Both items were recorded on a brush recorder fast enough to distinguish the variation in current over 1/60 second.

Both starting current and no load current indicated no change in magnitude or shape during the test. A change in running current is possible when the magnetic circuit changes or the rotational integrity (i.e., bearings) is affected by increased functional load. Since none of these factors were present during the test, no change in running current was expected. The results of this test are, therefore, consistent with expectations.

5. POST-MORTEM EXAMINATION OF MOTOR COMPONENT FAILURES

In order to verify the accuracy of the failure modes observed during motor testing and to gain additional insight into the effects of the failures, the test motor was disassembled and inspected. The results of this post-mortem examination are discussed in this section.

As indicated in the previous section, the motor bearing at the pulley end failed at 3.76 million reverse cycles. An increase in bearing noise was prominent enough to be heard after approximately 2 million reverse cycles. The bearing failure was indicated by excessive bearing noise which prompted the operator to stop the test and examine the condition of the bearing. The pulley end bearing came apart during disassembly from the shaft, as shown in Figure 5.1. The opposite pulley end bearing was also removed and is shown in Figure 5.2. After removal from the shaft, the failed bearing showed signs of severe damage. The cause and mechanism for this failure could not be established from the post-mortem examination. It is, however, believed that the reverse cycle load on the bearing contributed to prematurely reaching the end of bearing life.

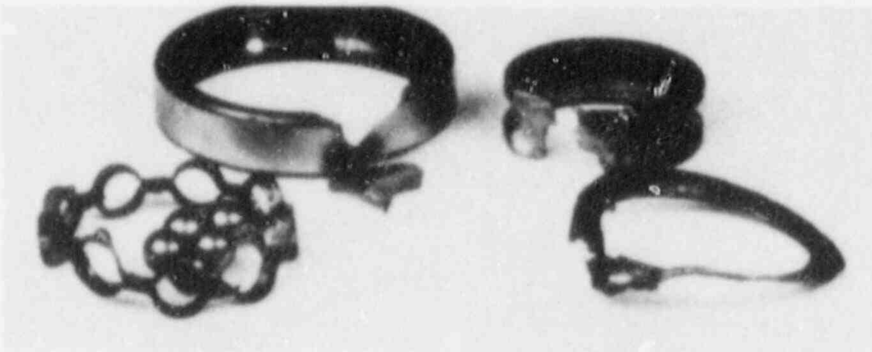


Figure 5.1 - Pulley end bearing after being removed because of noise (bearing came apart during disassembly).

After 3.79 million cycles, the stator was found to be grounded during the surge test at 1000 volts, as shown in Figure 5.3. Prior to the surge test, the motor passed the dc insulation resistance tests at all voltage levels. However, after the surge test the insulation resistance at 250 volts was 22 megohms (uncorrected) as compared to a previous test value of 180,000 megohms at a test voltage of 500 volts the stator was found grounded. Subsequent testing indicated that the failure site was where the conductors in the winding arced through the wedge to the stator iron. On examination, a pinhole was noted in a wedge, as indicated in Figure 5.4.

Based on the above test results, it is believed that the stator degraded at the failed wedge location. It is possible that weakened wedge on the Phase 2 winding at this location existed while performing the pre-surge test meggering. Therefore, this initial megger test did not indicate the ground short. During the surge test, a pinhole developed in the wedge which led to an arcing ground to the stator iron (see Figure 2.1, item 1) outside the wedge (see Figure 2.1, item 3). The point of wedge failure is illustrated in Figure 2.1 and is marked as item 6. After removing the surge voltage, the wedge still stood a meggering at 250 V which indicated good coil insulation resistance (i.e., greater than 2 megohms), but the insulation failed at the higher test voltage level because of stronger arcing which eventually burned the wedge and caused grounding.

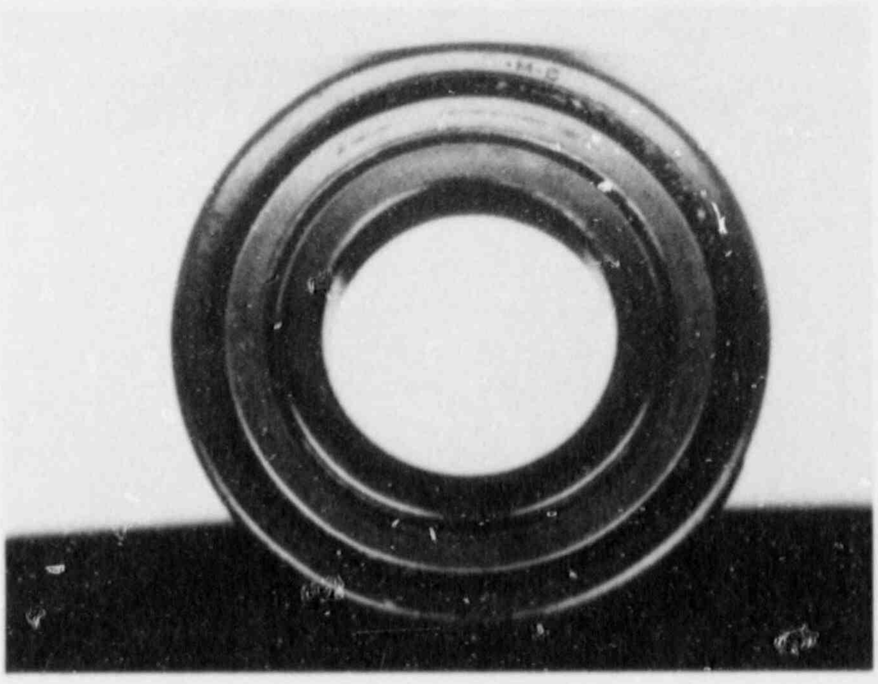
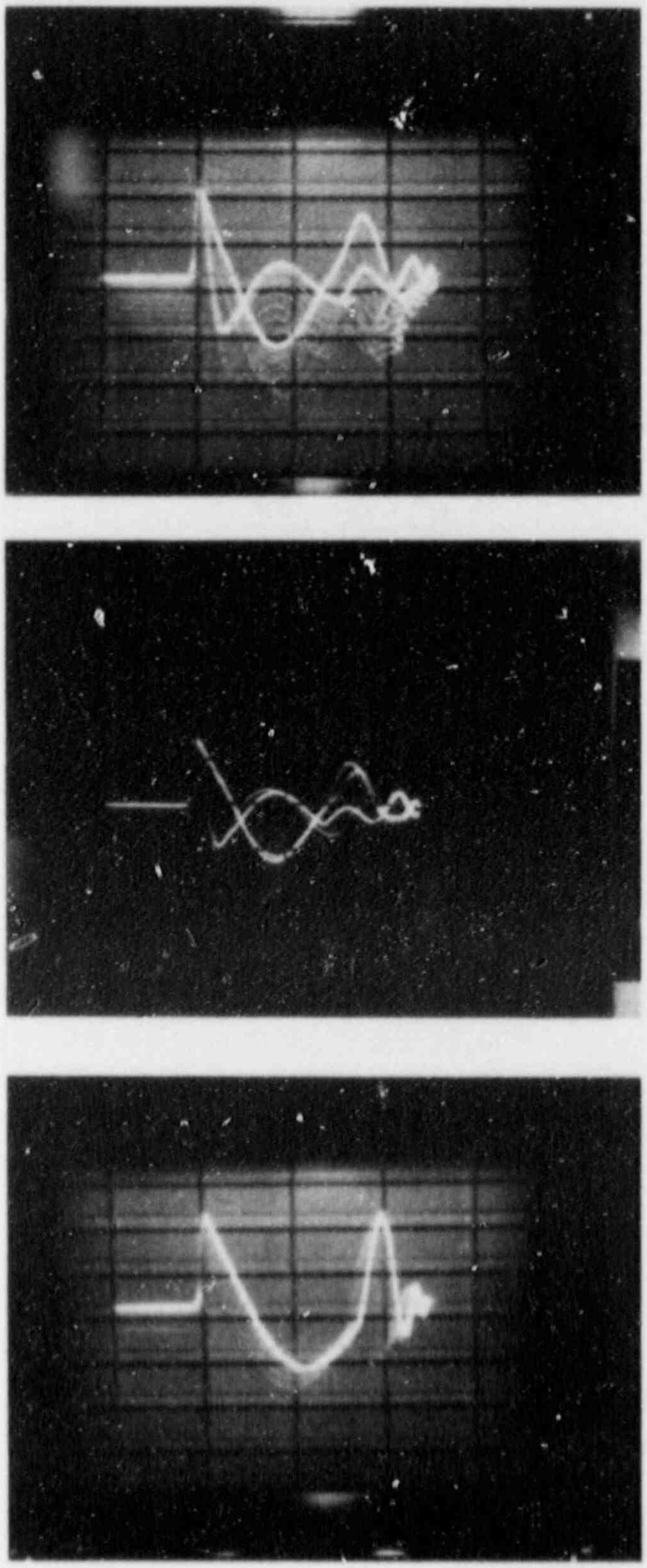


Figure 5.2 - Opposite pulley end bearing after being removed after test.



Phase 1-2

Phase 2-3

Phase 3-1

Figure 5.3 - Traces of surge test signals showing turn short in phase 2 (test voltage: 1000 volts).

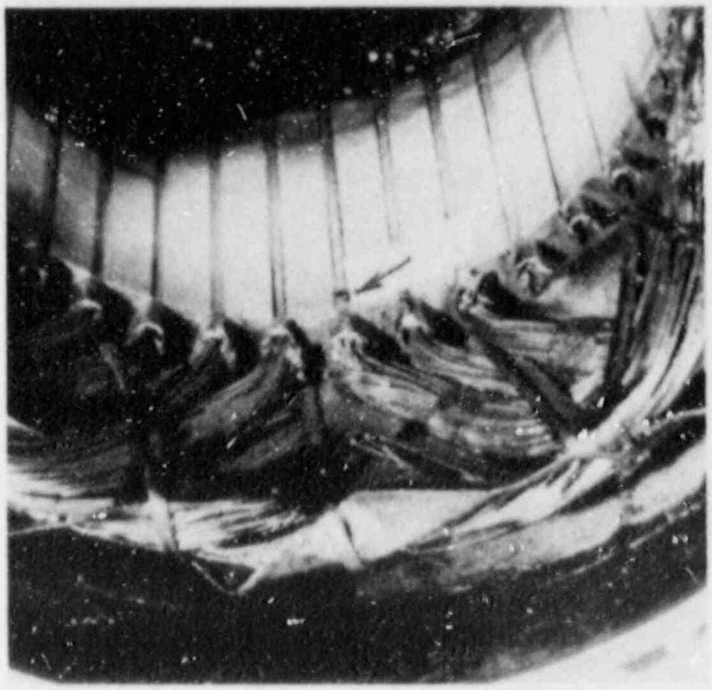
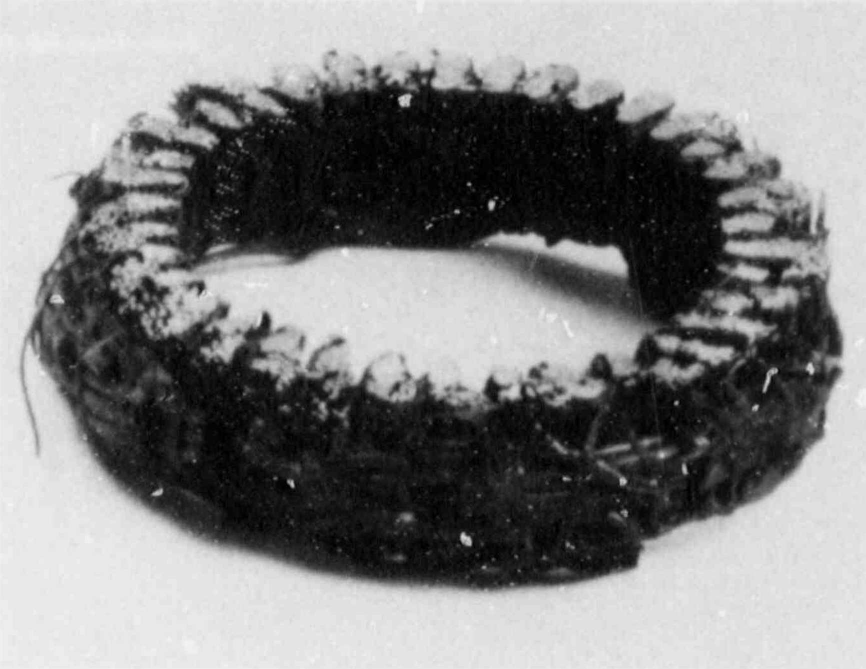
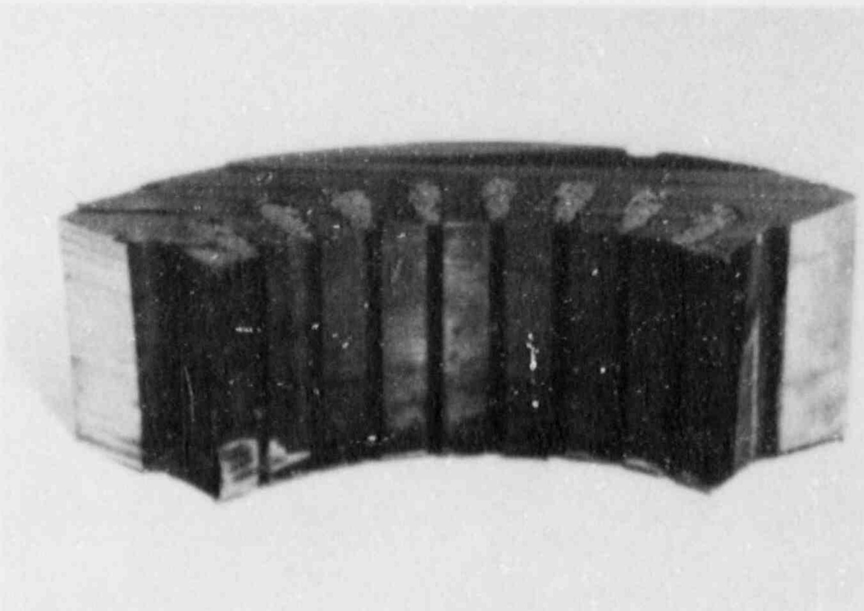


Figure 5.4 - Time exposure of the stator while being tested with a surge tester.

The stator was sectioned at the failure location to examine the slot insulation and wedges in the vicinity of the failure. Figures 5.5(a) and (b) show the sectioned stator. Further examination of the failed area revealed that the wedge damage was local. Figures 5.6(a) and (b) show a comparison between the damaged and undamaged coils. Examination of the failed wedge in the vicinity of the pinhole indicated a blackened area due to sparks and insulation burning, and the wedge was weakened with many smaller holes (i.e., perforations) around the damaged area.

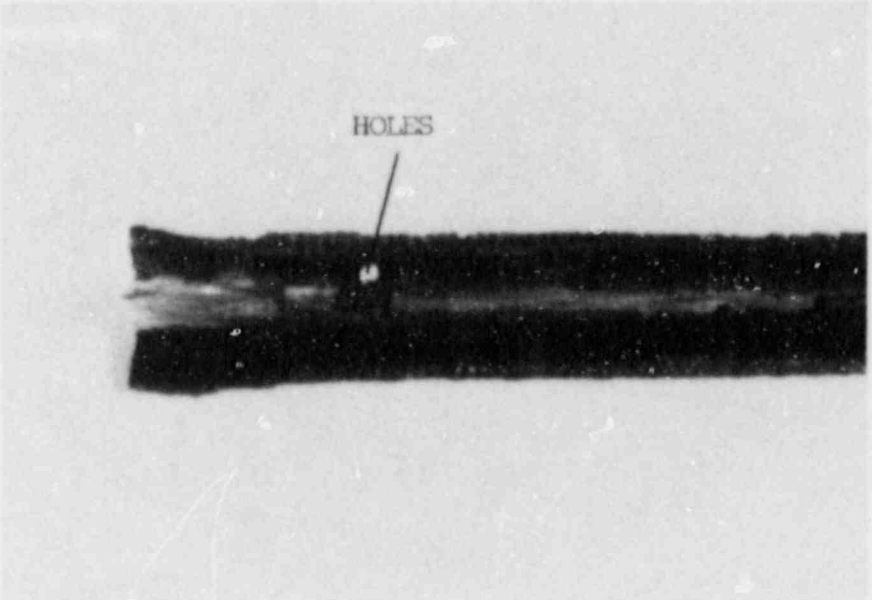


(a)

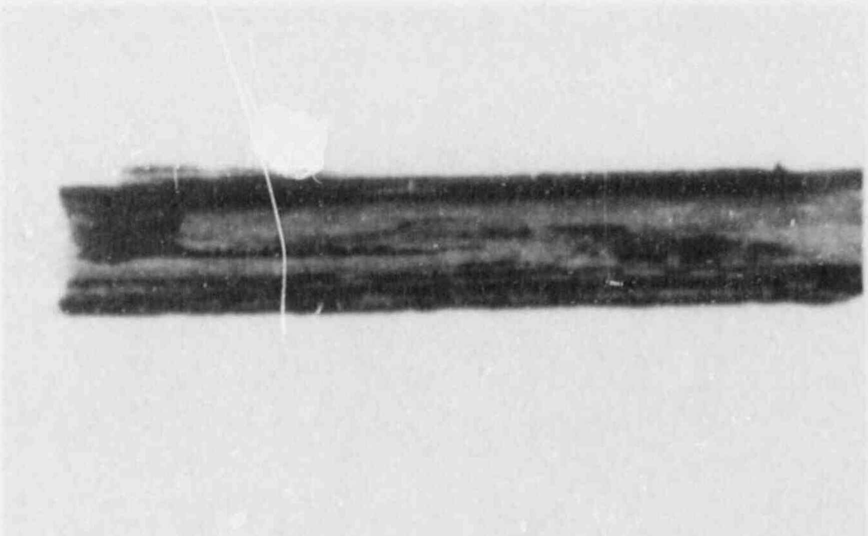


(b)

Figure 5.5 - Stator sections for investigating wedge degradations.



(a)



(b)

Figure 5.6 - Failed (a) and good (b) wedges from the failed stator.

6. CONCLUSIONS

The Plug Reverse Life Test [6] utilized in this test program was found to be a viable method of subjecting an electric motor to accelerated aging. This method allows control of the motor winding temperature by varying the reverse cycle frequency. The heat generated by the high starting current each time the motor is reversed maintains the winding at an elevated temperature and is preferred over the conventional oven approach. Since the motor is running, all the stresses normally present during motor operation are generated. When it reverses its direction of rotation, large cyclic mechanical loads are introduced on the bearings, stator assembly, and other mechanical components. Thus, while the accelerated thermal aging of the insulating system occurs, other motor subcomponents are also aged. It is, therefore, concluded that this method of accelerated aging of motors closely simulates the true operational conditions experienced during the normal life. The method is found suitable for laboratory testing and is recommended for motor qualification.

The motor condition monitoring test results obtained from this test program are discussed in the previous sections. Note that the results are from one test of this kind and caution should be taken in deriving conclusions on motor life estimation, design considerations, and other related findings. To obtain information for use in these areas, similar tests should be conducted on different sizes and types of motors with different kinds of insulating materials and bearing types.

6.1 Dielectric Insulation Resistance Tests

The dielectric insulation resistance tests include dc insulation resistance and polarization index tests. These tests are go/no go types of tests. They are essential for plant maintenance prior to motor startup after a long standby mode or before performing any high potential tests. These tests indicate the presence of insulation contaminants, specifically moisture. The dielectric resistance tests taken at 250, 500 and 1000 volts all showed trends of increasing resistance over the life of the test motor. All values were well above 1000 megohms, which is very high compared with typical levels of insulation resistance commonly used as indicators of performance in industry and IEEE Standard 43. The observed trend is attributed to the further curing of the epoxy resins that were applied prior to test initiation.

Polarization index is an average property (or characteristic) of an insulation material. It would not indicate the presence of cracks, voids, or other degradations. Results of the PI test performed for this study showed little change over the life of the test motor. Trending of this data for the subject motor winding provided little or no significant information on the insulation condition. This test is, therefore, not considered effective for monitoring aging degradation.

It is interesting to note that the polarization index averaged about 2.5, which is at the lower limit prescribed in IEEE Standard 43. This reflects a rapid charging, believed to be characteristic of dry non-contaminated epoxy resins.

As insulation aging proceeds, the material will become dry and harder. The insulation material will lose mechanical strength and become more susceptible to cracking. As cracking occurs, grounding paths could be established, leading to a decrease in the overall insulation resistance. This suggests that dc resistance could be an effective parameter for monitoring the age of the insulation by trending insulation resistance measurements. However, charging current effects on currently available meggers make it difficult to measure resistances accurately enough for trending purposes, particularly at high voltage potentials. Use of this parameter as an indicator for monitoring aging degradation is, therefore, not recommended at this time.

Considerable time was expended during the test in obtaining reproducible data at levels above 1000 megohms because of charging current problems. Improved megger equipment, which could eliminate charging current problems and other interferences, would reduce the time of testing and improve accuracy in determining insulation resistance during motor life. Compensation due to temperature of the motor, if any, must be considered in evaluating the test parameters.

6.2 Surge Testing

The surge test is a good method for detecting turn shorts, grounds, and improper or open connections. The test uses voltage signals for comparing phases in a motor or coils in a disassembled motor. The surge test can be best used on random wound motors, like the 10 hp test motor, which are rated for lower voltages and have less copper. The test will detect connection problems and imbalance between phases.

Surge testing is limited by the breakdown voltage of the insulation to ground. The voltage across the turns in a large high voltage motor is greatly reduced and the surge test may not detect failures.

Results of the surge testing performed for this study showed no turn shorts until the insulation finally failed. The failure, which occurred at a wedge, was then detected by the surge test after the winding had passed a megger test. This demonstrates the additional predictive accuracy obtained by performing surge testing in addition to simple meggering.

Although this test has limitations for large motor applications, it can be used in rewind/repair shops for all types of motors where complete motor or individual coils can be tested. With the equipment currently available, surge testing does not lend itself to trending for age degradation monitoring and it is not recommended for that purpose. The development of digital equipment for storing wave forms will enhance the use of the surge tester in maintenance programs.

6.3 Ac Dissipation Factor and Capacitance Tests

The dissipation factor and capacitance tests show the effects of voids, cracks and thinning of insulation. Both of these tests are recommended for maintenance programs. In addition to evaluating existing insulation condition, it is felt that test results can be trended to monitor aging degradation. This was not, however, demonstrated in this test program. Both dissipation factor and capacitance were shown to have a downward trend, indicating an improvement in insulating properties. This is believed to be due to curing of the new insulation applied prior to testing and is consistent with other test results. However, in actual applications where insulation has sufficiently cured prior to operated, it is expected that changes in both dissipation factor and capacitance would be experienced as aging progresses.

6.4 Ac Partial Discharge Tests

The tests gave the best indication of insulation deterioration. Over the life of the motor tested for this study, the inception voltage fell from approximately 1100 to 800 volts showing that there was increasing partial discharge across the insulation to ground. This was an indication of insulation degradation. The post-mortem of the subject motor winding determined that discharges at the degraded wedge caused the motor to fail. The partial discharge inception voltage trend was found to support this final failure diagnosis. Therefore, this test is considered to be a good test for monitoring insulation condition.

This is a difficult test to perform on low voltage motors because of noise levels and the sensitivity of the test equipment. To get adequate results, a plotter had to be used to amplify the output of the tester. To use this test as part of a maintenance program on small low voltage motors, more sensitive equipment is needed which includes better means of detecting partial discharge (corona) inception voltage. The plotter approach used in the 10 hp test program appears to be a good way to record the discharges and determine the inception voltages.

6.5 Ac/Dc Leakage Current Test

These tests showed little change in leakage current over the life of the motor. This is primarily due to the difficulty in measuring the extremely small currents present. If the ac voltage is raised to a level where differences can be noted, the test could be destructive. Ac hi-pot testing is best used in repair shops or by the manufacturer to establish the insulation endurance at the breakdown voltage. These tests are not recommended for regular maintenance of electric motors.

Dc leakage current test is a high voltage dc test similar to the insulation resistance test in which case the resistance of the insulation is measured instead of the leakage current. This current becomes significant once the condition of the insulating material is severely degraded with holes, cracks or contaminants. In this test program, this functional indicator remained small throughout the test period and did not indicate any sign of insulation degradation. Since this test involves high potential level, this should be performed by increasing the test potential in steps and in no case should exceed the insulation breakdown voltage.

6.6 Dc Winding Resistance Tests

The winding resistance test is primarily used in a maintenance program to detect shorted turns, broken wires or open connections. When taking resistance values, temperature must be considered. In the 10 hp motor study, little or no change was detected in winding resistance as the motor aged. Trending of this parameter is, therefore, not felt to be an effective means of monitoring aging degradation.

6.7 Winding End Turns Movement

This is a good parameter to monitor for maintenance programs if it is possible to put sensors (strain gages or accelerometers) on the motor end turns. Further development of sensors may be required.

On the 10 hp motor, no movement was detected because the epoxy vacuum impregnated end turns did not move or soften at high temperatures. At the end of the test its structure was still rigid, which is typical of aged epoxy structures. If the insulation treatment involved polyester or silicons, which soften at high temperatures, movement probably would have been recorded and could have led to a turn failure.

6.8 Bearing Noise and Vibration Test

This test is essential to a maintenance program for measuring the condition of the bearings. As seen from the 10 hp motor, bearing failures are preceded by increased noise and vibration. Bearing noise is a primary indication of bearing degradation; however, it does not provide sufficient information for establishing the degree of bearing damage. Vibration monitoring including bearing velocity and displacement is useful for this purpose. Trending of this parameter is possible and is recommended for monitoring bearing degradation.

6.9 Bearing Grease

Analysis of aged grease from the motor showed the presence of wear metals (irons and nickel), which are not present in fresh grease. This suggests that the grease analyses could be used to trend wear metal concentrations. After establishing a normal wear metal deposition rate, corresponding to normal bearing wear, abrupt changes in the deposition rate could indicate incipient bearing failure. However, this was not demonstrated in this test program. This test analysis of grease samples should be considered in the maintenance programs.

6.10 No Load Motor Running Current

Motor running current plots are useful for a maintenance program to detect changes in the magnetic circuits in the motor and changes in the winding due to broken or shorted wires and charges in the connection. In order to obtain consistent results, the input voltage must be controlled at a constant level. As evidenced from the results of this study, running current provides little information for monitoring aging degradation.

7. REFERENCES

1. Subudhi, M., Burns, E. L., Taylor, J. "Operating Experience and Aging-Seismic Assessment of Electric Motors", NUREG/CR-4156, June 1985.

2. Subudhi, M. et al., "Improving Motor Reliability in Nuclear Power Plants: Performance Evaluation and Maintenance Practices", NUREG/CR-4939, BNL-NUREG-52031, Volume 1, June 1987.

3. Sugarman, A.C., et al., "Testing Program for the Monitoring of Degradation in a Continuous Duty 460 Volt, Class B, 10 hp Electric motor," BNL-Technical Report A3270-3-86, March 1986.

4. Discussions with J. Craig of Epoxylite Corp., Irvine, CA on September 3, 1986.

5. Discussions with D. Wetzel of Westinghouse, Pittsburgh, PA on October 16, 1986.

6. Crawford, D.E., "A Mechanism of Motor Failures," IEEE Transaction, pp. 126-129.

7. Rene Seeberger, "Capacitance and Dissipation Factor Measurement", IEEE Electrical Insulation magazine, 2 (1) 27-36 (1986).

8. ANSI/IEEE Std. 43-1974, "IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery", sponsored by the Rotating Machinery Committee of the Institute of Electrical and Electronics Engineers, (IEEE) Power Engineering Society and published by the IEEE.

9. M. Olyphant, Jr., "Effects of Cure and Aging on Dielectric Properties", Committee on Education Supplement of the Proceedings of the Sixth Electrical Insulation Conference, pp, 12-19, Sept. 13-16, 1965. Co-sponsorship was by The Institute of Electrical and Electronics Engineers (IEEE), The National Electrical Manufacturers Association (NEMA) and The Department of the Navy-Bureau of Ships.

10. Vladimir Adamec, "Electrical Properties of an Epoxy Resin During and After Curing", J. Polymer. Sci., Part A-1, Vol. 10, pp 1277-1295 (1972).

11. John Delmonte, "Electrical properties of Epoxy Resins During Polymerization", J. Appl Polymer Sci. II, 4, pp. 108-113 (1959).

12. A. H. Sharbaugh, "Dc Conduction in Polymeric Insulation", Proceedings of Fourth Electrical Insulation Conference, pp. 81-82, Washington, D.C. (1962).

13. R. W. Warfield and M. C. Petre, "Electrical Resistivity of Polymers", SPE Trans. pp. 80-85, April, 1961.

14. R. W. Warfield and M.C. Petre, "A Studv of the Polymerization of Thermosetting Polymeres by Electrical Resistivity Techniques", SPE Transactions, Vol. 1, No. 1, pp. 3-8, Jan., 1961.

15. "High Voltage Measurement, Testing and Design" by T.J. Gallagher and A.J. Pearmain. John Wiley & Sons, New York (1983).

APPENDIX A

Small Motor Test Equipment for Monitoring Motor Integrities

APPENDIX A

MOTOR TEST EQUIPMENT

Descriptions of each piece of test equipment utilized in the test program are discussed in this appendix.

A.1 Dc Insulation Resistance Tester

The insulation resistance and polarization index were measured with a battery-powered, Biddle Model RM 290 Sullivan Megohmmeter Type T2900 (Figure A-1). The instrument had four test voltages (100,250, 500 and 1,000) and a resistance range of 10^{15} to 10^{12} ohms in 8 Ranges. The current range is 100 pA to 1 mA in 8 ranges. The test voltages are selected by push button giving four discrete values. The accuracy of the instrument in the range 10^{5} to 10^{12} ohms is $\pm$ (2+ scale reading)%. At 10^{14} ohms the accuracy is $\pm$ (4+ scale reading)%.

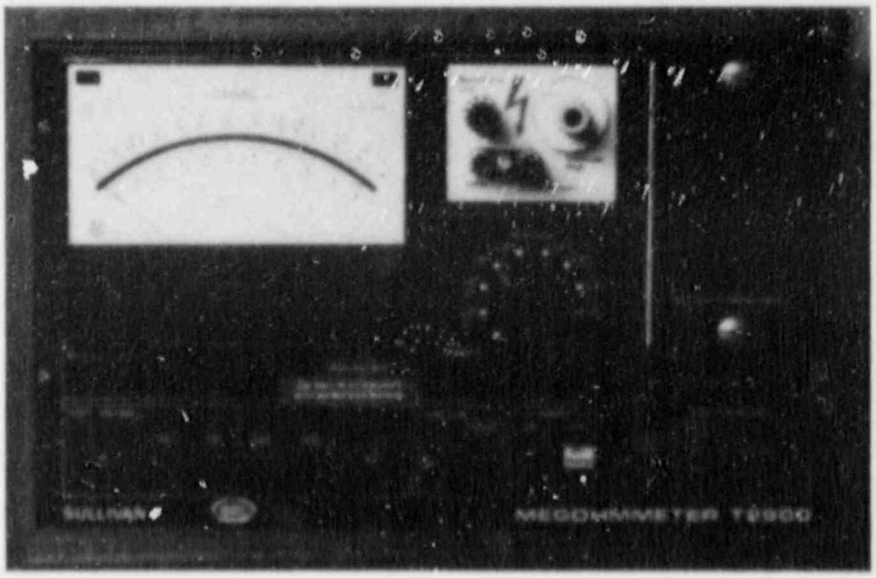


Figure A.1 - Biddle Model RM 2900 Sullivan Megohmmeter.

A.2 Ac Dissipation Factor Capacitance Test Set

The dissipation factor and capacitance were measured with a Biddle Model 670025 Capacitance and Dissipation Factor Test set shown in Figure A-2. In addition to these two test parameters, the test equipment provides the ac leakage current measurements at various applied voltages. The maximum test voltage this test equipment can provide is 2.5 kV. The dissipation factor is displayed in digital form in percentage, where the capacitance values are obtained by balancing the capacitance bridge and expressed in pF (picoFarad). The ac leakage current is read in digital form in milliamperes.

A.3 Ac Partial Discharge Test Set

The inception and extinction voltages for partial discharge were measured with Biddle Model 661072 Partial Discharge System. The system required a primary voltage of 120V ac, at 60 hz and 5 amps maximum with 3-wire grounding. The system included a model 17000 partial discharge detector, digital kilovoltmeter panel assembly, partial discharge digital evaluation unit, phase-sensitive noise blanker, ground cable assembly, power separation filter and a calibration signal coupler. This system required an electrical noise filter which was provided by Wendell Starr. The arrangement of the test set up for the systems is shown in Figure A.3. To measure partial discharge (corona), a high potential tester must be used along with the partial discharge tester. The partial discharge tester only shows the corona discharge from ac high potential test. For a high potential voltage, the ac dissipation factor/capacitor test set was used. For output from the partial discharge tester, the Hewlett Packard 7015B X-Y recorder shown in Figure A.4 was used. Figure A.5 (a) and (b) show the Biddle parts of the partial leakage tester.

Figure A.2 - Biddle Model 670025 Capacitance and Dissipation Factor Test Set.

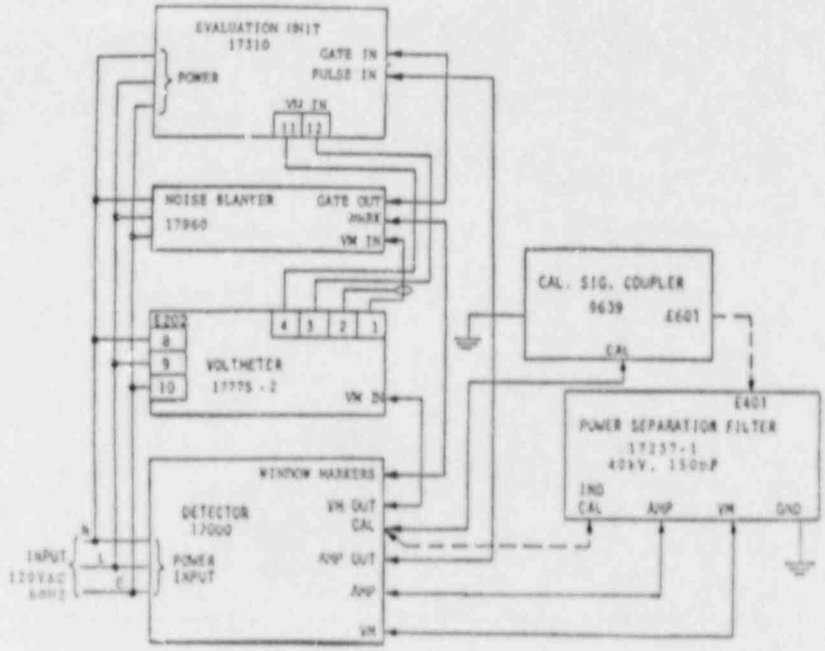


Figure A.3 - Schematic of the partial discharge test setup.

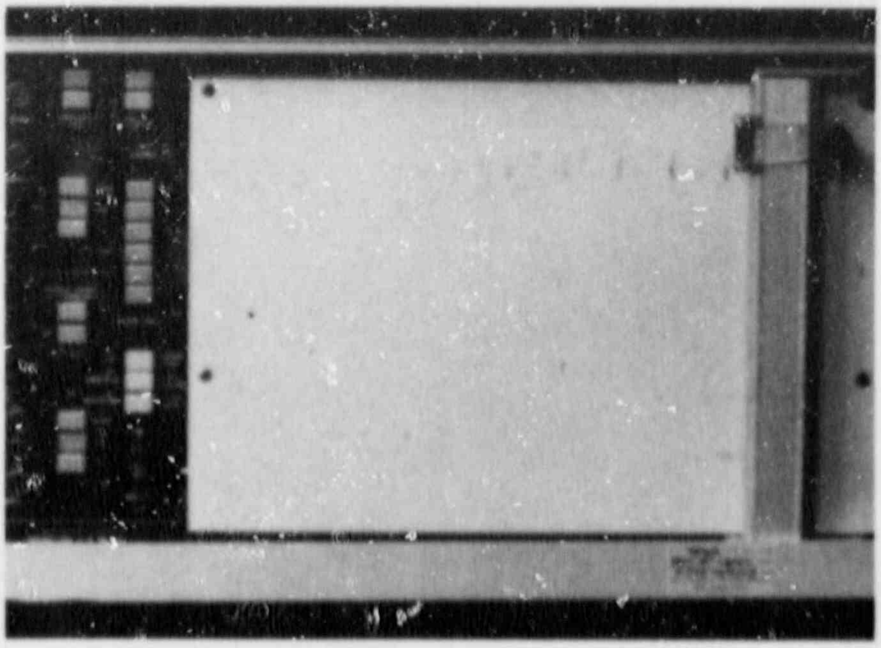


Figure A.4 - Hewlett Packard 7015 X-Y Recorder.

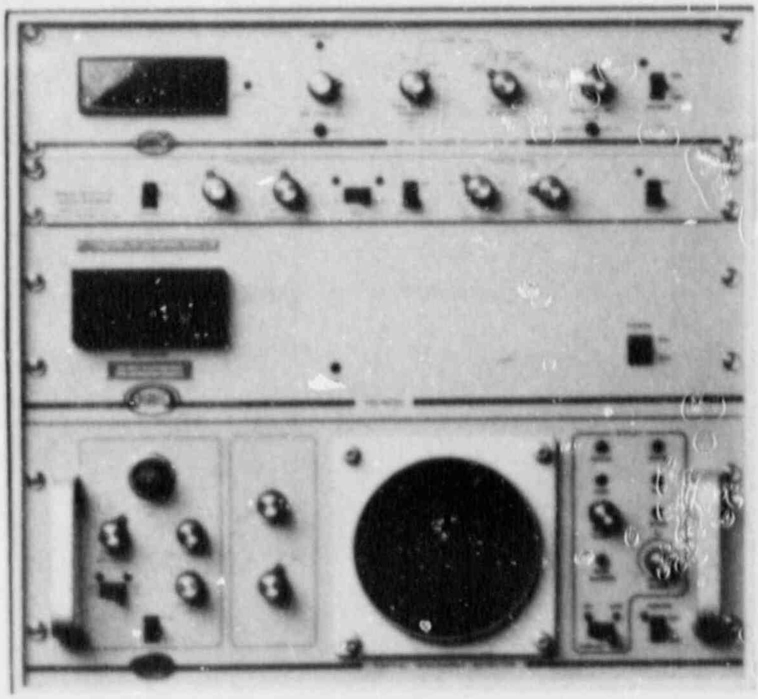


Figure A.5 (a) - Biddle Model 661072 Partial Discharge Tester.

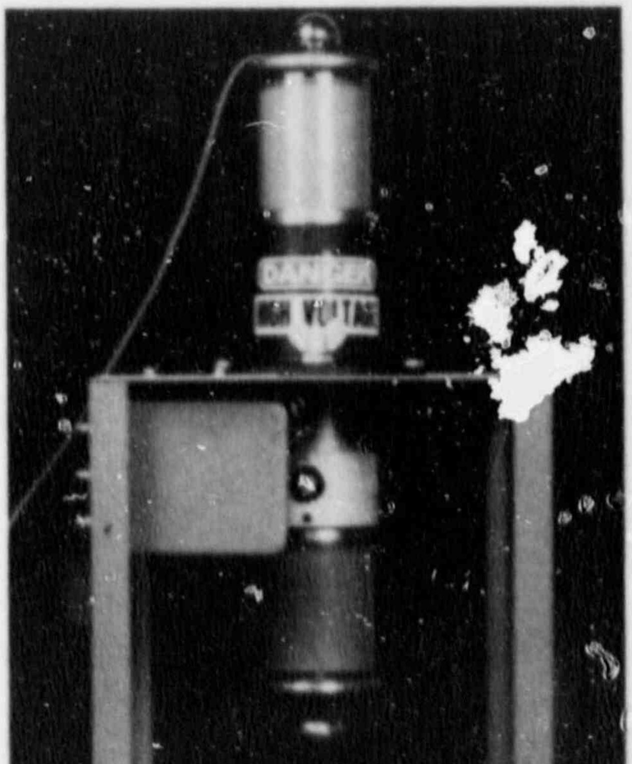


Figure A.5 (b) - Biddle Power Separator Filter.

A.4 Surge Test Winding Dielectric Tester

Surge testing of the stator windings was performed with a Baker Model ST106 Winding Dielectric Tester as shown in Figure A.6. This tester has the capabilities of both surge testing and dc hipot testing with a maximum test voltage of 5000 volts. The built-in oscilloscope on the unit displays the voltage wave forms for the two coils or phases being compared for winding defects. If the wave patterns diverge, then the two phases are not identical and a fault exists in one or both of the phases. If the fault is intermittent, then the wave patterns on the CRT will flicker and change.

The test was performed much like a step voltage test with a dc hipot. The applied voltage was raised slowly while the wave patterns on the CRT were observed for any sign of a change or fault. If the wa e patterns remained stable up to about 2600 volts [i.e.(2x460+1000)1.6], then the winding exhibited sufficient turn-to-turn and phase-to-phase dielectric strength to remain in service. If the wave patterns became unstable below this level, then some weakness was expected in the turn-to-turn, coil-to-coil, or phase-to-phase insulation.

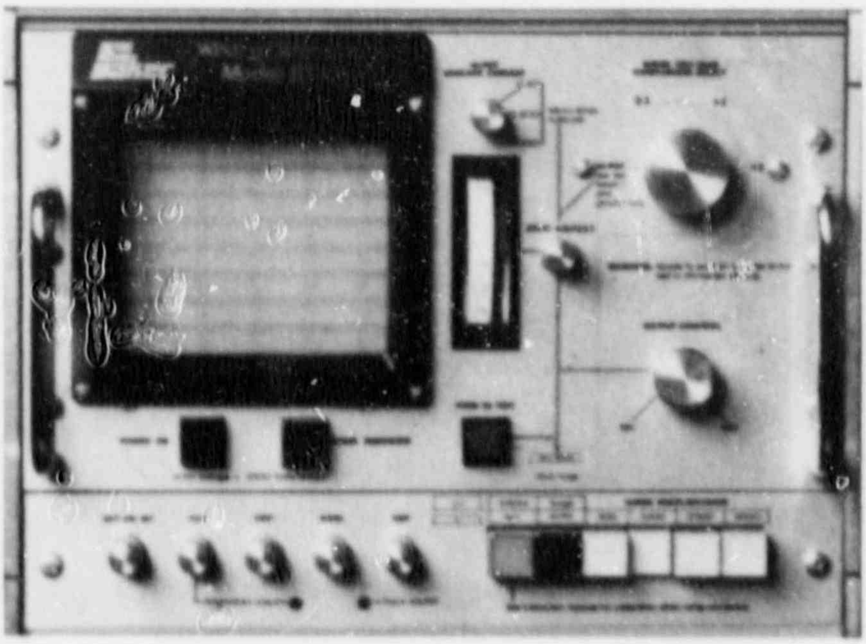


Figure A.6 - Baker Instruments Model ST106 Surge Tester

A.5 Ac/Dc Hipot Tester (Ac Current Leakage Test)

The ac/dc leakage current tests were conducted with the Hipotronics Model H303B ac/dc Hipot Tester as shown in Figure A.7. Since ac hipot test can be destructive at a high test voltage level, this test was performed less frequently than other tests.

A.6 Dc Winding Resistance

The resistance of the motor windings was measured with a Biddle Model 72-430 Wheatstone Bridge as shown in Figure A.8. This instrument has a range of 0.1 ohms to 11.1 megohms in 7 ranges when used as a bridge, and from 0 to 11,110 ohms when used as a resistance box. The limits of error as a resistance box (which is the way it was used for this work) are ± (0.05% of reading + 0.2 ohms).

A.7 Motor Running Current

The average motor running current during cycling was measured with a digital clamp-on ammeter. A continuous recording of the motor running current during cycling was obtained over several cycles using a high speed recorder manufactured by Brush Instruments Company and is shown in Figure A.9

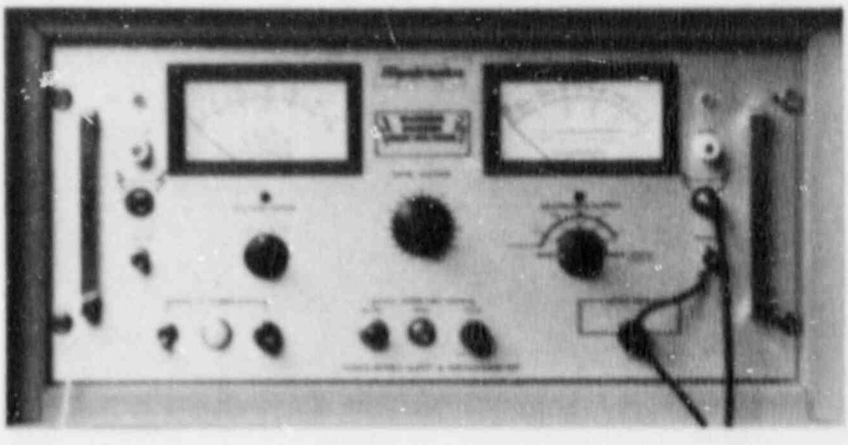


Figure A.7 - Hipotronics Model #303B Ac/Dc Hipot Tester.

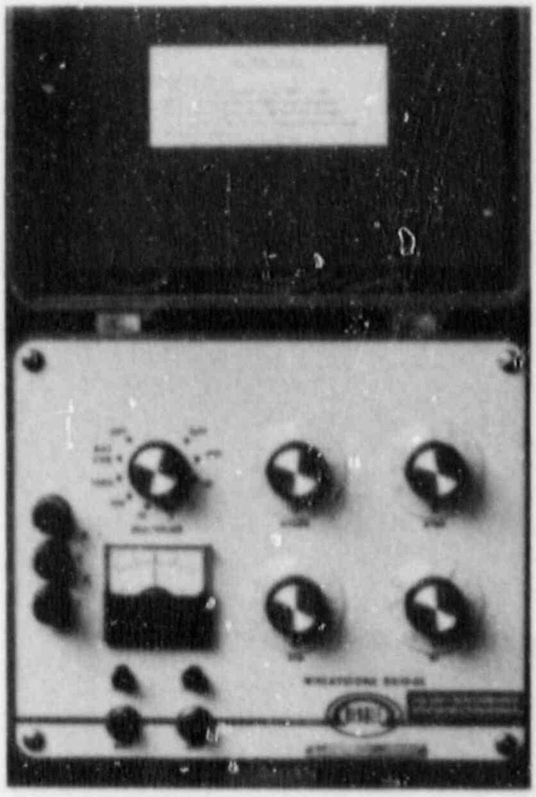


Figure A.8 - Biddle Model 72-430 Wheatstone Bridge used for testing the winding resistance.

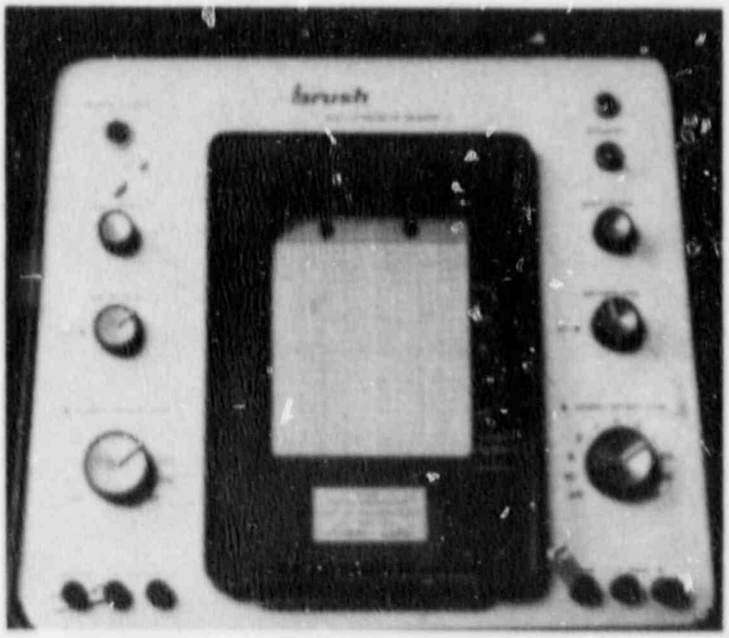


Figure A.9 - Brush instruments high speed recorder for recording the 60 cycle motor running current.

A.8 Winding End Turn Movement

While the motor was running continuously, the signal from the accelerometers epoxied to the end turns of the motor was processed in a Model 2512 GenRad spectrum analyzer, as shown in Figure A.10. This analyzer is a one-channel spectrum analyzer using digital Fast Fourier Transform (FFT) techniques for high-speed narrowband analysis of the frequency content of analog or pre-digitized input signals. It resolves the input into 400 frequency lines (or filters) equally spaced across selectable analysis ranges from 10 Hz up to 100 Hz. The g-Hz (which is the product of acceleration and frequency) was plotted on a Hewlett Packard plotter and is shown in Figure A.4.

A.9 Bearing Noise and Vibration

Bearing noise and vibration was measured with a Model 308 Vibration-Sound meter and a Model 544 Vibration Probe manufactured by IRD Mechanalysis, Inc. as shown in Figure A.11

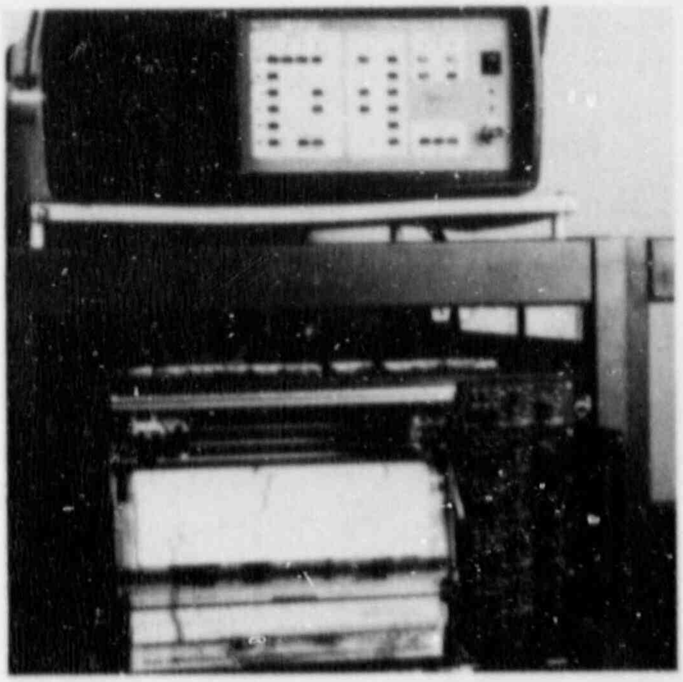


Figure A.10 - Omego ten channel temperature recorder with GenRad Model 2512 spectrum analyzer on top.

A.10 Motor Winding and Bearing Temperature

The thermocouples on the end turns of the winding and the bearing were recorded on an Omega Ten Channel Temperature Recorder shown in Figure A.10.

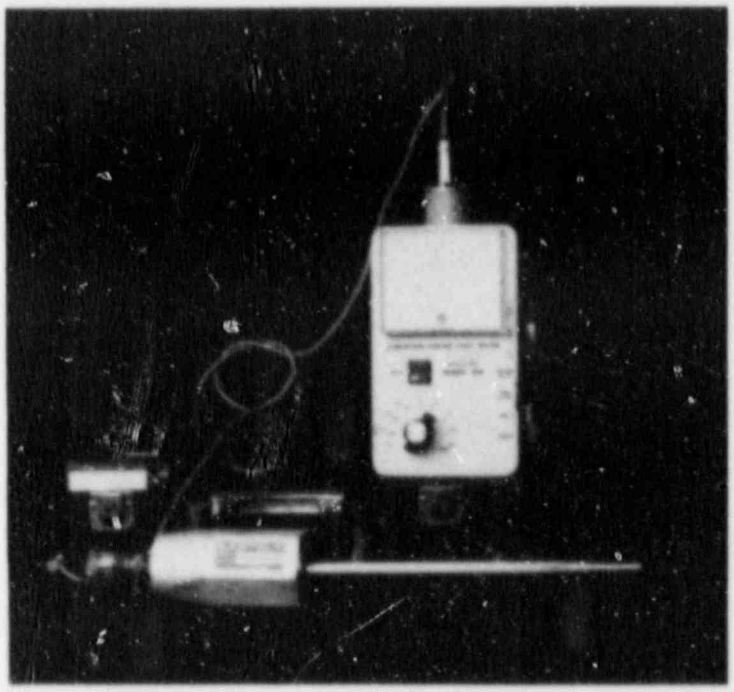


Figure A.11 - IRD Mechanalysis Model 308 vibration-sound meter.

APPENDIX B

Analysis of Zeniplex R-2 Grease Used in the Test Motor Bearings

TECHNICAL SERVICE REPORT

KEYSTONE
PENNWALT
CHEMICALS ■ EQUIPMENT
HEALTH PRODUCTS
21ST AND LIPPINCOTT STREETS, PHILADELPHIA, PA 19132 U.S.A.

DATE January 12, 1987

For: NAME & TITLE Mr. Alfred Sugarman

COMPANY Nutech

STREET ADDRESS 145 Martinvale Lane

CITY San Jose STATE California ZIP CODE 95119

Analysis of USed Zeniplex-2 Lubricating Grease

Two samples of lubricating grease were analyzed. The greases were labeled OPE & PE. Spectrochemical analysis of both samples reveals lower values for elements representative of Zeniplex grease (i.e. aluminum, phosphorus, zinc & barium). Ferrous wear and airborne abrasive contamination were also present in moderate to high amounts. Dropping point values show them to be typical for normal Zeniplex. All elements are in parts per million.

	Nutech OPE	Nutech PE	Zeniplex-2 Typical
Aluminum: (Thickener)	640	2020	2500
Phosphorus: (Additive)	190	370	1000
Zinc: (Additive)	150	950	750
Barium: (Additive)	50	180	750
Iron: (Wear Metal)	110	250	nil
Silicon: (Airborne Contamination)	50	790	nil
Dropping Pt. °F: (ASTM D-2265)	470	474	440-480

P.R. Kanga

Percy R. Kanga
Chemist, Product Development

PRK/mp

TSR #5149

cc: S. Arbocus
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TECHNICAL SERVICE REPORT

KEYSTONE
PENNWALT
CHEMICALS ■ EQUIPMENT
HEALTH PRODUCTS
21ST AND LIPPINCOTT STREETS, PHILADELPHIA, PA 19132 U.S.A.

DATE April 16, 1986

For: NAME & TITLE Mr. Alfred Sugarman

COMPANY Nutech

STREET ADDRESS 145 Martinvale Lane

CITY San Jose STATE California ZIP CODE 95119

Analysis of Used Zeniplex[R]-2 Grease

Three samples of lubricating grease (one unused and two taken from a bearing on the pulley end of a motor), were analyzed. The greases were labeled Unused, Inboard Side Pulley End, and Grease Housing Pulley End.

Spectrographic analysis on all three products shows varying results. The unused sample as expected, indicates all the additive and thickener levels to be at or above the typical concentrations. The Inboard sample shows the virtual absence of all the abovementioned elements while the Pulley sample shows most of these elements to be present but at levels far below normal. The Pulley sample also exhibits abnormal levels of iron and nickel wear. A check of the dropping points of these greases (an approximate measure of their thermal stability) indicates all three samples to show aluminum complex grease type results. It is also possible that the absence of elements normally found in Zeniplex (as seen in the inboard sample) may also mean that this grease may not be Zeniplex.

		ZENIPLEX Nutech-Unused	ZENIPLEX Nutech-Inboard	ZENIPLEX Nutech-Pulley	ZENIPLEX Typical
Aluminum	(Thickener)	2200	60	730	2500
Phosphorus	(additive)	2000	0	300	1000
Zinc	(additive)	1700	40	200	750
Barium	(additive)	500	0	0	750
Iron	(wear metal)	—	40	850	nil
Nickel	(wear metal)	—	0	290	nil
Dropping Pt., °F, ASTM D-2265		475	461	492	440-480

P.R. Kanga

Percy R. Kanga
Chemist, Product Development

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TSR: #4958

TECHNICAL SERVICE REPORT

KEYSTONE
PENNWALT
CHEMICALS ■ EQUIPMENT
HEALTH PRODUCTS

21ST AND LIPPINCOTT STREETS, PHILADELPHIA, PA 19132 U.S.A.

B-5

DATE September 21, 1986

For: NAME & TITLE Mr. Alfred Sugarman

COMPANY Nutech

STREET ADDRESS 145 Martinvale Lane

CITY San Jose, STATE California ZIP CODE 95119

Analysis of Used Zeniplex ^{R}-2 Grease

Four samples of lubricating grease were analyzed. The greases were labeled OPE Outboard, OPE Inboard, PE Inboard, and PE Outboard. Spectrochemical analysis on all four samples shows varying results, as shown below.

OPE OUTBOARD: Except for barium, we found the elements that are supposed to be present in Zeniplex-2. Wear metals such as iron and nickel were also found. Calcium, an additive element not formulated into Zeniplex-2, was also present. Silicon may either be due to dirt, or may be due to another lubricant.

OPE INBOARD: All Zeniplex type elements are present, but at lowered amounts. There was evidence of high iron & nickel wear. Calcium & silicon were both found again, but at increased levels.

PE INBOARD: All Zeniplex type elements were absent. Low levels of iron & tin wear were found. Some calcium was also present. This does not appear to be Zeniplex grease.

PE OUTBOARD: Aluminum and phosphorus were present but zinc and barium were not. Some iron wear was present. Calcium (not found in Zeniplex) was again present.

A check of the dropping points of these greases (an approximate measure of their thermal stability) indicates values far below that of Zeniplex-2. It is also possible because of the absence of elements normally found in Zeniplex (as seen in the PE INBOARD sample), that this grease may not be Zeniplex. All elements are in parts per million.

		ZENIPLEX OPE OUTBOARD	ZENIPLEX OPE INBOARD	ZENIPLEX PE INBOARD	ZENIPLEX PE OUTBOARD	ZENIPLEX TYPICAL
Aluminum	(Thickener)	1250	1830	30	940	2500
Phosphorus	(additive)	500	700	0	300	1000
Zinc	(additive	300	500	0	0	750
Barium	(additive)	0	200	0	0	750
Iron	(wear metal)	380	760	30	60	nil
Nickel	(wear metal)	30	70	0	0	nil
Calcium	(additive)	200	300	200	100	nil
Silicon	(airborne contamination)	90	180	20	0	nil
Tin	(wear metal)	0	0	30	0	nil
Dropping Pt., °F	(Astm D-2265)	375	359	Insufficent sample	383	440-480

Percy R. Kanga

PERCY R. KANGA
CHEMIST, PRODUCT DEVELOPMENT

PRK/ms
SR: #5055

cc: G. Arbocus

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A ten shorespower electric motor was aritifically aged by plug reverse cycling for test purposes. The motor was manufactured in 19[illegible] and was in service at a commercial nuclear power plant for twelve years. Various tests were performed on the motor throughout the aging process. The motor failed after 3.79 million reversals (3 seconds per reversal) over seven months of testing. Each test parameter was trended to assess its suitability in monitoring aging and service wear degradation in motors. Results and conclusions are discussed relative to the applicability of the tests performed to nuclear power plant motor maintenance programs.

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