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VOLUME 1

IMPROVING MOTOR RELIABILITY IN NUCLEAR POWER PLANTS

VOLUME I: PERFORMANCE EVALUATION AND MAINTENANCE PRACTICES

M. Subudhi, W.E. Gunther, and J.H. Taylor

A.C. Sugarman and M.W. Sheets
Nutech Engineers

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ENGINEERING TECHNOLOGY DIVISION
DEPARTMENT OF NUCLEAR ENERGY, BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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M. Subudhi, W.E. Gunther, and J.H. Taylor
Engineering Technology Division
Brookhaven National Laboratory
Upton, New York 11973

A.C. Sugarman and M.W. Sheets
Nutech Engineers
San Jose, California 95119

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ABSTRACT

This report constitutes the first of the three volumes under this NUREG. The report presents recommendations for developing a cost-effective program for performance evaluation and maintenance of electric motors in nuclear power plants. These recommendations are based on current industry practices, available techniques for monitoring degradation in motor components, manufacturer's recommendations, operating experience, and results from two laboratory tests on aged motors. Two laboratory test reports on a small and a large motor are presented in separate volumes of this NUREG. These provide the basis for the various functional indicators recommended for maintenance programs in this report.

The overall preventive maintenance program is separated into two broad areas of activity aimed at mitigating the potential effects of equipment aging: Performance Evaluation and Equipment Maintenance. The latter involves actually maintaining the condition of the equipment while the former involves those activities undertaken to monitor degradation due to aging. These monitoring methods are further categorized into periodic testing, surveillance testing, continuous monitoring and inspections.

This study focuses on the methods and procedures for performing the above activities to maintain the motors operationally ready in a nuclear facility. This includes an assessment of various functional indicators to determine their suitability for trending to monitor motor component condition. The intrusiveness of test methods and the present state-of-the-art for using the test equipment in a plant environment are discussed.

In conclusion, implementation of the information provided in this report, will improve motor reliability in nuclear power plants. The study indicates the kinds of tests to conduct, how and when to conduct them, and to which motors the tests should be applied. It should be noted that the recommendations and conclusions provided in this report are based on research findings, and as such should not be construed as regulatory or statutory requirements for motors in nuclear power plants.

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PREFACE

For all practical purposes this NUREG, comprising three volumes, completes the Nuclear Plant Aging Research (NPAR) program study of electric motors in nuclear applications. The results of the Phase I study were issued in June 1985 as NUREG/CR-4156. This NUREG addresses the results of the Phase II work. Volume 1 of this NUREG describes various motor test methods and includes recommendations for their use. Volume 2 describes the results of a small motor test performed to evaluate functional indicators, and volume 3 contains an analysis and a diagnostic test on the stator windings of a large motor.

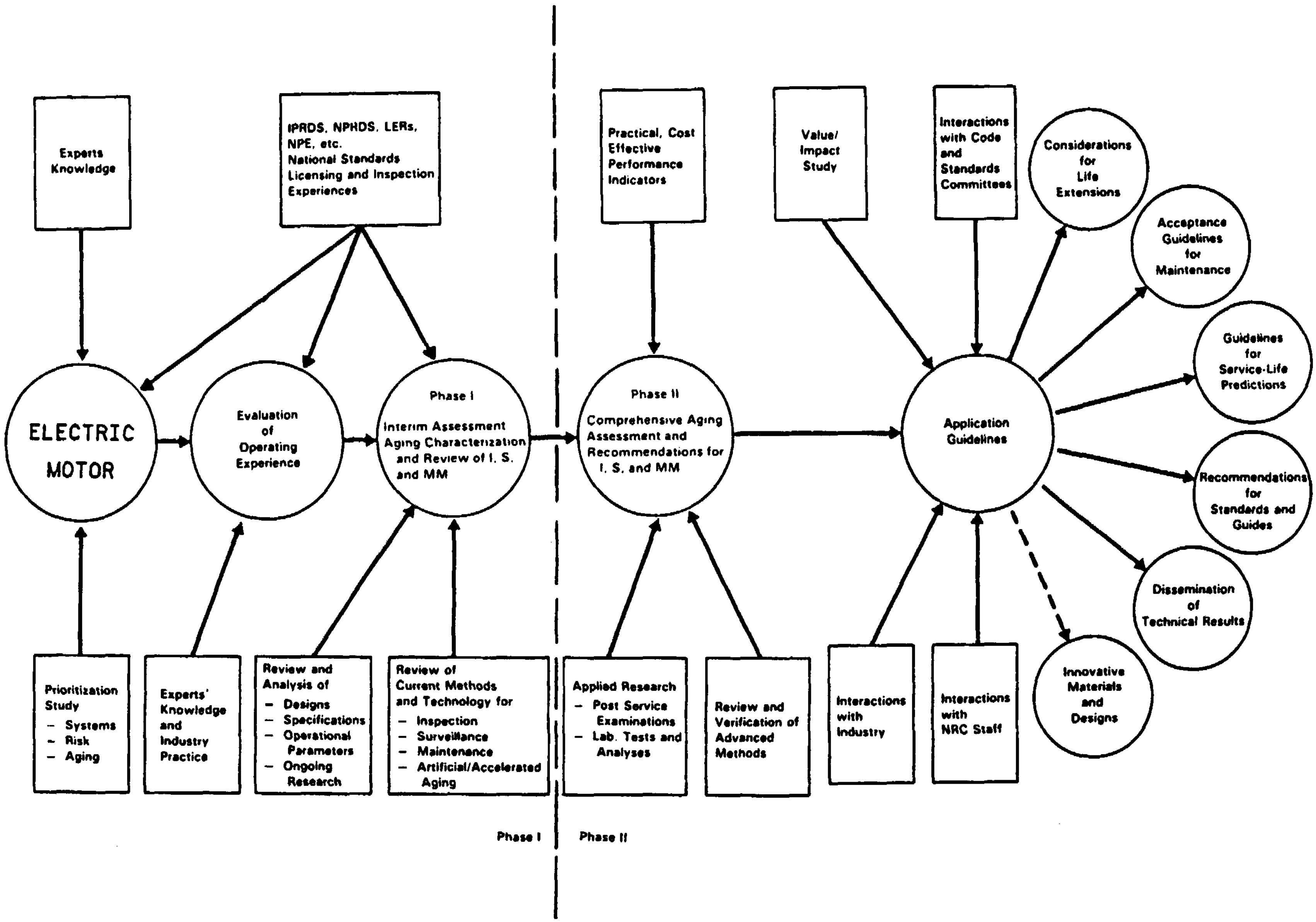
Recommendations provided in this report are based on the large body of work completed in Phase I, consultations with experts in the field, and the two series of motor tests conducted in Phase II. The authors feel the results are sound and worthy of implementation. Conclusive verification of these recommendations can only be achieved by in situ application. Therefore, it is hoped that the nuclear industry will develop pilot programs implementing the recommendations embodied in this work.

This is the first complete aging assessment conducted under the NRC NPAR program, and the authors feel it demonstrates the usefulness of this important research program.

J. Taylor
BNL Program Manager

(The NPAR program strategy as defined in the NRC program plan, NUREG-1144, is attached for the readers information.)

NPAR Program Strategy



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We would like to express our gratitude to various members of the Engineering Technology and Reactor Divisions of BNL who contributed towards the completion of this work. In particular, we wish to thank Mr. Robert Hall, Mr. James Higgins, Mr. William Shier, Dr. John O'Brien and Mr. Otto Jacobi who provided technical assistance, guidance, and editing of the report.

We thank Mr. J. E. Thomas of EPRI Equipment Qualification Advisory Group (EQAG), Mr. Philip M. Holzman of Strategic Technology and Resources Inc., Mr. George Sliter of EPRI, and the utility respondents for their input on the Motor Maintenance/Surveillance Survey (MM/SS) conducted in June 1987.

The assistance of the Word Processing Center in typing this manuscript is also deeply appreciated.

SUMMARY

The objectives of this Phase II NPAR motor study are 1) the assessment of inspection, surveillance, maintenance, and condition monitoring methods and 2) the development of criteria which can be used for the formulation of a cost effective maintenance program. The Phase I study (NUREG/CR-4156) identified the typical motor failures and various functional indicators to monitor age-related degradation.

In order to make decisions related to motor maintenance, the sizes, types, and number of motors in nuclear power plants were assessed. Critical applications of motors for plant safety and availability were also identified. The contemporary BWR/PWR contains approximately 1100 motors, with the largest applications being for AC motor-operated valves and continuous duty motors in the 1-100 hp range.

Periodic testing, surveillance techniques and continuous monitoring methods were reviewed and assessed. Methods are presented herein for performance evaluation and trend analysis, as well as for a value impact analysis.

Current industry maintenance practices were assessed by reviewing the motor maintenance requirements at four nuclear power stations. Insulation resistance is always measured, whereas motor running current is recorded only in some cases. Most testing is done for the driven equipment, such as MOV stroke time or pump speed, which gives little indication of motor condition. With exception to large motor bearings, trend analysis is not that extensive for insulation condition.

A discussion of reliability centered maintenance (RCM) is presented, along with a logic chart to make motor maintenance decisions using RCM philosophy. This logic is applied to the specific application of containment fan cooler motors. The resultant maintenance recommendations do not necessitate any hard ware modifications, but do require more testing and trend analysis than is currently performed at most nuclear power plants.

A 10 hp industrial motor with 12 years of service life in a commercial nuclear plant and a 400 hp failed motor with more than 24 years of service life in a nuclear research reactor facility were tested. The 10 hp motor was subjected to plug reversal cycling to induce age-related degradation while monitoring various functional indicators. The 400 hp motor stator was tested to diagnose age-related deterioration of insulation dielectric properties. The test objectives were to identify the functional indicators which were cost-effective and provide adequate feedback indicating whether or not degradation was occurring. These test results are discussed in separate volumes of this NUREG Report.

In conclusion, a strategy has been developed for establishing a motor maintenance program. Tests, monitoring and inspection activities are recommended to detect as well as monitor degradation in motors due to aging and service wear. These techniques are intended to identify any local defects or the average condition of dielectric and rotational integrities of motors at an incipient stage. Technical

information is provided on the kinds of tests to conduct, how and when to conduct them, and for what sizes of motors these tests are applicable.

The information presented in this report can be applied directly by utilities to establish an effective motor maintenance program. By following the logic diagram presented in section 6.2, the type of maintenance program best suited for a particular motor or group of motors can be determined. The method used is based on reliability centered maintenance and will result in a maintenance program tailored to meet the specific needs of the plants. Once the type of program required has been determined, the information presented in section 6.4 can be used to obtain details on the specific tests and inspections that should be performed. This is based on motor size and application. Other factors which must be considered, such as data trending and administrative concerns, are discussed in sections 3 and 4, respectively. Supplemental information on performance of the various tests can be obtained from the Appendices.

1 INTRODUCTION

1.1 Background

Motor degradation due to aging and service wear significantly increases the potential for a catastrophic failure, particularly during a power plant accident and post-accident conditions. The impact of motor failures on plant safety is an important concern among the nuclear utilities and the government agency regulating this industry. Economic impacts, relating to plant availability and safety, as well as corrective maintenance, have prompted utilities to improve their maintenance programs to mitigate such aging effects.

Current motor maintenance activities in the utility industry do not seem extensive specifically in the areas of detecting and monitoring age-related degradation. However, with the high costs of plant down-time, coupled with the safety impact of a motor failure, the utilities and the regulating agency have focused their resources on achieving better maintenance and surveillance programs, thus improving plant reliability and safety. This effort includes establishing computer data bases, as well as evaluating motor conditions and the trend of motor performance data. The use of increasingly sophisticated techniques to identify motor defects at an incipient stage is being initiated by some utilities.

Despite the fact that modern motors are better and more sophisticated than older motors, and maintenance practices are more extensive, they still fail. Most motor failures described in the operating experience data bases had occurred during starting. The insulating system and bearing assemblies were the dominant failure modes, accounting for almost seventy percent of the reported failures. Monitoring the state of these two sub-components, using cost-effective techniques, could eliminate many untimely failures and thus improve the overall system reliability and plant availability.

Studies sponsored by industry (1-2) on motors have been conducted by the Electric Power Research Institute (EPRI) to identify failure modes, to extend motor life expectancy, and to develop a cost-effective preventive maintenance program. Other studies (3-6) have emphasized similar objectives and have developed similar recommendations to improve motor reliability. The electric utility industry, although recognizing the need and the benefit of a good motor maintenance program, has not implemented a uniform maintenance strategy. Many of the smaller safety-related motors are given minimal attention unless mandated by the plant maintenance programs. This is in contrast to the extensive maintenance conducted on many non-safety related large motors. This is due to the large differences in replacement or repair costs and also to their role in supporting electrical generation. In some instances, unnecessary prescriptive maintenance is done on components without analyzing or trending the test data to determine if it is warranted.

Numerous standards and guides are available for testing, maintaining and monitoring motor components. Electrical tests on the insulating system and mechanical tests on the bearing assemblies are described frequently. Studies (1-6) have successfully identified the predominant failure modes and the proceduresnecessary for restoring the equipment to a running condition. Standards published by the Institute of Electrical and Electronics Engineers (IEEE) (see Section 5.4) also describe monitoring techniques to diagnose the root cause of failure.

1.2 Objectives

The Phase I motor study (7) has identified the typical failures and various functional indicators to monitor age-related degradation. The objectives of the second phase studies under the Nuclear Plant Aging Research (NPAR) program are:

- to assess methods of inspection, surveillance, maintenance, and condition monitoring, or of evaluating residual life of motors, which will assure timely detection of significant aging and service wear effects from the abnormal indication of functional parameters (identified in the NPAR first phase study), prior to loss of safety function, and

- to formulate a cost-effective preventive maintenance program to be implemented for storage, maintenance, repair, and refurbishment of motors in mitigating the effects and in diminishing the rate and extent of degradation caused by aging and service wear.

This study is intended to help NRC resolve safety issues as well as to as sure the operational readiness of safety motors during normal and accident conditions. Also, it will help industry develop their own cost-effective maintenance program. Improving motor reliability will increase the component availability and hence, the plant safety. Other benefits of this study may include providing input to reviews of plant life extension, plant relicensing, and the lay-up and storage of equipment. Finally, improvements can be achieved in current codes, standards and guides to incorporate aging and service wear effects.

1.3 Strategy

By definition Maintenance is the "....action of maintaining or the state of being maintained..." and may include replacements, adjustments, repairs, overhauls and inspection of components or equipment. According to the NRC Maintenance and Surveillance Program Plan (NUREG-1212, Volume 1), Maintenance is defined as a process with the objective of preserving the reliability and safety of nuclear power plant structures, systems, and components or restoring that reliability when it is degraded. Preventive maintenance is that action which helps prevent equipment from failing prematurely. Recently, several studies (8-10) used maintenance-related terminology, such as surveillance, trending, condition monitoring, and testing as a part of their dialogue. This has created some confusion among researchers. The following discussion is intended to define this terminology, which will also help in understanding this report.

Maintenance, preventive or corrective, applicable to a component is defined as an activity or activities intended to keep the equipment in satisfactory condition or to restore it to a state at which it can perform its design function. This involves inspections, replacements, adjustments, overhauls, and repairs of the sub-components. Performance evaluation of a component is an essential counterpart of maintenance, as shown in Figure 1-1, and is defined as the qualitative or quantitative assessment of the equipment operational readiness by performing tests and/or inspections to monitor the "health" of the equipment. These activities are generally carried out by the maintenance group in a plant.

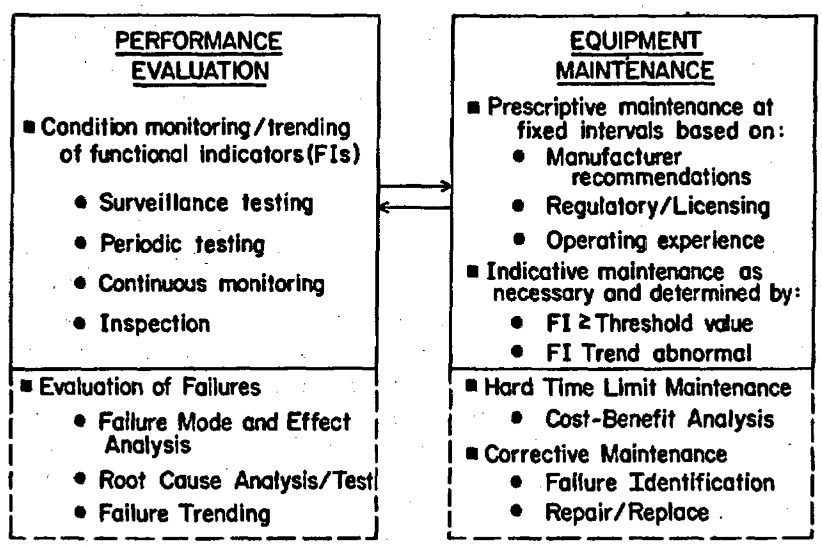

Figure 1-1: Motor Maintenance Concept

Preventive Maintenance (PM) is carried out with the intention of preventing faults or malfunctions from occuring during subsequent operation. It is designed to keep equipment operationally ready and is performed throughout the life of the equipment. It also is intended to reduce the possibility of catastrophic failures or the degraded performances of equipment. Activities under PM can be prescriptive or indicative. Prescriptive PM is done primarily as a result of manufacturer's recommendations, licensing/regulatory qualification requirements, and operating experience. Hard time limit maintenance is a subset of the prescriptive PM and refers to a complete replacement of the equipment or its components at a predetermined interval. This is based on the qualified life of the equipment or manufacturer's recommendations. Indicative PM is done when any of the functional indicators evaluated by trending or monitoring of condition have exceeded the threshold value, or when a trend of declining performance is exhibited. While the prescriptive PM is performed on a regular basis, the performance of the indicative PM depends on the characteristics of the functional indicators relative to the threshold values. This is the basis for reliability centered maintenance (RCM) programs.

Corrective Maintenance is carried out after a failure has occurred and is intended to restore the equipment to a state at which it can perform its function. Most testing, inspection and maintenance procedures described here for PM programs are applicable to Corrective Maintenance in order to diagnose the faults and to evaluate the post-maintenance characteristics of the equipment prior to its return to service.

The need for indicative maintenance is based on a qualitative or quantitative assessment of equipment functional indicators. This evaluation includes electrical, mechanical, or chemical tests to obtain quantitative values for the current functional indicators (FIs). It also includes continuous monitoring of certain FIs, as well as routine equipment inspection. A clear understanding of the various elements of performance evaluation is necessary as they pertain to current industrial practices.

In this study, the overall preventive maintenance (PM) program was thus separated into two broad areas of activity aimed at mitigating the potential effects of equipment aging: (1) Performance Evaluation, and (2) Equipment Maintenance. Equipment maintenance involves actually maintaining the condition of the equipment while performance evaluation involves only those activities undertaken to monitor signs of degradation due to aging. The equipment maintenance could be prescriptive and/or indicative. Performance evaluation activities include evaluation of the functional indicators obtained from (1) Surveillance Testing, (2) Periodic Testing, (3) Continuous Monitoring, and (4) Inspection, and are used as a basis for indicative PM. Also included in these activities are failure modes and effect analysis (FMEA), root cause analysis, tests on failed motor components, and trends associated with these failures.

The dictionary definition of surveillance testing is close observation of the condition of equipment to detect degradation that may lead to failure caused by aging and other environmental stresses (such as dust, humidity, vibration, and seismic motion). It is widely accepted in the nuclear industry that surveillance also means those mandatory tests required by the plant technical specifications (tech spec) and ASME section XI (11-12) for in-service testing (IST) of pumps and valves. This study refers to surveillance test as those tests required by plant tech spec commitments.

Periodic tests include in situ tests performed in the plant at scheduled intervals to detect failures and verify motor operation. The parameters, measured by test equipment, provide indication of age or deterioration related to service wear. Periodic tests are similar in type to surveillance tests, but are not required by tech specs. These tests typically are recommended by the manufacturers and are described in industry standards. Continuous monitoring, by definition, is the monitoring of certain functional indicators continuously and, requires data recording devices that are permanently installed (such as ammeters and voltmeters). Information from these devices is also important for checks of post-maintenance operability. Equipment inspection is defined as those activities which do not require test equipment or tools, and these include listening to the noise level, examining the surface for deterioration and applying hand forces to assess the mounting or structural integrity.

The motor functional indicators evaluated in this study for each of the four categories are summarized in Table 1-1. By definition, some of these parameters can be included in more than one category. For example, the motor running current, which may be easily measured by using a clamp-on ammeter (if it is not continuously monitored), can be part of the surveillance testing or the continuous monitoring program (i.e. on-line monitoring). Similarly, the motor or bearing vibration can be part of any of the four categories. If the testing is done with portable vibration units, then it becomes periodic testing. If it is included in the plant tech specs, then it can be considered as surveillance testing.

Large motors often have permanent instruments for vibration measurement and therefore can be monitored continuously or as part of the on-line monitoring system. If vibration is examined simply by touching with the hand or observing some abnormal motions without using any portable or sophisticated equipment, then this activity becomes part of the inspection program.

Therefore, the categorization of any motor functional indicator is dependent upon the type of measuring to which it is subjected. In this report, the motor running current is discussed under periodic testing. Vibration is reviewed in the surveillance testing section, since for pumps this parameter is sometimes included in the plant tech spec requirements as part of the ASME in-service inspection program.

The data gathered from tests and inspection activities can be generalized by the term performance evaluation. To quantify the performance of the equipment so as to predict its current and future state, trending of this data is essential.

The functional indicators identified in the phase I study (7), are monitored and/or trended by activities undertaken as part of the performance evaluation task of the motor maintenance program. Table 1-1 illustrates the correlation among the motor dielectric, rotational and mechanical integrities and testing, monitoring, and inspecting activities.

1.4 Scope

The phase 1 motor study (7) included a description of motor designs and construction materials. Failure modes, causes, and mechanisms were determined by reviewing the environmental and operational conditions experienced by motors in nuclear power plants, augmented by the last decade of operating experiences in nuclear applications. The study also included a preliminary review of design and specifications, along with standards and guides. To determine the motor dielectric, rotational, and mechanical integrities, the functional indicators were identified. When properly monitored, these parameters indicate component deterioration due to aging.

The second phase study, with the specific objectives mentioned earlier, includes all the salient points to develop a cost-effective preventive maintenance program. Although no program can provide absolute assurance that failures will be eliminated, proper implementation of the procedures recommended in this report can improve motor reliability which, in turn, will improve plant safety and availability.

A nuclear power plant contains motors of various sizes and types, located throughout the facility. As a result, it is difficult to generalize motor characteristics for all plant environments and applications. Therefore, a study was made to identify the size, type, and specifications of motors used in safety applications in a typical Pressurized Water Reactor (PWR) and in the Mark I, II, and III Boiling Water Reactor (BWR) designs. A reasonable estimate of the plant maintenance effort could be achieved for implementing the recommended practices for a particular class of motors.

Table 1-1: MOTOR FUNCTIONAL INDICATORS - PERFORMANCE EVALUATION TESTING MATRIX

Motor Integrities (Motor Components)	Performance Evaluation Tests and Methods			
	Periodic Tests	Surveillance Tests	Continuous Monitoring	Inspections
Dielectric (Insulating System in stator and rotor)	• Insulation Resistance/ Polarization Index • Ac/dc leakage/hi pot • Power factor/ Dissipation factor/ Capacitance • Voltage Impulse/Surge • Motor running current* • Partial discharging • Dc winding resistance • Winding end turn movement	• Motor running current*	• Winding Temperature • Line/phase Current	• dust • presence of water or other contamination • winding vibration • corona marks • visible voids/cracks • shorts/breakdowns • burn marks • corrosion in bars • poor electrical connections
Rotational (Rotor and Bearing Assembly)	• Lubrication Analysis (Lubricity/viscosity) • Bearing Vibration*	• Bearing Vibration* • Bearing Temperature (eddy current leakage) • Speed	• Oil Temperature • Bearing Temperature (large motors) • Bearing Vibrations* (large motors)	• rotor bar loose • bearing corrosion • bearing noise • bearing temperature (small motors) • jamming/freezing balls • lubrication level • alignment • clearances
Mechanical (Motor Accessories)	• Motor vibration • Non-destructive testing	• Valve stroking (MOV's)		• environmental conditions • surface corrosion • surface cracks • loose mountings/shims • seals/gasket leaks • wear/distortion • motor vibration*

*Can be part of the periodic test or surveillance tests or continuous monitoring depending on the test equipment, plant tech spec or the permanently installed devices on the motor.

Regardless of application and size, motors have similar components; stator, rotor, bearings, and accessories, as identified in the phase 1 study (7). Because of their construction and material characteristics, motors require certain maintenance activities and tests no matter where they are located. How ever, safety considerations, economics, environmental parameters, and motor applications may dictate the type and frequency of maintenance work activities. For example, performing sophisticated tests on a fractional horsepower motor used for strip-chart recording in the control room is not a wise decision since this motor could be replaced every year at minimum cost with no impact on safety. On the other hand, for 5,000 hp safety related motors equipped with sophisticated monitoring features, good maintenance practices are mandated for both safety and economic reasons.

Nuclear motors have similar histories of failure as those with non-nuclear applications. Insulating systems (dielectric integrity) and bearings (rotational integrity) are responsible for most motor failures. As a result, most industry standards and guides are written on testing and maintenance of these components. Very little maintenance guidance is available for other motor components.

A summary was made of the tests used by the nuclear industry in plant maintenance and surveillance programs. Each test procedure is described to provide the basic principles of measurement followed by these discussions:

- present industry practices
- industry standards/guides
- required test equipment
- major sources of measurement errors
- recommendations with test frequency (if possible) and safety limits.

Insulation test recommendations are taken from publications by the Institute of Electrical and Electronics Engineers (IEEE) and National Electrical Manufacturers Association (NEMA) while bearing tests are obtained from the American Society of Mechanical Engineers (ASME) and Anti-Friction Bearing Manufacturers Association (AFBMA). Other recommended standards also are considered in the study. Maintenance tests are listed separately from the surveillance procedures currently adopted by the power industry.

A survey of the maintenance and surveillance programs for continuous duty as well as intermittent (valve operator) motors was conducted at four nuclear facilities. The plants included two PWR and two BWR facilities with several years of operating experiences. The survey included a review of selected maintenance and surveillance procedures and computerized Preventive Maintenance (PM) programs. The comparison of different procedures provided the following types of information:

- tests performed and the procedures needed in processing the test data
- acceptance criteria
- data recorded
- procedure formats.

The purpose of this evaluation is to familiarize the reader with the current practices adopted in nuclear industry and to study procedural developments.

Performance evaluation of the equipment is also a part of the maintenance and surveillance activities and is a quantitative, predictive technique for assessing the "health" of the equipment. Trending the maintenance testing data is an important aspect of the condition monitoring (CM) program. In recent years, utilities have given special consideration to condition monitoring of certain motors which are either very expensive or vital to plant safety. However, an unpublished EPRI study indicated that CM on motors using insulation resistance and polarization index tests provided no trending data that was useful in describing the motor condition. This study was based on motors that were artificially aged in a mild environment without humidity. The components were aged to an equivalent life of 50 years. With this type of aging, the motors may not have experienced any insulation damage because of the lack of heat and humidity cycles, which is a key factor for insulation degradation. Therefore, monitoring a motor for its condition remains an uncharted topic of significant importance.

A scheme is presented for performing cost-benefit analysis. Recommendations for testing are based on the motor size and its importance to plant safety. Other elements governing a good maintenance program also are discussed.

Thus, the scope of this phase of the motor study includes basic elements for developing a good maintenance program for motors in nuclear power plants. However, with the present knowledge, the suitability of using any particular insulation test for a motor is difficult to assess. Test programs were conducted to define the applicability of the functional indicators for condition monitoring as part of the motor PM program. The test results are presented in separate volumes of this NUREG report. It is concluded that certain functional parameters change as the components degrade with age. Therefore, by trending these parameters, the motor can be maintained in an operationally ready condition.

Motor classification and various functional indicators are discussed in Section 2. Condition monitoring methods and functional indicator trending obtained from the plant maintenance and surveillance program are given in detail in Section 3. Section 4 describes the other elements relating to motor maintenance, that include planning, management, human factors, environmental and operational factors, test equipment, spare parts, and quality assurance. Section 5 includes survey results which indicate the present industry practices used to keep motors operating for the life of the plant. Section 6 describes procedures to select maintenance types for nuclear plant motors and Section 7 gives the conclusions of this phase 2 study. The basic principles of all the tests utilized in maintenance and surveillance applications are discussed in Appendices A and B, respectively. Appendix C outlines some of the continuous monitoring and inspection procedures applicable to motor performance evaluation. Appendix D discusses motor design and specifications for protecting components from abnormal conditions and their application to nuclear power plants.

1.5 Definitions

1. Maintenance - An activity or activities intended to keep the equipment in satisfactory condition or to restore it to a state in which it can perform its design function, thus preserving the reliability and safety of the nuclear power plant. This involves (a) diagnostic or periodic testing, surveillance, continuous monitoring, and inspection, (b) preventive and corrective actions such as replacements, adjustments, overhauls, and repairs, and (c) proper equipment isolation, restoration to service, and post-maintenance testing.

2. Corrective Maintenance - Activities carried out after a failure has occurred and intended to restore the equipment to a state in which it can perform its function. These activities do not occur on a regular schedule or period.

3. Preventive Maintenance (PM) - Tests, measurements, readouts, inspections, replacements, adjustments, repairs and similar activities carried out with the intention of preventing faults or malfunctions from occurring during subsequent operation. With exception to Indicative PM, these activities are regularly scheduled and intended to reduce the frequency and impact of equipment failure. In case of Indicative PM, this is done at varying intervals based on performance evaluations.

4. Prescriptive PM - A special form of mandatory or discretionary PM used to identify and minimize incipient failures and is done as a result of manufacturer's recommendations, licensing/regulatory qualification requirements, and operating experience.

5. Indicative PM - A form of PM used when any of the functional indicators (FIs) evaluated by trending or condition monitoring have exceeded the threshold value, or when a declining performance trend is exhibited.

6. Hard Time Limit PM - This is a subset of prescriptive PM program where the complete equipment or the degraded subcomponents are replaced at fixed time intervals prior to failure, based on the manufacturer recommendations, qualification, or operating experience.

7. Performance Evaluation - An essential part of the overall maintenance program for a component and the means of qualitatively or quantitatively assessing the equipment's operational readiness by performing tests and/or inspections to monitor the equipment "health."

8. Surveillance Testing - These tests or activities are required by the plant technical specifications (tech spec) commitments. They are frequently carried out by the control room operators or instrument technicians to check operability of the equipment.

9. Periodic Testing - In situ tests performed in the plant on the equipment or its associated controls at scheduled intervals to detect failures or degradations and verify operability. These tests require test equipment to measure the performance parameters.

10. Continuous Monitoring - Observing or noting readouts of functional period indicators from continually measuring devices that are permanently installed either on the equipment or the associated controls. These parameters also can be recorded or examined on an on-line monitoring system.

11. Inspection - Those activities which do not require sophisticated test equipment or tools and include listening to the noise levels, examining any surface deteriorations, applying hand forces to assess the mechanical or structural integrity, and inspecting the physical condition of the equipment.

12. Condition Monitoring and Trending - Quantitative assessment of equipment's past performance and prediction of the present and future "health" of the equipment until the next scheduled PM.

2 MOTOR CLASSIFICATIONS AND TESTS

Motors are used in nuclear power plants for driving the equipment required for power operation as well as for safeguard functions. They range in size from fractions of a horsepower to several thousand horsepower, with the induction motor comprising approximately 90% of the total population.

This section discusses the four categories of motors based on their horse power ratings and types of power supply. Also discussed are the various diagnostic tests which can be used to monitor the present condition and to predict the future condition of motors. The suitability of a test parameter to each of the motor categories is assessed for application to maintenance programs in nuclear power plants.

2.1 Motor Classifications

Motors are categorized into four distinct groups according to their hp ratings: fractional (< 1 hp), small (1 to 100 hp), intermediate (125-250 hp), and large (> 250 hp). Other classifications based on voltage ratings are discussed within each of the above categories. These groupings are actually based on their type of power supply. Fractional and small integral motors are powered from motor control centers (MCCs), while large motors are powered from low or medium voltage switchgear. The intermediate-size motors may be powered from either MCC or switchgear, depending on their short-circuit (i.e. maximum) voltage or current ratings.

2.1.1 Fractional Motors (< 1 hp)

Fractional hp motors are generally single-phase, 115 volts, ac, 60 hz motors, with installed thermal-overload protective devices that interrupt power to the motor when the rated temperature is exceeded. Some larger ac fractional motors (> 3/4 hp) are suitable for three phase, 460 volt, 60 hz operations. Dc motors are used in 125 (or 250) Vdc applications and are designed to run continuously for one hour at a maximum voltage of 140 (or 280) volts. They also are capable of driving equipment at a minimum voltage as low as 100 (or 200) volts.

Fractional motors are sometimes activated by automatically controlled devices such as pressure, temperature, or float switches. In these cases, a 2-pole manual motor starting switch or a single phase magnetic contactor generally is used; in both instances, the controller is mounted close to the motor. These motors are supplied with power from a 120/208 Vac local distribution cabinet or panel board through a single pole, thermal magnetic molded case air circuit breaker which is rated for the short-circuit current at the bus and capable of ground fault interruption. Thus, the breaker provides protection against motor branch circuit overcurrent and ground fault, and often has a trip rating of less than 30 amperes.

This size motor is primarily used to drive small fans, pumps, and valves, and control devices such as strip-chart recorders.

2.1.2 Small Motors (1-100 hp)

Small motors are generally supplied with 460 volt, three-phase, 60 hz, ac and are primarily used as valve operators and to drive small pumps and fans. These motors are controlled by motor control centers (MCCs) which are sized according to the available short-circuit current at the power center.

The motor starter unit inside the MCC consists of an adjustable, instantaneous, molded case, air circuit breaker and magnetic starter. It is not generally equipped with one thermal overload relay per phase. These motors are also equipped with built-in thermal protective devices which are responsive to temperature as well as temperature rise, as shown in Figure 2-1. When these devices trip the motor, they are wired in such a way that the motor will not restart until the thermal device has cooled down sufficiently to reset itself. Some may require a manual reset before restart is possible.

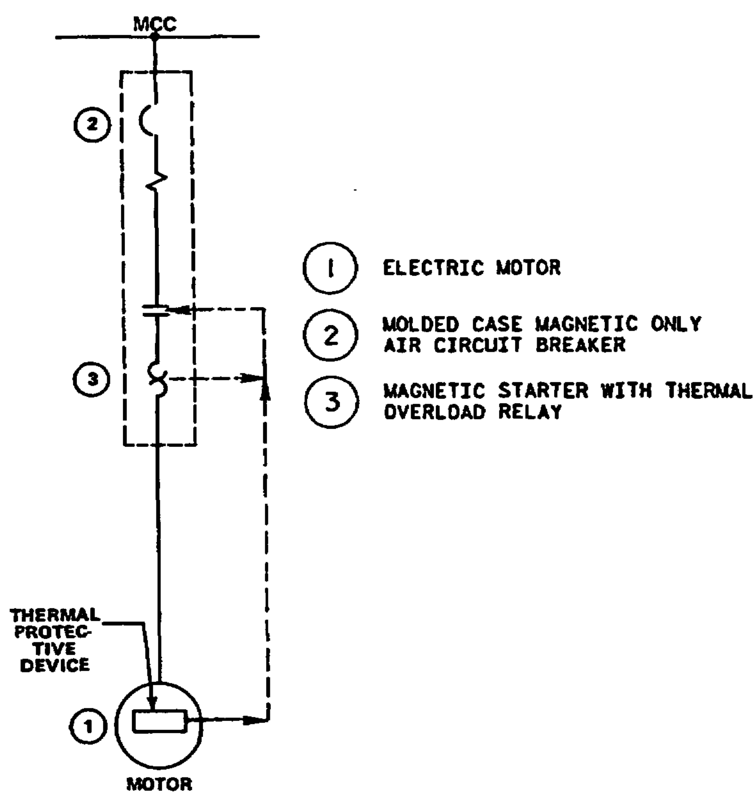

Figure 2-1: Schematic line diagram for small motor controls

Pump and fan motors generally are continuous-use motors, while valve operators are high torque and intermittent-use motors. Valve motors often have three phases and are supplied with power from motor control centers, which contain protection devices and control relays. For non-safety valve motors outside the primary containment, the controllers and protective devices at the MCC should allow for remote operation of the valve and provide protection for the operator and the power feeder. Selection of the thermal overload relay and heater depends on the following basis:

- motor normal load current
- motor locked rotor current
- allowable motor locked rotor time (safe stall time)
- valve stroke time
- motor current corresponding to 200 percent normal load
- valve pressure/temperature ratings.

Safety-related motor operators located outside the primary containment have controller and protective devices which should comply with NRC regulatory guide 1.106, Draft, Rev. 2 "Thermal overload protection on motor-operated valves for nuclear power plants," and recommendations made by the manufacturers. One of the design conditions in this regulatory guide is that the thermal overload relay tripping contacts should be bypassed automatically upon the actuation of a safety injection or an isolation signal. The NRC staff is currently considering that tripping of the overload thermal device should be indicated in the control room, and they also propose that the use of these thermal overload devices be recommended for all safety related motor operators.

Motor operators, of the safety or non-safety types, located inside the primary containment have additional controller and protective devices for remote operation and protection against electrical penetrations into the primary containment, complying with the NRC regulatory guide 1.63, Rev. 3, February 1987, "Electric Penetration Assemblies in Containment Structures for Nuclear Power Plants." This regulatory guide essentially endorses the IEEE Std-317 (1983) which requires one dual element fuse per phase. Figures 2-2 and 2-3 show the line diagrams for motors outside and inside the primary containment.

2.1.3 Intermediate Motors (125 - 250 hp)

Intermediate size motors, generally in the range of 125 hp to 250 hp, are supplied with power from circuit breakers in low voltage metal enclosed switchgear, as shown in Figure 2-4. This size motor usually has random wound stator and rotor windings. However, for some of the larger ones in this classification, form wound coils sometimes are used.

The power circuit breakers are equipped with adjustable direct tripping devices which operate by sensing each phase current. These devices have instantaneous and long-term overcurrent elements, and sometimes short-term ones as well. The instantaneous element is set initially at approximately 1.8 times the locked rotor current, but should be capable of being set at twice the motor locked rotor current. If used, the short-term element is set at minimum time delay and at approximately 1.2 times the locked rotor current. The long-time element is set to coordinate with the motor thermal capability and accelerating time-current characteristics. It provides protection for the locked rotor.

Thermal devices built into the motor provide protection against overload or rising temperatures. They usually trip the motor, but may be used only for alarm purpose when the motor is subject to short-term overloads or if its safety function is more important than any damage that might occur. For motors having exceptionally long starting times, breakers with a special short-term unit are used instead of the standard built-in devices.

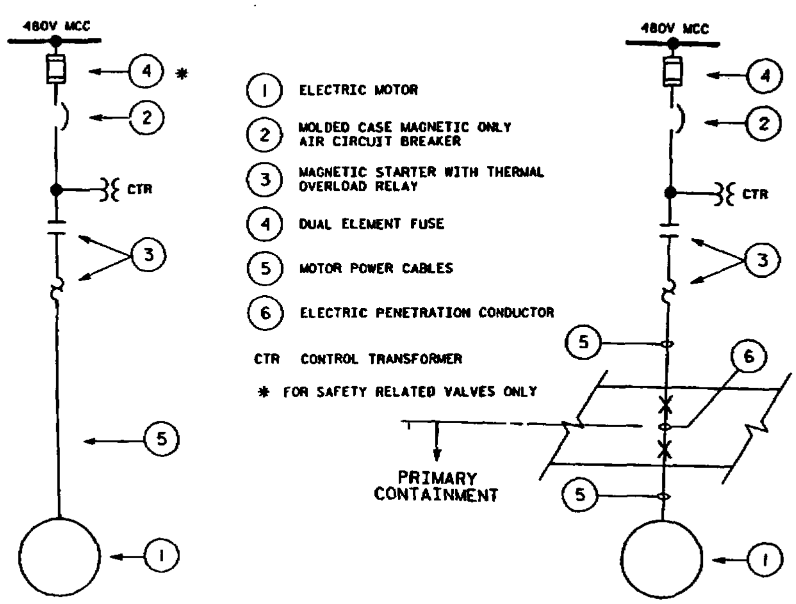

Figure 2-2: Schematics for outside containment motor controls

Figure 2-3: Schematics for inside containment motor controls

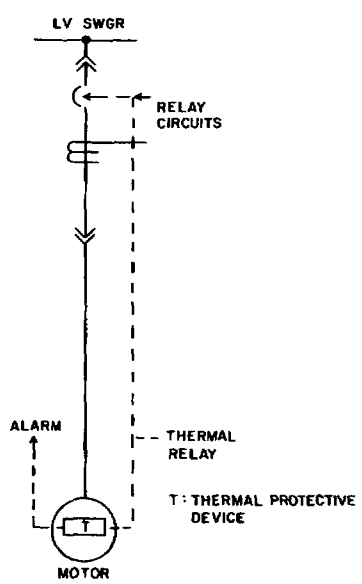

Figure 2-4: Schematics for intermediate size motor controls

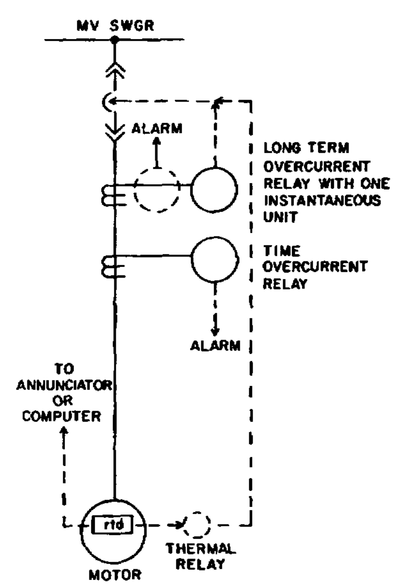

Figure 2-5: Schematics for large motor controls

2.1.4 Large Motors (> 250 hp)

Large motors are often equipped with many protective devices such as overcurrent, overvoltage, and under frequency protective relays, etc. because of their high replacement cost. These motors are continuously running or are in standby mode, and are started infrequently. The power supply is from medium-voltage metal clad switchgear, with medium voltage air or vacuum circuit-breakers. The typical supply voltage levels are 2.3, 4.0, 6.6, and 13.2 kv. The size of the switchgear is primarily based on the short-circuit current (maximum current) and the motor voltage ratings. Figure 2-5 shows a typical motor line diagram.

Large motors are protected from phase overcurrent either by three single-phase relays or one three-phase relay. If the locked rotor current of a motor exceeds a certain fraction of the symmetrical three-phase fault current available at the supply switchgear, the motor is further protected from phase imbalance by providing phase differential relays. Vertical outdoor pump motors above 2.3 kv use lightning arrestors and surge capacitors. Motors rated at 13.2 kv are generally provided with surge arresting capabilities located between the motor and the surge arrestor. Motors driving high inertial loads that require an acceleration time longer than 10 seconds usually are analyzed individually for protection during starting and acceleration.

2.2 Motor Aging and Diagnostic Tests

Two motor tests were performed to assess the suitability of various test parameters for monitoring motor integrities. A 10 hp motor was subjected to plug reverse cycling to accelerate the aging process in the insulating system as well as in the bearing assemblies. During testing, various parameters were measured periodically to monitor the condition of the motor. These are:

Dielectric Integrity:
- No Load Current Measurement
- Winding Resistance Measurement
- Dc Leakage Test
- Polarization Index Test
- Dc Insulation Resistance
- Ac Leakage Test
- Dissipation Factor and Capacitance Test
- Partial Discharge Test
- Impulse Voltage/Surge Test
- Winding Temperature Measurement
- End Turn Movement Measurement

Rotational Integrity:
- Bearing Vibration Test
- Chemical Analysis of Lubrications
- Bearing Temperature Measurements

Selected test data were trended as motor components were being aged. Note that the major thrust of this test program was to determine whether any of these FIs are suitable for predicting the motor incipient failures.

Another test program involving diagnostic tests on a naturally failed 400 hp motor was conducted to determine the failure causes and to assess the aged condition of the stator insulating system. The motor had served a test reactor facility for over 20 years to drive one of its recirculating pumps. Since the motor stator winding was constructed with ninety (90) individual form wound coils, each coil was separated for performing dielectric tests. The variation in aging characteristics of the coils was determined by comparison of the individual test data with baseline data corresponding to an insulating system exposed to 20 years of service. The dielectric tests performed on this motor winding include:

- Dc Resistance Test
- Surge Test
- Dc Leakage Test
- Ac Dissipation Factor Test
- Ac Capacitance Test
- Ac Leakage Test
- Ac High Potential Test

The test procedures and results from the two test programs are described in detail in the second and third volumes of this NUREG. The discussions in the following section on various motor functional indicators are based on results from these two test programs. Information was also obtained from discussions with experts on this subject, test equipment manufacturers, plant maintenance engineers, and motor manufacturers.

2.3 Dielectric and Bearing Tests

The first phase of the NPAR study (7) identified all modes, causes, and mechanisms of motor failures based on operating experience data from nuclear power plants. The study provided an extensive list of functional indicators for monitoring the dielectric, rotational, and mechanical integrities of motors. This second phase study evaluated each of these functional indicators for its suitability to motor maintenance programs in nuclear facilities. A discussion of each functional indicator is provided.

A review of various test methods available in industry standards, such as IEEE, ASME, ANSI, AFBMA, was conducted. A large number of these tests are currently used in repair and rewind shops to recondition motors. Some of them are also performed by manufacturers for qualifying the design of motor subcomponents. Thus, there exist many test methods that can potentially be used in the plant maintenance programs to monitor the condition of motors.

The basic principles of each test method and its applicability, limitations, and source of errors are discussed in Appendix A on periodic tests, Appendix B on surveillance tests, and Appendix C on continuous monitoring and inspection programs. Those test parameters considered in the two motor test programs are included in these discussions under the dielectric and bearing tests.

2.3.1 Dielectric Tests

Dielectric tests are performed on the insulating systems, specifically the motor stator windings. Dc Resistance and Polarization Index are the most common tests performed in motor maintenance programs. Other tests which are available are ac/dc leakage, power factor/dissipation-factor/capacitance, surge, dc winding resistance, and partial discharge. For certain insulating materials the looseness of the coils within stator slots can be monitored by the end turn movement measurements. In addition, trends in motor running current (load or no-load) and winding temperature are other potential indicators of abnormalities in the dielectric integrity. These two parameters could be included in one of the test or monitoring activities involving performance evaluation. Periodic inspection of the insulation is one of the most important maintenance activities and should not be given any less importance than the above tests.

(1) Dc Insulation Resistance/Polarization Index Tests

These two parameters (13) provide an average assessment of insulation condition and detect the presence of surface contamination or humidity. The tests are suitable for all motors, independent of their size, type and supply voltage level.

The most probable failure mode for small motors used in motor operators for valves is winding and lead insulation failure. Since the motors do not operate for long periods, bearing failure is much less likely to occur. The general electrical condition of the winding and lead insulation may be determined by periodic dc insulation resistance tests and polarization index tests. If the PI is low, it is an indication that leakage is relatively continuous and the insulation is not charging. For most insulating systems used in nuclear safety-related motors, a polarization index of at least 2 would be expected. A low insulation resistance also would be indicative of trouble either from surface contamination or internal imperfections or deterioration. Since most valve actuator motors are sealed, the probable cause of low insulation resistance would be its deterioration rather than surface contamination. The results of periodic measurements should be compared to establish the trend of the readings. If a deteriorating trend is observed, there will be a greater probability of insulation failure during periods of thermal stress caused by rapid cycling of the associated valve or overload during a design basis accident.

Both insulation resistance and polarization index are considered to be go/no go tests. They should be performed prior to starting a motor after a long shutdown or prior to performing a high potential test. These parameters failed to provide any early indication of insulation deterioration in both motor test programs. However, an upward trend in either test parameter indicates hardening and drying of insulating system, which decreases the mechanical strength of the material leading to developing cracks. These tests are performed from the motor control center, thereby including the power cables in the circuit.

(2) Ac/Dc Leakage Hipot Tests

Insulation leakage tests include a gradual increase in voltage as leakage current is measured and usually conclude with a high potential (HiPot) test. This test is generally performed on motors of 3,000 V and higher, and a curve of leakage current versus voltage is plotted. The leakage current should be fairly linear and the insulation resistance should remain stable until a point is reached at which current begins to increase rapidly with voltage. The test is then stopped (14) to prevent complete breakdown of the insulation, or it is stopped at a predetermined voltage if no breakdown occurs. An increase in the leakage current indicates cracks or deterioration of the insulation.

The dc leakage current measurements are found to be an alternate to the insulation resistance test in which case the resistance is measured instead of leakage current. Unless the insulation is severely degraded, the leakage current measurement is too small to exhibit any trends and hence, does not provide any useful information with regards to its condition. The ac leakage current (hipot) test, on the other hand, could be destructive since test voltages well above the motor rating are used. This test is an endurance test and can detect insulation breakdown at an incipient stage. However, because it can be destructive, this test is not recommended for preventive maintenance programs.

(3) Power Factor/Dissipation Factor/Capacitance Tests

Power factor and power factor tip-up tests are ac insulation tests that determine the ratio of the resistance current to the total charging current. For perfect insulation, the power factor should remain constant with increasing voltage. However, if partial discharges occur in cavities within the insulation, an increase in the power factor will occur when the inception volt age (the voltage at which discharge begins) is exceeded. This test is called a power factor tip-up test. Periodic test results are compared to determine if the inception voltage is decreasing, thus indicating deterioration of the insulation.

Dissipation factor tests are similar to power factor tests except that the ratio of the capacitive current to the resistive current is measured. As with the power factor, the dissipation factor should remain relatively constant with increasing voltage. Trending of the voltage at which the dissipation factor changes may be used to trend deterioration of the insulation. A larger dissipation factor, when compared to a baseline value for good insulation, indicates the presence of voids and cracks. These defects allow paths for leakage current and are sources of corona discharges. Like dissipation factor, the capacitance measurements of the insulation indicate insulation deterioration such as thinning. The diagnostic tests on the 400 hp failed motor support the conclusion that both dissipation factor and capacitance values could be used to detect incipient insulation deterioration due to aging.

Power factor tip-up tests are reserved for high voltage motors (4000V and up) and are performed only on motors with insulation systems that are susceptible to partial discharge problems. These tests are lengthy and are difficult to perform due to the nature of the test equipment.

(4) Voltage Impulse/Surge Tests

Surge testing is used on motor windings to detect turn-to-turn failures and incorrect electrical connections. Although it has not been widely used in maintenance programs, recent technological developments have provided the tools for performing these tests in power plants. A comparison of the waveshapes of voltage pulses between a good and bad winding can reveal insulation failures.

A turn short in one of the form wound coils in the 400 hp motor and the first detection of stator ground in the 10 hp motor were revealed by surge tests. The test can be performed at the motor control center or switchgear, and includes both the cable and the motor windings. Disconnection for further testing would be performed only if a problem is indicated and isolation is necessary to determine the motor or the cable is failing.

With the available test equipment this test is limited to low voltage motors. The test is a good tool for detecting turn short conditions. If a turn short remains undetected, application of a low voltage gradient across it will cause current leakage through the insulation, resulting in heating. A temperature rise further reduces dielectric strength, which causes increased current and further heating. Ultimately, this cascading effect will cause insulation failure. The tendency of a weak spot to cascade to failure is worsened during periods of motor overheating from overload and rapid cycling, since the additional temperature rise rapidly reduces the dielectric strength of the weak spot in the insulation.

(5) Motor Running Current Test

In the two motor test programs, monitoring of this test parameter did not provide any information to assess insulation condition as aging occurred. Also, there are numerous factors which can produce current fluctuations which make the interpretation of results from this test uncertain.

In some cases, the running current indicates the condition of the driven equipment if there exist any rotational resistances. When a motor is subjected to an overload condition, this may be indicated by higher running current. If it is left for a long duration, overheating of the windings may result in insulation burning.

(6) Partial Discharge Test

Partial discharge tests are performed to determine the inception or threshold voltages at which partial discharges occur. The power supply for a partial discharge test must be capable of providing rated phase-to-ground volt age and the charging current required by the cable and winding insulation system. In the small motor testing, the trend in inception voltage indicated slot wedge degradation in the stator slot while the small motor was subjected to accelerated aging.

Like surge testing, this parameter is a good indicator for discharges at local defects such as hot spots and voids. However, for low voltage motors this test is difficult to perform. Unless advanced test equipment is available to detect low voltage discharges this test is recommended only for higher volt age motors. Since it requires higher ac voltage, this test should be performed with caution, otherwise this test could induce degradation in the insulating material.

(7) Dc Winding Resistance Test

Dc resistance of the stator windings of the 10 hp motor were found to remain relatively constant and the trend of insulation degradation was not revealed until there was a break in the windings. However, this indicator could detect unbalanced windings, bad connections and broken wire. Comparisons of winding resistance measurements with previous readings may indicate significant deterioration in turn-to-turn insulation for the winding. This test, although easy to perform in a plant environment, does not seem to detect any defects in the insulation at an incipient stage.

2.3.2 Bearing Tests

The operating experience data assessment concluded that the dominant bearing problems were due to excessive or insufficient lubrication, wear of bearing surfaces or misalignment, leakage of lube oil through seals and gaskets, and intrusion of water or steam which changes the lubricity and viscosity of lubricant. The study also determined that the functional indicator that detect incipient bearing degradation are (1) Vibration and temperature measurement, (2) Lubrication analysis, and (3) a good inspection program.

(1) <u>Vibration/Spike Energy</u>

Each motor has a characteristic vibration signature when it is in good condition. This signature reflects bearing performance, electrical field balance, structural integrity and rotor shaft alignment. Table 2-1 provides the frequency characteristics of various fault conditions one would encounter in motor performance (15,16). One of the more sophisticated monitoring schemes uses Fast Fourier Transform (FFT) instrumentation coupled to a computer analyzer that periodically compares the results of the FFT to the vibration signature of the healthy system. Changes in amplitude of the various frequencies are trended and, if potentially dangerous, an alarm is activated (17). Such a system installed at a nuclear power plant would continuously monitor pumps and their drive systems. It must be recognized that such sophisticated systems are presently justified only for large, difficult-to-replace machinery.

Displacement, velocity and acceleration signatures can be measured for diagnosing faults in motor components (18). The results can be displayed in terms of frequency using a high-resolution FFT frequency analyzer. Velocity is a function of both displacement and frequency, and the lines defining zones of severity are constant velocity. Problems are, therefore, better indicated with a velocity measurement rather than displacement, regardless of whether it is due to an unbalance or a worn bearing. However displacement recordings are also a measure of vibration severity provided the frequency is known. The disadvantage to velocity readings is that below 600 cpm the vibration amplitudes are small and are difficult to measure. Displacement is a better parameter to monitor for this reason. Continuous monitoring systems often are used to monitor equipment which requires high operational reliability, long-term stability and immunity to adverse environmental conditions. Because of the initial cost of such a system, this type is typically applied to large motors.

Periodic vibration measurements are generally made as a part of surveillance testing and as good maintenance practice. Portable instruments, such as IRD, Bruel & Kjaer vibration/spike energy analyzers, are now available for taking measurements at a regular interval. The periodicity for these measurements depend upon the average operating time before failure of the motor. A built-in spectrum analyzer is used to identify the root-cause of vibration problems detected during the periodic measurements.

TABLE 2-1: VIBRATION INDENTIFICATION CHART

CAUSE	AMPLITUDE	FREQUENCY	REMARKS
Unbalance	Proportional to unbalance. Largest in radial direction.	1 x RPM	Most common cause of excess vibration in machinery
Misalignment couplings or bearings and bent shaft	Large in axial direction 50% or more of radial vibration	1 x RPM usual 2 & 3 x RPM sometimes	Best found by appearance of large axial vibration. Use dial indicators or other method for positive diagnosis. If sleeve bearing machine and no coupling misalignment balance the rotor.
Bad bearings anti-friction type	Unsteady - use velocity measurement if possible	Very high (2-60kHz) several times RPM, related to radial resonances in bearings.	Bearing responsible most likely the one nearest point of largest high-frequency vibration
Eccentric journals	Usually not large	1 x RPM	If on gears largest vibration in line with gear centers. If on motor or generator vibration disappears when power is turned off. If on pump or blower attempt to balance.
Loose bearings	Primarily radial	Sub-harmonics of shaft RPM exactly 1/2 or 1/3 x RPM	Looseness may only develop at operating speed and temperature.
Oil film whirl or whip in journal bearing	Primarily radial	Less than half shaft speed (42% - 48%)	Applicable to high speed machines.
Bad gears or gear noise	Low - use velocity measure if possible, radial & axial	Very high gear teeth times RPM.	
Mechanical looseness		2 x RPM	Usually accompanied by unbalance and/or misalignment.
Bad drive belts	Erratic or pulsing radial	1, 2, 3 & 4 x RPM of belts	Strob light is best tool to freeze faulty belt.
Electrically induced vibrations	Disappears when power is turned off. Radial & axial	1 x RPM, or 1 or 2 x synchronous frequency	If vibration amplitude drops off instantly when power is turned off cause is electrical.
Aerodynamic hydraulic forces	Radial & Axial	1 x RPM, or number of blades on fan, or impeller x RPM	Rare as a cause of trouble except in cases of resonance.
Unbalance reciprocating forces	Primarily radial	1, 2 & higher orders x RPM	Inherent in reciprocating machines. Can only be reduced by design changes or isolation.

Bearings and enclosures are typically equipped with transducers for monitoring the vibration characteristics of motors.

(2) Acoustic Emission

An acoustic emission test is a dynamic test method in that it monitors the response of a material upon application of stress (19). It is defined as a transient elastic wave, generated by the rapid release of energy at ultrasonic frequencies from a localized source within a material. As applied to non-destructive testing (NDT), the emissions occur when a material is stressed. Elastic energy is released as a result of sudden material displacement due to crack propagation, dislocation avalanching in the plastic zone at the edge of a discontinuity, and numerous other lesser mechanisms.

Reactor coolant pump motors are large vertical, squirrel-cage induction machines fitted with heavy flywheels to increase the rotational inertia of the motor. Rotational inertia prolongs the pump's coast-down, thus assuring a more gradual loss of main reactor coolant flow to the core in the event that pump power is lost. Arkansas Power & Light Company (20) recently utilized acoustic emission techniques for testing flywheels on their RCP motors, which allowed them to avoid the time-consuming disassembly of restraint girders, rotor, and upper guide bearings, which was required when other conventional methods were used. The acoustic emission tests also can be used to monitor the enclosure and support integrity, for detecting leaks, and sensing damage or wear in rotating equipment.

(3) Lubrication Analysis

For motors with oil-based lubrication systems with reservoirs, lubricant sampling for condition and contamination may be performed. Such tests of the lubricating oil will preclude the need for, and usefulness of lubricant testing. For grease-packed bearings, lubricant sampling is not practical. Generally periodic changing and repacking is performed.

2.4 Temperature Monitoring

Two common locations for monitoring temperature in motors are bearing housings and winding slots. If bearing temperatures rise above the manufacturer's rating, deterioration of lubricant and/or damage to the bearing may occur. While not as sensitive as vibration analysis, temperature monitoring may indicate certain problems, such as significant lubricant deterioration prior to vibrational changes. Winding and stator-core problems will be indicated by increased winding or slot temperature. Such problems include motor overload, excessive starts and damage to lamination insulation. Motor slot temperature detectors are installed at the time of manufacture.

Because temperature monitoring of all motors for valve operators would be cost prohibitive and return little useful information, a continuous temperature monitoring system is not recommended. However, one method of determining if a motor has experienced thermal overloads during an interval between inspections is the application of temperature indicating labels that permanently change color at a particular temperature (21). While not useful for determining the exact cause of the temperature rise, such labels indicate that further investigation of valve operator condition and operating practices is required. A close scrutiny of insulation resistance tests is then needed to show that permanent damage to the insulation has not occurred. If there are repeated indications of high temperatures, investigation of the application and sizing of the motor should be performed. As of this writing, temperature-indicating labels are not known to be used in the nuclear industry as a condition monitoring technique.

For some large motors equipped with sleeve bearings, an increase in the lubricating oil temperature indicates degradation of the bearing.

2.5 Physical Inspection

Internal inspection of motors can reveal physical deterioration in the insulation and loosening of winding materials that may not be evident from other tests, such as insulation resistance. Powdering of insulation materials from chafing will generally leave deposits in dead air spaces within the motor. Usually looseness of end-turn support and binding material is easy to detect. Periodic physical inspection is not often performed due to its costs and the need for not disturbing the physical condition of the motor. However, whenever the endbells of the motor are removed for bearing replacement or maintenance, a physical inspection should be made.

Appendix C discusses various inspection activities that can be included in a plant maintenance program. The "10-point" comprehensive list describes all possible checks required to monitor the physical condition of a motor.

2.6 Miscellaneous Tests

The end turn movement of the stator assembly provides useful information on the looseness of windings in the stator slots after sufficient breakdown in the insulating materials. However, this requires installing monitoring devices on the stator end turns and usually does not warrant the benefit.

Non-destructive testing can be performed on large motors for detecting metal cracks or voids. However, the cost of performing these tests can be too prohibitive to be included in a motor maintenance program.

Those pumps and valves that are important to plant safety are subjected to surveillance testing as required by the plant tech specs. The pumps are tested for their flow and pressure characteristics while valves are tested for stroking times. There exist almost no current regulatory requirements for testing the motors driving these components. Some utilities, however, have already included certain tests such as motor running current, speed, and valve stroking measurements in their surveillance test programs. Appendix B discusses some of these test methods in detail.

3 CONDITION MONITORING AND DATA TRENDING TECHNIQUES

To evaluate motor performance, monitoring methods are available which can provide valuable information about the motors present and future conditions. Measurements of vital parameters when analyzed over time, can alert the user cooperational degradation. This section discusses the condition monitoring methods that can be used for motors and describes several statistical methods for evaluating the data.

Condition monitoring is the quantitative or qualitative assessment of the motors past performance, and is used to predict the present and future "health" until the next scheduled preventive maintenance. This is achieved by trending the functional indicators and comparing the trend with the parameter threshold limits. It requires various reliable performance tests on motor components. Acceptance and alert criteria for each test parameter should be established and the data base maintained for trending. Based on the overall trend, the type of maintenance necessary is decided. Monitoring also helps to evaluate the root cause of any degradation. A flow diagram that illustrates how the tests can be incorporated into a condition monitoring program is shown in Figure 3-1.

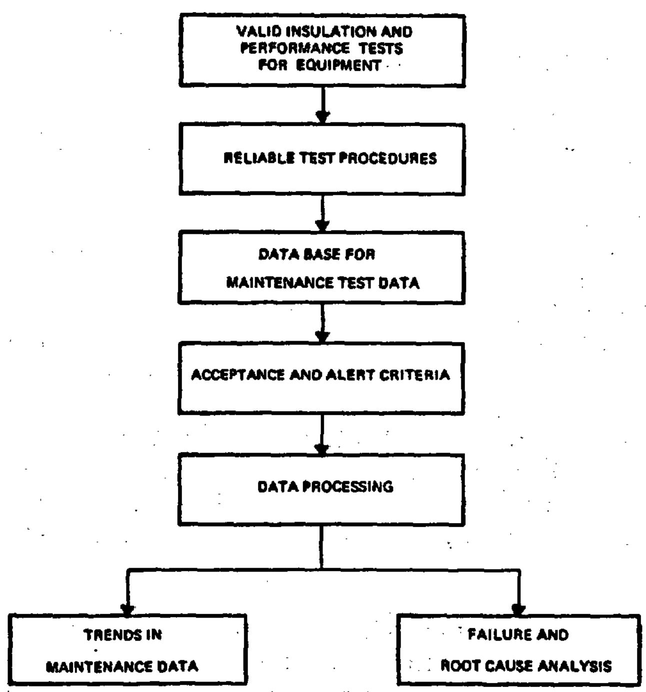

Figure 3.1: Flow diagram for condition monitoring program

Because electric motors are electro-mechanical devices, there are two basic types of monitoring: physical (mechanical, vibration and temperature), and electrical.

Most physical measurements, such as bearing vibration and winding temperature, must be performed with the motor operating. On the other hand, most electrical tests require the motor to be out of service, but not necessarily disconnected from its power leads.

The condition monitoring techniques that are applicable to the various types of motors depend on their size and voltage level, and the type of application (such as continuous duty or intermittent duty). In general, the tests for small and intermittent duty motors, such as valve operators, may be limited to electrical tests of insulation resistance, polarization index, and stator coil resistances. For larger, higher voltage, continuous duty machines, many electrical and physical tests may be used. In most cases during condition monitoring, the motor will not be disconnected from its power leads or uncoupled from its load. Therefore, most measurements will be made on combinations of motors and other system elements, such as electrical tests of windings and power leads, or vibration tests which may include vibrations from the coupled load. In the case of vibration, some monitoring systems allow filtering or frequency analysis to assist in isolating the source of trouble.

Development in the condition monitoring of motors and motor operators is proceeding along two paths:

(a) Analysis and trending of data from maintenance tests presently performed, such as megger tests, polarization index, and stroke times.

(b) Introduction of new test methods, such as signature analysis (MOVATS) and power factor and surge testing of the motor insulation.

The high temperatures occurring during motor starting and from ambient temperature are the major contributors to motor insulation deterioration and failure. Widely used tests to monitor the insulation in motors are meggering and polarization index. Several studies sponsored by EPRI (22,23) and by others (24) have recommended additional tests for monitoring the condition of the insulation, including power factor tip-up and controlled overvoltage tests.

Many limitations affect a condition monitoring program. For periodic tests of motors inside containment, access is limited by operating and radiation conditions. With regard to condition monitoring of the physical parameters of larger motors outside containment, the cost of sophisticated monitoring may preclude all but the largest motors.

Another consideration in trending is the usefulness of the monitored parameters for detecting incipient failures with adequate time for corrective action. Many monitoring methods detect the initial stages of failure and serve to minimize damage rather than to prevent it. For the present, knowing that the initial stages of failure have occurred, may make condition monitoring worthwhile, even if the existing methods do not always provide long lead times between detection and failure. Assuming corrective action is taken, prevention of significant damage reduces cost of repair. In addition, removal of a failing component from service prevents any reliance being placed upon it to perform its safety function.

Condition monitoring techniques should not create significant potential for malfunction. Therefore, it is preferable not to require disruption of power and control circuits to a motor, since this introduces the possibility of improper reconnection. In the case of large pump motors, an improper reconnection can be disastrous, since it could cause reverse rotation of the motor, which often will cause severe damage to the pump.

The cost of condition monitoring and the value of the information received must be considered in choosing alternatives. It must be recognized that no correlation has been shown between the results of condition monitoring and the ability to withstand accident conditions. However, it must be assumed that a motor with detectable levels of deterioration may not be capable of required operation during accident conditions.

3.1 Condition Monitoring Techniques

The basic types of condition monitoring are:

- Vibration detection (continuous or periodic, with or without analysis) for bearing and rotor condition.
- Temperature monitoring of bearings and windings (generally continuous).
- Lubricant analysis (periodic, generally limited to oil reservoir lubricating systems).
- Physical inspection of internals.
- Electrical insulation tests.
- Insulation resistance/polarization index.
    - Ac/Dc insulation leakage tests.
    - Dissipation factor/capacitance and power factor tip-up.
    - Partial discharge.
    - Surge/impulse voltage tests.

The Ac leakage (hipot) test is not recommended unless the test is performed with utmost caution for not exceeding the breakdown voltage of aged coils. The partial discharge test, on the other hand, is a good test for condition monitoring and trending; but the test setup is difficult to perform in a plant environment, especially for small motors. Note that for condition monitoring and trending purposes, baseline data for each test parameter corresponding to the post-installation condition of the motor should be determined first.

Table 3-1 summarizes the maintenance activities and functional indicators which comprise a condition monitoring program intended to detect and monitor the effect of aging degradation. The usefulness of each indicator and its trends with respect to a baseline or threshold value is discussed. This information is based on the two BNL motor test, expert judgment, and prior work.

Condition monitoring techniques discussed here consist of three distinct different types of evaluations. These include go/no go condition monitoring, local degradation detection monitoring, and average deterioration monitoring. Each of these conditions can be achieved by monitoring certain functional indicators. A comprehensive physical inspection program can provide the greatest cost/benefit value, specifically to those motors which are accessible during normal operations. Specific frequency is determined based on environment, importance, and duty. This activity can contribute information to each of the three monitoring techniques mentioned above.

Table 3.1: Functional Indicators for Condition Monitoring

Maintenance Activities	Average Frequency	Functional Indicators	Condition Monitoring and Trending
Physical Inspection	2 weeks-3 months	Overall motor Condition	Provides an assessment of • Dirt, dust and contaminants • Moisture, water, grease and lube oil. • Bearing noise and loose mountings. • Adverse environmental condition such as cracks, corrosions, erosions, etc. • Overall motor deterioration.
Continuous Monitoring and Surveillance Tests	Continuous 1 month-6 months	Bearing Temperature Lube Oil Temperature	Increase indicates excessive bearing wear and higher friction.
		Winding Temperature	Increase indicates high winding current which may have been caused by overload, overvoltage, or insulation deterioration due to cracks, voids, corona, etc.
		Line/Phase Current*	Increase/phase imbalance may have been caused by overloads, fluctuations of supply voltage and/or load, insulation defects such as cracks, voids, corona, etc.
		Bearing Vibration** Rotor Speed	Increase in vibration amplitudes and change in peak frequencies or rotor speed indicate bearing degradation due to wear, broken parts, intrusion of foreign material, etc.
		Valve Stroking (MOV's)	Changes in valve open/close time indicate possible defects in motor torque generation.
Periodic Tests	1 month-18 months	Insulation Resistance Polarization Index DC Winding Resistance Motor Running Current*	In general, these tests are go/no-go type. However, increase in insulation resistance indicates curing of insulation material leading to cracking and decrease indicates contamination by humidity, dusts, dirts, etc.
	1 month-6 months	Surge/voltage impulse Partial Discharge/corona Bearing Vibration**	Both insulation tests utilize hipot voltages. Abnormal traces in oscilloscope during surge test indicate winding problems such as turn short, phase imbalance, or connection problems. Decrease in corona inception voltage indicates increase in discharge activities in insulation. These are suitable for local condition of motor integrities.
	3 months-12 months	Power Factor/Dissipation Factor Capacitance Lube Oil Analysis	Increase in PF/DF or capacitance indicates insulation deteriorations due to cracks, voids, thinning. Increase of metal in lube oil indicates metal wear in the bearing. All of these parameters suitable for average/overall condition of motor integrities.
Preventive Maintenance	As recommended by Manufacturers or determined by operating experience	Grease/lube oil change Gasket/seal change Terminal/winding cleaning Tightening bolts Realignment	These activities should be performed periodically to assure the operational readiness of the motor.

*This functional indicator alone does not assure insulation condition.
**This test is good for bearing condition evaluation.

The second input for the condition monitoring program comes from data obtained from motors with continuously monitored parameters and from data obtained for motors which drive pumps, fans, and valves. The driven equipment must be operated periodically to determine design functional integrity (go/no go condition) in accordance with the tech specs while performing surveillance tests. These include pump flow and discharge pressure, pump speed, motor current, lube oil level or pressure, valve stroke times, etc. A small manpower increment of additional data collecting and analysis can provide information for monitoring the average condition of the motor.

Change in temperature of bearings, lube oil, or windings is the first indication of trouble or deterioration occurring in the corresponding component. Hence, these parameters should be evaluated against the previously recorded data as well as against the operational and environmental conditions to assess the bearing and winding conditions. Increase in bearing vibration level should be further evaluated in assessing the root cause of this abnormal condition as described in table 2-1.

Periodic tests comprise the third input into the condition monitoring program and include testing which most utilities presently perform such as insulation resistance and polarization index. However, use of this data has been limited to a go/no go evaluation. Motor testing programs have shown that these two insulation tests along with dc winding resistance and motor running current provide information only suitable for go/no go type of condition monitoring. However, an increase in insulation resistance is an indication of insulation hardening, thus increasing the potential for cracking, while a decrease indicates insulation contamination. Even for the 20 year old motor insulation tested, this parameter did not indicate any age-related deterioration.

Both the surge test and the partial discharge (corona) test are suitable for detecting as well as monitoring local defects such as turn shorts, hot spots, discharges, break in the windings. These defects constitute the initiation of the insulation degradation that could lead to complete stator burnouts. Early detection and monitoring can avoid catastrophic motor failures. It should be noted that both of these tests utilize high potential input for exaggerating the effects of the flaws. Surge test utilizes dc potential and the available test equipment is suitable for small random wound motors (F 600 volts rating). The partial discharge test is reserved for high voltage motors in which case the local discharges can be seen without raising the test voltage much higher than the rated voltage. These tests should be performed periodically (at least twice a year) for early detection of localized flaws.

The last kind of tests which are good for monitoring the average condition of the motor components include power factor/dissipation factor and capacitance tests, and periodic chemical analysis of lube oil. Increase in dielectric factors is a definite indication of insulation deterioration due to cracks, voids, or thinning, whereas increase in metal wear in lube oil indicates bearing degradation. Since these tests provide average parameters, they should be performed less frequently (at last once a year or plant outage) than the previously mentioned tests.

Finally, even rather routine preventive maintenance activities such as regreasing, cleaning, tightening bolts, realignments, and gasket changes can be incorporated into a condition monitoring program. This total data input must be reviewed on a routine basis to assure the operational readiness of all motors that are part of this program.

3.2 Evaluation of the Data

There are statistically based methods for establishing whether the data show a trend or if a data point corresponds to a sudden change (or is an outlier or "discrepant" observation). These tests can be performed on time dependent data (parametric tests) or on order-dependent data (non-parametric tests). Non-parametric tests make no assumptions of the data having statistical parameters, such as mean and standard deviation. Order dependent data may exist for a non-parametric test where the results depend on the number of cycles, temperature changes or other factors that may be difficult to measure.

3.2.1 Trend Test

Nonparametric Trend Test Using Reverse Arrangement Statistics Very often, maintenance data, when plotted will look like those in Figure 3-2 where it is difficult to discern a trend and where it is incorrect to assume the data is linear. A statistical method for establishing the presence of a trend, called reverse arrangement statistics, can be used without the need for linearizing the data and calculating population parameters, such as slope and intercept.

$x_1 = 5.5$	$x_6 = 5.7$	$x_{11} = 6.8$	$x_{16} = 5.4$
$x_2 = 5.1$	$x_7 = 5.0$	$x_{12} = 6.6$	$x_{17} = 6.8$
$x_3 = 5.7$	$x_8 = 6.5$	$x_{13} = 4.9$	$x_{18} = 5.8$
$x_4 = 5.2$	$x_9 = 5.4$	$x_{14} = 5.4$	$x_{19} = 6.8$
$x_5 = 4.8$	$x_{10} = 5.8$	$x_{15} = 5.9$	$x_{20} = 6.0$

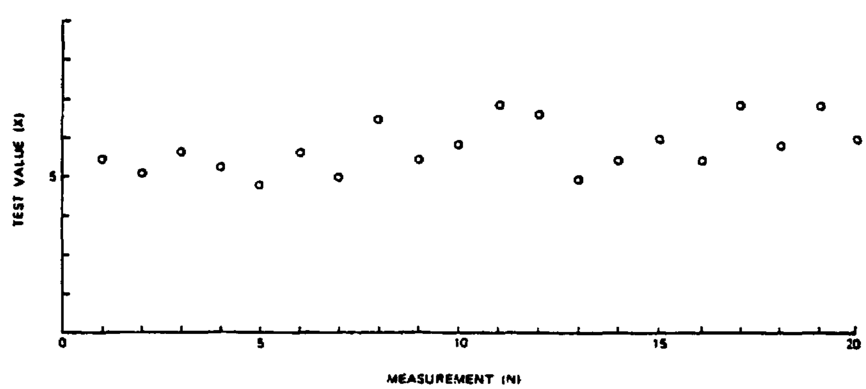

Figure 3-2: Illustration of sample test data

For a sequence of observations: $X_1, X_1, \ldots X_N$,

$$h_{ij} = \left.\begin{matrix} 1 \text{ if } X_i > X_j \\ 0 \text{ if } X_i \leq X_j \end{matrix}\right\} \quad \text{for } i<j$$

Also, let

$$A_i = \sum_{J=i+1}^{N} h_{ij}$$

and

$$A = \sum_{i=1}^{N-1} A_i$$

and when there is no trend and the probability of h equals to zero is 0.5 (or one half the h's equal 0), the mean value of A (μ_A) is

$$\mu_A = \frac{N\ (N-1)}{4}$$

and the variance of A (σ_A^2) is

$$\sigma_A^2 = \frac{N\ (2N+5)\ (N-1)}{72}$$

where N = number of observations

The acceptance region for no trend at the a level of significance will therefore be

$$\mu_A - \sigma_A Z_{\alpha/2} < A \leq \mu_A + \sigma_A Z_{\alpha/2}$$

where $Z_{\alpha/2}$ = Fractional points of the t-distribution at α-level of probability (i.e. tail areas under the curve). This is available in any mathematical handbook on t-Distribution Fractionals.

An example using the data in Figure 3-2 is given below.

Since $X_1 > X_2, X_4, X_5, X_7, X_9, X_{13}, X_{14}$, and X_{16}, $A_1 = 8$. Likewise, since $X_2 > X_5, X_7, X_{13}$, $A_2 = 3$. This can be repeated until A_{19} is obtained, as shown in Table 3-2. Substituting the data from Table 3-2 into the expressions for μ_A and σ_A gives

TABLE 3-2: 'A' VALUES FOR DATA IN FIGURE 3-2

$A_1 = 8$	$A_6 = 5$	$A_{11} = 7$	$A_{16} = 0$
$A_2 = 3$	$A_7 = 1$	$A_{12} = 6$	$A_{17} = 2$
$A_3 = 7$	$A_8 = 8$	$A_{13} = 0$	$A_{18} = 0$
$A_4 = 3$	$A_9 = 1$	$A_{14} = 0$	$A_{19} = 1$
$A_5 = 0$	$A_{10} = 3$	$A_{15} = 2$	

TOTAL A = 57

$$\mu_A = \frac{20(20-1)}{4} = 95$$

$$\sigma_A = \left[\frac{20(45)\ (19)}{72}\right]^{1/2} = 15.4$$

By solving the expression for the acceptance region for no trend, at the $\alpha = .05$ level of significance for a 20 degrees of freedom sample (i.e. $Z_{\alpha/2} = 2.086$), one gets

$$64 < A \leq 125$$

Since A = 57 (from Table 3-2) an upward trend is confirmed. A downward trend would be confirmed by A being greater than 125.

Parametric Trend Test Using Linear Regression Analysis

If in Figure 3-2, the horizontal axis was time (τ) and it could be assumed that a linear relationship existed between the measured value (X) and the time of measurement, this relationship can be expressed as

$$X = A + B\tau$$

where A is the linear intercept and B is the slope of the line and t is the constant time interval between points.

Estimates of the quantities B(b) and σ_X^2 (S_X^2) can be obtained from the expressions,

$$b = \frac{S\ (\tau X)}{S\ (\tau^2)}$$

$$S_X^2 = \frac{1}{N-2}\ (S\ (X^2)\ - b^2\ S\ (\tau^2))$$

where:

$$\bar{\tau} = \frac{1}{N} \sum_{i=1}^{N} \tau_i$$

$$\bar{X} = \frac{1}{N} \sum_{i=1}^{N} X_i$$

$$S\ (\tau^2) = \sum_{i=1}^{N} (\tau_i - \bar{\tau})^2$$

$$S\ (X^2) = \sum_{i+1}^{N} (X_i - \bar{X})^2$$

$$S\ (\tau X) = \sum_{i=1}^{N} (\tau_i - \bar{\tau})\ (X_i - \bar{X})$$

The acceptance region for no trend (B = 0) at the a level of significance is

$$- \frac{S_X}{(S(\tau^2))^{1/2}} Z_{N-2;\ \alpha/2} < b \leq \frac{S_X}{(S(\tau 2))^{1/2}} Z_{N-2;\ \alpha/2}$$

Where $Z_{N-2;\alpha/2}$ is the fractional points of the t-Distribution for N-2 degrees of freedom at a-level of significance.

For the example given in Fig. 3-2, the following values are obtained assuming time intervals of unity:

$\bar{\tau} = 10.5$

$\bar{X} = 5.755$

$S(\tau^2) = 665.0$

$S(X^2) = 8.0295$

$S(\tau X) = 34.2475$

$b = 0.0515$

$S^2{}_X = 0.3481$ which gives $S_X = 0.59$

For the acceptance region for no trend at $\alpha = 0.05$ level of significance, the fractional value for N = 20 degrees of freedom sample is given as:

$$Z_{N-2;\alpha/2} = Z_{18;0.025} = 2.10\ .$$

Substituting the above numerical values, the acceptance region for no trend at $\alpha = .05$ level of significance is calculated as before. The region is

$$-0.0480 < b \leq 0.0480$$

Since the estimates of the slope b is calculated to be 0.0515, an upward trend is detected as before.

3.2.2 Sudden Change Test

Use of Normal Tolerance Intervals

It is sometimes of interest to know if a test measurement is following the trend or is an "outlier" and is a sudden change from that predicted. Furthermore, a linear regression analysis on the data may not be desired.

For this case, consider the sequence of observations in Figure 3-2, X_1, X_2, ... X_N for which the average, X is

$$\bar{X} = \frac{1}{N} \sum_{i=1}^{N} X_i$$

and the estimate of the variance (S^2) is

$$S^2 = \frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X})^2$$

The acceptance region for no sudden change in X_{N+1} at the a level of significance is therefore

$$\bar{X} - SK < X_{N+1} \leq \bar{X} + SK$$

where values of K for α = .05 level of significance with 95 percent confidence are:

N	K	N	K	N	K
2	37.67	7	4.01	15	2.95
3	9.92	8	3.73	20	2.75
4	6.37	9	3.53	30	2.55
5	5.08	10	3.38	40	2.45
6	4.41	12	3.16	50	2.38

Substituting the values for $\bar{X}$ = 5.755, S = 0.65, and K = 2.75 from the data in Figure 3-2 into the expression for the acceptance region, the acceptance region for no change in X_{N+1} at α = .05 level of significance is,

$$3.94 < X_{N+1} \leq 7.52$$

Therefore, if X_{21} = 7, a sudden change is not detected, but if X_{21} = 8 a sudden change is detected.

Sudden Change Test Using Linear Regression Analysis

If the sequence of observations in Figure 3-2 were taken over N equally spaced time intervals and it is assumed that the linear relationship

$$X = A + B\tau$$

exists, then a test on the sudden change of a point from the predicted line can be constructed. If the expressions given for the estimates of B(b), and $\sigma_X(S_X)$ that were used previously are used here and the estimate for A(a),

$$a = \bar{X} - b\bar{\tau}$$

is calculated then the acceptance region for no sudden change in X_{N+1} at a level of significance is

$$a + b\,\tau_{N+1} - KS_X\, Z_{N-2;\,\alpha/2} < X_{N+1} \leq a + b\,\tau_{N+1} + KS_X\, Z_{N-2;\,\alpha/2}$$

where

$$K = \left[1 + \frac{1}{N} + \frac{(\tau_{N+1} - \bar{\tau})^2}{S(\tau^2)}\right]^{1/2}$$

If the data from Figure 3-2 are used to calculate the acceptance region at the $\alpha = .05$ level of significance, then a = 5.214, $\tau_{N+1} = 21$, K = 1.103, $S_X = 0.59$, and $Z_{18;\,0.025} = 2.10$. Substituting these values the acceptance region is given as:

$$4.93 < X_{N+1} \leq 7.66$$

If $X_{21} = 7$, a sudden change is not detected and if $X_{21} = 8$ a sudden change is detected as was found for the test using normal tolerance intervals.

4. OTHER ELEMENTS AFFECTING THE MAINTENANCE PROGRAMS

In addition to the performance evaluation and actual maintenance activities, the development of a good maintenance program (preventive or corrective) requires several other considerations. These include a good planning and management program, effects of human interaction, environmental and operational factors, test equipment and spare parts availability, and a quality assurance program with proper documentation. Each of these factors, although not essential, plays a major role in developing an effective maintenance program. More over, each of them is approached very differently by utilities. A general discussion on each subject is provided in this Section.

EPRI studies (8-9) provided excellent guidance for developing preventive maintenance programs which can play an effective and essential role in minimizing equipment failure and enhancing plant safety and availability. Other factors affecting the overall maintenance program are the existing preventative maintenance and surveillance programs, mandatory maintenance activities, regulatory and licensing requirements, plant monitoring instrumentation and designs, and the electricity rates. The Phase I study within the NPAR scope identified the major sources of motor failures experienced in nuclear power plants, and identified the functional indicators which can be measured and monitored to mitigate the most frequent failures. In the preceding sections, all of the techniques and procedures available to test or evaluate these functional indicators were discussed. This section describes other elements involving administration and cost aspects which must also be considered in developing an effective motor maintenance program.

4.1 Planning and Management

4.1.1 Budget and Scheduling

Managing the total maintenance budget and planning the different maintenance schedules in a power plant are interrelated activities. The total maintenance budget spent in a nuclear facility covers the two separate activities, corrective maintenance and preventive maintenance (PM). The latter can include both mandatory and discretionary programs. Mandatory programs are those required by operating experience, vendor warranty, government regulation or other safety regulations. Discretionary programs are performed at the plant operators discretion because benefits resulted from them may override the cost. It is typical that the cost for corrective maintenance takes a larger proportion of the total budget than the preventive. Since these two activities are strongly related, an effective preventive maintenance program (which might require a larger share of the budget) could significantly reduce the corrective costs. This kind of program management may better achieve safety goals, as well as improve the availability of power generation related equipment. Since nuclear facilities are required to maintain the above two goals, preventive maintenance is considered to be an even more important program.

Scheduling of PM activities requires a good planning effort by the management/supervisory team, including scheduling of the performance evaluation and maintenance activities illustrated in Figure 1-1. This depends on the availability of maintenance personnel, test equipment, maintenance tools, the equipment (i.e. motor) under maintenance, and many other plant specific factors. Consideration of all of these variables in the development of an effective maintenance schedule is extremely complex and, therefore a computerized system is essential.

4.1.2 Cost-Benefit Considerations

Optimization of the preventive maintenance interval (which includes condition monitoring) is easy to do in theory, but difficult to implement because of the lack of reliable data. Computer-based time dependent unavailability analysis (25,26) can be performed for planning the maintenance intervals, taking into account the plant risk factors. In this section the principles of a cost-benefit analysis for optimizing the maintenance interval will be discussed using a simple approach and giving an example of the analysis.

Principles of Cost-Benefit Analysis

To perform a cost benefit analysis for optimizing the PM interval (27) it is necessary to know the failure rates of the equipment in question and the costs associated with the PM and the repair costs (labor plus parts and services). Then the annual costs for repairing the equipment and for the PM can be compared.

The effect of periodic maintenance or monitoring on equipment can be evaluated if it is assumed that the equipment is restored to a "good as new condition" each time. The success in achieving this goal can be enhanced by performing condition monitoring (CM) in addition to the PM, which is commonly recommended by the vendor and ordinarily performed by maintenance personnel. The more parameters that can be evaluated to provide an accurate picture of the health of the equipment, the greater the probability of preventing an unexpected common-cause failure of a critical component. In fact, if regular CM is performed, then PM can be performed on condition rather than on a fixed schedule. This is the basis of a Reliability Centered Maintenance (RCM) program as used in the aerospace industry (28).

The failure rates for equipment are generally described by the classic bathtub curve which shows high instantaneous failure rates for very new and very old equipment, and a lower, random instantaneous failure rate in between these periods (29). The failure rates for equipment can be determined by collecting failure rate data as a function of time and finding a model to describe the data, so that predictions can be made. Below is a discussion of failure rate models taken from several sources (30,31) that are applicable to equipment in a nuclear plant.

The instantaneous failure rate, $\lambda(t)$ is defined as

$$\lambda(t) = \frac{dN_f(t)}{d(t)} \times \frac{1}{N_s(t)}$$

where:

$N_f(t)$ = number of devices failing

$N_s(t)$ = number of devices surviving

N_o = total number of devices under test

$$N_f(t) + N_s(t) = N_o$$

The probability density function, f(t) for the failure rate can be expressed by

$$f(t) = \frac{dN_f(t)}{dt} \times \frac{1}{N_o}$$

The Weibull Distribution is a very general failure distribution which applies to a large number of diverse situations. The failure rate can be expressed by

$$\lambda(t) = \frac{a}{\delta} \left(\frac{t-\tau}{\delta}\right)^{a-1} \quad \text{for } t \geq \lambda$$

where:

a = Weibull slope (shape parameter) which is a direct function of the uniformity of the item. The larger the slope, the greater the uniformity. For $a < 1$, $\lambda(t)$ is decreasing. For $a = 1$, $\lambda(t)$ is constant. For $a > 1$, $\lambda(t)$ is increasing.

τ = location parameter (determined from test data)

δ = data dispersion parameter (determined from test data).

The probability density function, f(t) for the normal distribution of failures can be expressed by

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(t-t_m)^2}{2\sigma^2}\right)$$

where:

σ = standard deviation (evaluated from test data)

t = age of equipment

t_m = mean wearout life (evaluated from test data)

The gamma distribution of instantaneous failure rates is appropriate for equipment subjected to an environment of repetitive and random shocks generated according to the Poisson distribution. In other words, when the rate of aging is random, the gamma distribution is appropriate. The probability density function for the gamma distribution, f(t), can be expressed by

$$f(t) = \frac{1}{b\Gamma(a+1)} \left(\frac{t}{b}\right)^{a} \exp\left(-\frac{t}{b}\right)$$

where:

Γ = gamma function

a,b = experimentally determined constants

Also, the instantaneous failure rate, g(t) can be expressed by

$$\lambda(t) = \frac{1}{b(a+1)}$$

The instantaneous failure rate for the Poisson Distribution of failures is for phenomena for which the average probability of an event is constant and independent of previous events. The failure rate is assumed constant in time so that

$$\lambda(t) = \lambda$$

Since the Poisson Distribution assumes a time independent failure rate, it is not important in the type of cost benefit analysis discussed in this section.

Application of a Cost-Benefit Analysis

A cost-benefit analysis for optimizing the maintenance (including CM) interval for a motor operated valve can serve as an example of how such an analysis can be performed. It is assumed that there is sufficient redundancy and diversity of the MOVs to make the probability of a forced outage so low as to be insignificant.

The cost for PM of a MOV will include the labor for performing visual inspection, meggering and measuring the polarization index. These costs are summarized in Table 4-1.

The optimum PM schedule can be determined by comparing the costs for performing PM with the costs of repairing the equipment, assuming a failure rate. While published literature on equipment failure rates is rare, Sheliga (32) collected data at Cleveland Electric Illuminating Company on 10,000 failures over several years for 23 categories of electrical equipment. From this compilation, it was found that the failure rate for the equipment could be expressed by

$$\lambda = \lambda_b \times P^2$$

TABLE 4-1: SUMMARY OF COSTS TO PERFORM PM AND TO REPAIR A SAFETY RELATED MOV

Cost to Inspect MOV	Engineer	Manhours Technician	Administration
Prepare Work Package & Hang Clearance Tags[a]	5	1/2	2
Prepare Work Area		1/2	
Travel to Equipment & Perform Tests		2	
Post Maintenance Testing		(not required)	
Complete Records & Submit to Records Management System	2		2
Total Labor to Inspect MOV	7	3	4

7 Engineering Manhours	x $45/hour =	$315
3 Technician Manhours	x $35/hour =	105
4 Administration Manhours	x $35/hour =	140

Total Cost to Conduct PM on one MOV (M) = $560

Cost to Repair MOV	Engineer	Manhours Technician	Administration
Prepare Work Package for Repair of MOV(a)	6	2	2
Prepare Work Area		1	
Disassemble MOV		3	
Repair by Vendor		4	
Reassemble Repaired Motor		3	
Post Maintenance Inspection	2	1	
Complete Records & Submit to Records Management System	2		2
Total Labor to Repair MOV	10	14	4

10 Engineering Manhours	x $45/hour =	$450
14 Technician Manhours	x $35/hour =	490
4 Administration Manhours	x $35/hour =	140

Total Cost to Repair MOV (F) = $1,080

[a] Quality Assurance review for Safety Related equipment is included.

where:

λ_b = a failure rate (in events per hour) when the maintenance interval is one year

P = the maintenance period in years

2 = an exponent that is an acceptable approximation for the data at Cleveland Electric Illuminating Company.

The annual repair cost (ARC) of the equipment can be expressed by

$$ARC = F \times \lambda \times 8760$$

where:

F = cost of an equipment failure

8760 = number of hours in a year

The annual cost of PM is

$$ARC_{PM} = M/P$$

where:

ARC_{PM} = annual cost of performing PM on the equipment

M = cost of performing PM on one equipment

P = the maintenance interval in years

The total annual cost of maintaining the equipment (TC) is

$$TC = ARC + ARC_{PM}$$

The optimum PM schedule is determined by plotting ARC, ARC_{PM} and TC with the maintenance period and observing the PM interval where the minimum TC is located. The annual cost to inspect the MOV (ARC_{PM}), the annual cost to repair the MOV (ARC) and the annual total cost (TC) are calculated in Table 4-1. The data used in the Table is based on discussions with personnel in the electrical maintenance department of a utility with a pressurized water reactor that entered into commercial operation approximately one year ago. The repair costs are representative of the most frequently occurring corrective maintenance for MOVs. Because of the generality of the assumptions in this example analysis the results are useful only for illustrating how to perform the analysis.

The failure rates for MOVs are obtained from the In-Plant Reliability Data Study (IPRDS) and have been summarized by Greenstreet et al. (B2). For motor driven globe valves, the failure rates were 48.0×10^{-6} per hour for one plant and 39.1×10^{-6} per hour for a second plant.

By using these expressions for calculating the costs for different PM intervals, the costs can then be plotted as in Figure 4-1, where the minimum total cost for maintaining the equipment is shown to be between nine months and one year. For the purpose of this analysis the failure rate is assumed to be 48.0 x 10^{-6} per hour for a preventive maintenance interval of one year.

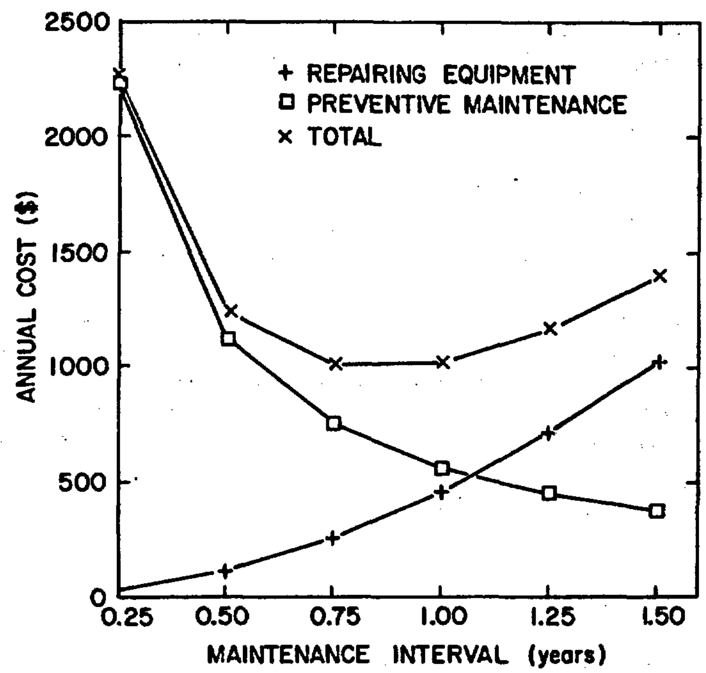

Figure 4.1: Optimization of the Maintenance Interval for a Motor Operated Valve

4.1.3 Qualified Personnel Acquisition

It is the responsibility of the management to hire qualified personnel for specific jobs. Operating experience has proved that unexperienced personnel performing maintenance was counter productive, sometimes even requiring corrective maintenance. Adequate staffing for the program is important for scheduling various maintenance activities in the plant. Since maintenance personnel undergo a specific training and orientation program for each job, longevity in the job is essential for a better maintenance program. Too many personnel turnovers, even after proper training, significantly affects the overall performances. A recent NRC study (33) comparing practices at Japanese and U.S. facilities proved that equipment performance in Japanese plants is superior to that in U.S. nuclear plants, as a result of differences in work ethics including low personnel turnover.

4.2 Human Factors

4.2.1 Personnel Training and Skills

Maintenance performed by unskilled personnel can be disastrous. Therefore it is important that job task analysis be conducted so that the necessary skills for each position are identified, and that training is implemented to teach these skills. Training should not be a one time event, but must be periodically refreshed and improved upon. INPO, NRC, and the nuclear utilities are expending considerable resources on improving NPP training.

4.2.2 Personnel Protection and Safety

Unlike fossil fuel power stations, nuclear power plant designs have motors in harsher environments, specifically, high radiation areas (inside containment and other fuel storages areas), where personnel exposure should be kept to a minimum. Motors located there must be monitored and maintained while minimizing personnel exposure to radiation. If needed, sophisticated monitoring devices, including probes mounted on the equipment (i.e. accelerometers, RTDs, transducers, etc.) can be provided to monitor its performance outside the high radiation area at the switchgear, MCC, or control room. Since maintenance, personal safety, and protection are specific for the particular equipment, all the precautionary measures should be included in its maintenance procedure. Notices and information on the particular equipment itself relative to human safety are considered to be a good practice as well.

4.2.3 Human Reliability

The Phase I study verified that electric motors do degrade with age and a number of performance measures were identified which may indicate the onset of motor degradation. In this study, the overall maintenance program was separated into two broad areas of activity aimed at mitigating the potential effects of equipment aging: (1) Performance Evaluation, and (2) Equipment Maintenance. Equipment maintenance involves actually maintaining the condition of the equipment, while performance evaluation involves only those activities undertaken to monitor signs of degradation due to aging. This section discusses the human factors which may be of importance in Performance Evaluation.

Periodic Testing

Periodic testing involves measuring performance indicators of a motor and test equipment to monitor those indicators. For example, to test phase-to-ground insulation on a motor, a maintenance technician would bring a shunt box to the motor, make certain connections to the motor terminals and record the resistance while operating the motor. Another example would be the removal of a part from a motor so that it could be brought to a laboratory for testing. These activities typically are planned and scheduled in advance, involve the use of written procedures, and are tasks for which training has been extensive.

The effectiveness of periodic testing is highly dependent on (1) the skill of the technician conducting the tests, and (2) the accuracy of the calibration of test equipment by the I&C staff. These two activities should be examined separately since a failure of either task could cause the results of the test to be misleading. (It must be noted that the actual conduct of the test may serve as feedback on the calibration; however, this mode of feedback cannot be relied on.)

These two areas of human activity should be examined using task analysis techniques to identify aspects of human performance which may be affected by performance shaping factors (PSFs). As an illustration, the testing task described above may be very dependent on the level of training given to the maintenance technician. If a certain application of periodic testing involves motors that require unique procedures compared to most other motors tested, a measure of whether training as a PSF significantly affects the likelihood of technician error can be ascertained from examining the training curriculum. If the unique procedure is not covered explicitly in the course material, then some other means of assuring adequate performance must be present (e.g. extensive explanation in the tasks procedures.) Task analysis allows for identification of these types of PSFs.

After a general task analysis has been undertaken, a logic model of the general tasks can be constructed. These models are very similar to an event tree and in the case of the particular testing task involved may be called a "Maintenance Technician Action Tree." It can be used to identify the most sensitive tasks from the standpoint of failure in conducting the overall test, and is done much the same way as the minimum cut-set runs for a PRA plant model.

Continuous Monitoring

Continuous monitoring involves reading or observing built-in performance measure indicators (i.e. instrumentation) at the location of the motor, motor control centers, or control room. For example, if an operator is checking the current draw on a particular motor he would walk to the location of the motor control center or switchgear and record his observation of the ammeter. While these activities are generally planned and scheduled, a certain amount of informal continuous monitoring also takes place. It would be useful to examine means of strengthening the informal level of continuous monitoring as well as assuring the quality of scheduled and planned activities.

Formal observations of equipment instrumentation normally are done according to a schedule, with procedures and checklists. In terms of these tasks, it can be assumed that training and procedures will be principal PSFs. Task analysis can identify those factors that are important in correctly performing these tasks and then develop review criteria for training curricular and procedures reflecting those factors.

The informal level of continuous monitoring occurs when an operator or technician is on other duties and comes close enough to a motor to observe its instrumentation. Much of the time, the individual will not have all necessaryreferences to note any small deviations from normal, but will be able to identify larger deviations, especially if indicators are appropriately marked with alert or red line values. The next step will be to notify the cognizant supervisor or otherwise communicate the information. Because of the small deviations which may characterize advanced signs of aging, these may remain unreported. As a consequence, there are two principal areas for examination in the realm of continuous monitoring on an informal level: (1) the success or failure of individuals to notice aging-related deviations from normal readings on built-in equipment instrumentation, and (2) the means by which these reading are reported, received and addressed in the overall plant organization.

The first area can be examined by task analysis. Some measures might be considered, like indicating safe operating ranges on meter faces or, for equipment that varies depending on plant operating conditions, posting near the instrumentation normal readings and acceptable deviations and regularly updating them. However, making an actual assessment of this area will require conducting a task analysis. The second area will require some degree of organizational analysis to identify optimal means of encouraging reports of deviant readings as expediently as possible.

Surveillance Testing

It would be possible to examine means of improving surveillance testing to provide information about the performance of motors. Generalized task analyses of tech spec performance monitoring tasks involving motors could be undertaken to find opportunities for gathering data on aging performance indicators and to transfer those data to the proper organizational sub-unit (e.g., maintenance, I&C, reliability program, etc.)

Inspection

Inspection can be defined as any activity which involves observation of performance measures which are not given by remote or built-in instrumentation, for example, the physical condition or appearance of motors, or water leaks in the area. These inspections are performed on a planned and scheduled basis. However, any operator can recognize significant deviations from an acceptable indicators if they are sensitive to them. Operators action models could be developed for the planned and scheduled inspection activities and also for informal observations during normal operation. In addition, informal inspection aids such as posting acceptable performance measures and deviations could be considered.

General Discussion

In addition to identifying the proper performance measures and developing reasonable means for assuring that the appropriate data will be collected, the final use and disposition of the data collected is clearly important. There are many human factors involved in data collection and analysis. Another area which should be systematically examined involves how the results of analyses are used to obtain optimal responses. It is likely that many of the indicators being monitored will be relatively minor, or are cumulative in nature so that an inductive approach should be used to decide on actions to be undertaken. In many cases the optimal response may be that no equipment maintenance actions will be taken, but rather increased performance measurements. It is important to consider human factors that affect the likelihood of an optimal response.

4.3 Environmental and Operational Factors

4.3.1 Environmental Conditions

The age of the motor, coupled with consideration of the environmental and operational characteristic, can help determine the frequency of maintenance. Motors in a harsh environment but not critical to safety or plant availability, are the least important and will have longer maintenance intervals, while those motors in the same environment and critical to the plant need to be maintained more frequently. As the age of the motor increases, its components degrade faster and hence, the maintenance intervals should be shortened until it is established that the required reliability is achieved. On the contrary, if a particular motor exhibits a higher reliability, the interval may be increased.

Good housekeeping and good operational procedures can increase the life of the equipment. Most motors in the plant are designed to withstand the designated environment and operating modes for their lifetime. However, in many cases, abusive operation and poor maintenance can accelerate the degradation process.

4.3.2 Operating Condition

Operating schedules of motors in the plant also dictate the maintenance schedule. For example, safety system motors that remain in standby during plant operation are maintained while not operating. Non-safety large motors (i.e. RCP and Recirculation Pump Motors) which are located inside the containment and are important to plant availability, are scheduled for maintenance during a plant outage. An optimized schedule should compromise between the need for keeping motors in operational readiness and keeping the plant operating while performing the evaluations.

4.4 Test Equipment and Spare Parts

4.4.1 Test Equipment, Tools and Procedures

Maintenance in nuclear power plants is constantly being upgraded with the advent of more sophisticated test equipment and tools. The test equipment industry has been facing the challenge to monitor and to maintain nuclear components in functional condition inside the containment. For motors, the industry developed many test devices for the age-related degradations of components as well as for their operability. The size of these devices has been decreasing with the use of microprocessors for performing in situ test on the component or at the control center.

The operating experience of motor performance in nuclear facilities shows that the bearings and insulating systems are the significant contributors to motor failures (7). Abnormal vibration measurements typically are indicative of either bearing or stator core degradation. Large motors are often equipped with built-in vibration transducers at the bearing housings for continuous monitoring. During the last decade, portable vibration monitoring units with Fast Fourier Transform (FFT) capability became available for testing the velocity response of smaller motors. The frequency content of the response is used to diagnose the root-cause of motor component degradations with age.

For insulating systems there are available power factor, insulation resistance, partial discharge, hi pot, and ac/dc leakage test units, together with corona detections for higher voltage machines, for periodic testing of the motor dielectric integrity. This equipment often is used at the control center instead of the motor physical location (Figure 4-2). In such cases, the test results indicate the condition of the motor supply cable and the motor winding insulations.

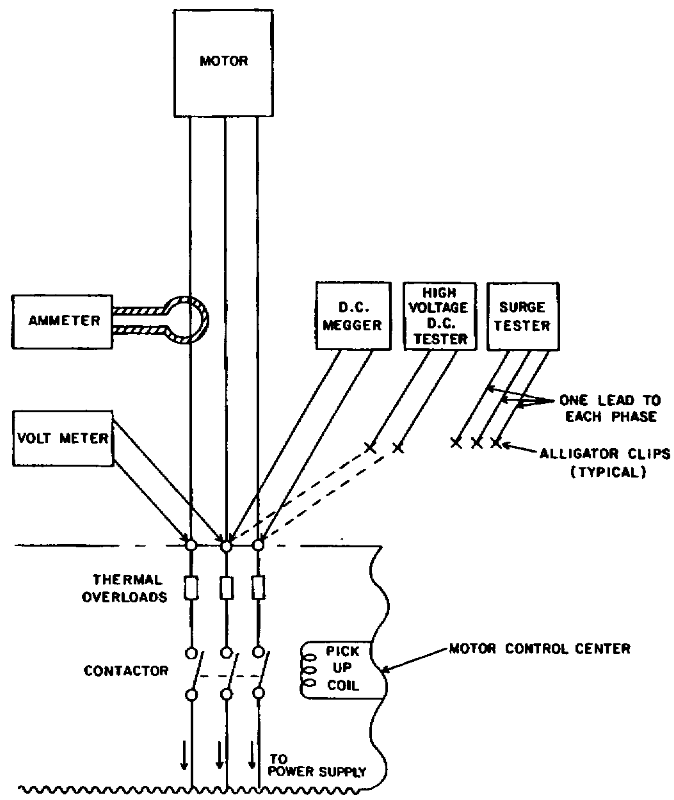

Figure 4.2: Block diagram for test instrument location at the plant

4.4.2 Spare Parts

Unavailability of motor replacement parts during scheduled maintenance may impede the plant safety as well as plant availability. A typical motor contains many different parts especially in case of large units. Maintaining spare parts for each subcomponent within a motor is unwise and uneconomical. However, sub-components which degrade with age (i.e. gaskets, seals, lubrications, etc.)or have significant wear as the motor runs (i.e. brushes, bearings, etc.), are required to be readily available at the plant with proper qualifying documents. The effect of storage of those parts should be considered in evaluating the overall life of these components. Other considerations for procuring spare parts for safety-motor use should include the dedication programs to use nonsafety-related and/or commercial grade parts.

4.4.3 Vendor Assistance/Manuals

Each motor from the manufacturer is furnished with instructions for installation and operation of the machine. These manuals generally describe the standard warrantee policy, handling and storage instructions, installation procedures, electrical connections, insulation resistance characteristics, operational characteristics, maintenance instructions for all subcomponents, renewal parts list, line-by-line instructions for assembling and disassembling the motor, and discussions of any special features in the machine. They also include common problems and remedies that are useful to keep the motor operating. Therefore, it is important that the maintenance crew should become familiar with the machine prior to performing any diagnosis on the motors. These manuals should be stored either in the qualification document for the particular motor or at the machine location for easy reference during the maintenance. Often manuals are updated or maintenance bulletins are issued by the manufacturer, with whom periodic contact should be maintained to ensure that the utility has the latest technical information and manuals.

Rarely, a case comes up where the abnormal motor performance is beyond the scope of the instruction manuals or the maintenance engineer. In such events, prompt vendor assistance for bringing the motor to operation should be available.

Unless proven otherwise, it is a good practice to utilize the replacement parts and grease or oil recommended in the manufacturer's instruction manuals.

4.5 Quality Assurance and Documentation

4.5.1 Quality Assurance

In operating a nuclear power plant in United States, the utility company is required to adopt a detailed quality assurance (QA) program, as required by 10CFR50, App. B, for all activities affecting the safety-related structures, systems, and components. These activities include designing, purchasing, fabricating, handling, shipping, storing, cleaning, erecting, installing, inspecting, testing, operating, maintaining, repairing, refueling and modifying. Quality assurance comprises all those planned and systematic actions necessary to provide adequate confidence that a structure, system or component will perform satisfactorily in service. It also includes quality control (QC) which comprises those assurance actions related to the physical characteristics of a material, structure, component, or system.

All maintenance procedures and activities, therefore, are required to have a quality assurance program, when used on safety related motors. Test equipment procedures, use of spare parts, and other related activities should contain a quality control mechanism to ensure the functional readiness of the equipment. Some aspects of the QA/QC Program are often applied to other important motors in the plant.

4.5.2 Technical Specifications

Each motor performing a safety function in a nuclear power plant is subjected to the technical specification (tech spec) requirements for its system defining the allowed outage times (AOTs) and surveillance test intervals (STIs). Typically, tech spec requirements are applied when a motor fails to deliver its intended function. These activities are described under surveillance tests in Appendix B.

Since the objective of a good preventive maintenance is related to that of the tech spec activities involving safety motors, the scheduling of tests and maintenance should be chosen to be commensurate with the tech spec intervals. It should be noted that there are no specific tech spec requirements for motors alone, however, this requirement for motor operated valves and motor driven pumps also include the driver.

4.5.3 Documentation

One of the differences between operating a nuclear facility and a non-nuclear facility is maintaining a documentation file on each safety-related component. Because of the volume of information, many utilities prefer a computerized handling system to afford easy access and control on the data. The data base includes all pertinent equipment records, such as name plate and manufacturing data, qualification documents, instruction manual, and other design information. Inspection and maintenance records, checklists and their schedules also are part of the system for training or future reference.

5. REVIEW OF CURRENT MAINTENANCE PRACTICES IN INDUSTRY

Prior to assessing a maintenance procedure for motors, it is important to gain an understanding of the current practices in motor maintenance in nuclear plants. Surveying all nuclear facilities for this information is beyond the scope of this study. However, a representative sample of maintenance and surveillance programs were reviewed by Sugarman and Sheets (34) and are described here. Section 5.1 gives the details about the surveyed plants, Section 5.2 includes the survey results, and 5.3 discusses the current trends in industry in evaluating the motor performances.

Although no definitive condition monitoring program exists in any of these plants, the trend in American utilities is to:

a. Establish computer data bases which contain files for maintenance histories, seismic and environmental qualification, replacement parts, etc..

b. Perform "Condition Monitoring" on equipment which previously was only maintained.

c. Use increasingly sophisticated techniques for obtaining physical data that can diagnose anomalies associated with equipment failures.

The reason for these trends is the concern by the Nuclear Regulatory Commission and the utility industry for achieving a greater assurance of the reliability of safety related and important-to-safety equipment as well as the pressure on the utilities to improve the availability of their plants. Section 5.4 summarizes industry standards applicable to motors. Section 5.5 discusses the EPRI Survey [Motor Maintenance/Surveillance Survey (MM/SS)] on motors. The last section 5.6 concludes the results from the four plant surveys.

5.1 Description of Surveyed Plants

Four stations (two PWRs and two BWRs) were included in the survey on motor maintenance procedures. The A-PWR station includes two units which began commercial operation within the last five years. The construction permits were issued in 1973. This station has well developed preventive maintenance (PM), corrective maintenance and surveillance programs.

The B-PWR station includes two units which began commercial operation in last ten years. This station has a well developed, computerized PM program in which work orders are automatically displayed on a screen at the time they are to be performed, and are transmitted to the Maintenance Department which attaches a procedure to them before they are taken into the field. The Work Planning and Tracking System Department is developing a trending program for the PM data.

The C-BWR station began commercial operation in 1984. This station has a comprehensive computerized PM program and a well developed corrective maintenance program. The PM program has provisions for the required plant modes, special plant conditions per the technical specifications, the desired start and completion date, critical completion date and historical schedular data in addition to the information commonly provided (i.e. description and identification of the component, task numbers and the task description).

The D-BWR station includes two units which began commercial operation in the early 1970's. The station is developing a PM program, but at present relies only on its surveillance and corrective maintenance programs.

According to their recent Systematic Assessment of Licensee Performance (SALP) ratings, these plants have had average rating on maintenance programs and hence, could be considered as typical programs, neither exemplary nor in need of major improvement.

5.2 Summary of Survey Results

The maintenance and surveillance requirements for several different types of motors and motor operators are summarized in this section. Only those tests are included which could provide quantitative data for motors and which are suitable for trending. For example, maintenance procedures for adjusting torque/limit switches, inspecting the oil level in the gear case, overhauling motors, cleaning components, changing seals, are omitted, as are the procedures for the maintenance and surveillance of driven equipment, such as pumps, valves and fans. Some of the procedures for the driven equipment, however, are included for trending the vibration test results which are important for continuous duty motors.

While most of the procedures are for small motors, the same procedures are used on high voltage motors (e.g. those greater than 4.16 kV).

Meggering of insulation resistance is performed by the plants. Some plants require that the phase-to-ground and phase-to-phase insulation resistance be measured, while others require only a phase-to-ground insulation resistance test. Since the phases in most electric motors are electrically connected to each other internally it is not clear how the phase-to-phase insulation resistance can be measured unless the phases are determinated. Some of the plants correct the megger values for the resistance at 40:C, according to the requirements in IEEE Standard 43. Some of the procedures specify that the reading should be taken after waiting one minute while other procedures have no such instructions. The acceptance criteria for the insulation resistance varies; some plants require the minimum insulation resistance be greater than a fixed number (e.g. 1.5 megohms) while other plants use a formula provided in IEEE Standard 43 to establish the minimum acceptable level.

Some plants perform a polarization index (PI) test and at one plant the test is performed at two pairs of durations - 10 minutes/1 minute and 60 seconds/30 seconds intervals. It was required by one plant that the ambient temperature be < 40°C before the PI be taken. The effect of temperature on the PI is not well known, but there may be some effects because the leakage current is the sum of several different components, each making different contributions to the total absorption current over time and having different temperature coefficients. The acceptance criteria for PI varies from 1.4 to 2, with no reference made to the motor insulation class. The IEEE standard 43 recommends minimum PIs of 1.5 (for Class A insulation), 2.0 (for Class B insulation) and 2.0 (for Class F insulation). None of the plant procedures reviewed indicated a recognition of the fact that even though the PI may be better than the specified value, the resistance readings in the ratio may be so low that the acceptability of the test should be questioned. On the other hand, low PI values may be the ratios of acceptably high resistance readings.

The valve motor running current is measured by three of the utilities. The acceptance criteria established by one of the utilities was a reading of $< 125\%$ of the nameplate current. This value is within the range of service factors (a multiplier for the permissible horsepower loading which may be carried under specified conditions) recommended in NEMA Standard MG1-12.47 for General-Purpose Alternating-Current Motors.

The range of service factors in NEMA Standard MG1-12.47 for a four pole motor is 1.15 (for a 1-1/2 to 125 H.P. motor) to 1.4 (for a 1/20 H.P. motor). MOV running current screening values are also being developed based on manufacturer recommendations.

Other motor tests are:

a. Motor noise and vibration
b. Motor winding continuity
c. Phase rotation
d. Stroke time
e. Leakage in valve pressurized with nitrogen
f. Measurement of limit/torque switch actuation cycle, motor running current, valve stem thrust with MOVATS.

The motor maintenance and surveillance procedure formats were compared to evaluate the consistency among nuclear plants: the results are summarized in Table 5-1. They showed that certain portions of the procedure, such as objective (or purpose), references, prerequisites (or special tools or equipment), precautions, procedure (or instructions) and sign-offs were found in all cases. Most of the procedures had tables of contents (or indices) and some had sections for acceptance criteria, post-maintenance testing (or restoration) and records. The "Records" Section is generally a statement directing the maintenance personnel to complete certain data forms and forward them to the responsible supervisor.

The only surveillance test performed on MOVs is stroke time. The procedures for the plants reviewed always provided acceptance criteria either on the data sheets or by referring to the Technical Specifications, Safety Analysis Report (SAR) and NSSS Vendor Specifications. The surveillance tests did not always require that the test data be recorded but only a statement on the acceptability of the test results (a yes or no response).

It is noteworthy that the data record requires that both the uncorrected and corrected resistance readings be entered and the acceptance criteria are provided in the maintenance procedure.

The PM frequency on equipment in different systems may have different schedules and tasks depending on their quality classification (e.g. safety related, not safety related, important to plant availability) and their function. Table 5-2 illustrates some test frequencies which are performed on rotating electrical equipment.

TABLE 5-1

ORGANIZATION OF MAINTENANCE AND SURVEILLANCE PROCEDURES

PLANT A - PWR	PLANT B - PWR	
Maintenance Procedure XXXXXXXXXXXX and Operator Surveillance Test XXXXXXXXXXXX	Preventive Maintenance - Electrical XXXXXXXXXXXX	Electrical Maintenance Procedure XXXXXXXXXXXX
Table of Contents	System	Index
Objective	Component	Purpose
References	PM Description	References
Prerequisites	Initial Conditions & Precautions	Prerequisites
Precautions	PM Code	Tools & Special Equipment
Check-Off List(s)	Related PM(s)	Initial Conditions
Procedure	References	Limits & Precautions
Records	Special Tools & Materials	Instructions
Attachments	Procedure	Post Maintenance Checkout & Testing
	Acceptance	Attachments[a]
Sign Offs:	Sign Offs:	Sign Offs:
Prepared by:____________	Completed by:____________	Recommended Approval:____________
Approved by:____________	Supervisor:____________	QC Reviewed:____________
		Approved by:____________ (Chairman Station Nuclear Safety and Operating Committee)

[a]These procedures are two sided, single sheet formatted.

TABLE 5-1 (Continued)

PLANT C - BWR				PLANT D - BWR
Maintenance Instruction XXXXXXXXXXX	Maintenance Instruction XXXXXXXXXXX	Maintenance Instruction XXXXXXXXXXX	Plant Operations Manual (POM) Procedure XXXXXXXXXXX	Maintenance Procedure - XXXXXXXXXXX Maintenance Surveillance - XXXXXXXXXXX Operators Surveillance -XXXXXXXXXXX
Table of Contents	Table of Contents	Purpose	Table of Contents	Purpose
Purpose	Purpose	Discussion	Purpose	References
References	References	References	(Equipment Location)[b]	Prerequisites
Special Tools & Equip.	Special Tools & Conditions	Special Tools or Equip.	References	Precautions
Precautions & Limitations	Initial Conditions	Precautions and Limitations	Required Equipment	Limitations and Actions
Prerequisites	Test Procedure	System Initial Conditions	Precautions & Limitations	Procedure
Procedure	Dynamic Testing	Procedure	Prerequisites	Checklists
Post Maintenance & Testing	Restoration	Records	Procedure	Technical Specification References
Restoration	Enclosures		(Acceptance Criteria)[a]	
Enclosures	Attachments		(Enclosures)[a]	
Attachments			(Attachments)[a]	
Sign-Offs:	Sign-Offs:	Sign-Offs:	Sign-Offs:	Sign Offs:
Originated by:__________	Originated by:__________	Originated by:__________	Name of Preparer:__________	(On Data Sheet Only
Approved by:__________	Approved by:__________	Approved by:__________	Technically Reviewed by:__________	
			Reviewed/Concurred by:__________	
			Approved by:__________	
			(Additional for Safety-Related or Superintendent - Designated Procedures	
			Recommended by:__________	
			Approved by:__________	

[b]Not on all procedures.

TABLE 5-2: PM TEST FOR SOME ROTATING MACHINERY AT A NUCLEAR PLANT

Equipment	Test	Inspection Frequency (Days)
Recirculation Pump Motor MG Set	Inspect Motor and Generator Windings, PI	550
Control Rod Drive Pump Motor	PI	550
RHR Service Water Pump Motor	Clean and Inspect Motor and Bearings, PI	550
Reactor Feedwater Pump Motor	Clean and Inspect Motors, PI	550
Booster Pump Motor	Clean and Inspect Motor and Bearings, PI	550
Diesel Generator Cool Water Pump Motor	Clean and Inspect Motor, Replace Bearings Megger	550
Main Generators and Alternating Exciter	Visual	Weekly (if running)
Main Generator	Shaft Voltage Readings, Megger, Hydrogen Seals, Brush Length, Inspect Brush Lenght, Vibration, Rings, Shunts	7
Main Generator	Clean and Inspect Brush Rigging, Replace Brushes,	550
	Check Connections, Inspect Rings, Clean Exciter, Filter and Housing	
Emergency Bearing Oil Pump Motor	Clean and Inspect Motor, Check Brushes and Holder Megger	550
Ac Motor Inspection	Winding Resistance, PI, Oil Level, Running Current, Vibration, Visual	550
250 VDc Motor Inspection	Inspect Brushes, Communicator, Field Resistance, Armature Resistance, Megger (Field, Armature), Running Current in Field, Armature, Vibration	550
Recirculation Pump Motor Motor/Generator Inspection	(Procedure Not Available)	550
RPS Motor Generator Set	Inspect Motor and Generator Check Brushes and Holders, PI	550

5.3 Motor Performance Evaluation

In recent years, several utilities initiated computer based maintenance programs. One of the reasons for this is a concern for achieving a greater assurance of the reliability of safety related equipment, as well as the economic consideration of improved plant availability. A similar trend has been observed in the electrical equipment manufacturing industry where instrument systems have been developed that can be programmed to conduct tests, gather data, compensate for temperature and automatically measure important parameters. Portable test units also are available for instantaneous measurement of functional indicators without disassembly of equipment.

To improve reliability and performance and to reduce radiation exposure to personnel, a remote monitoring program should be established to evaluate and diagnose the testing data. This is typically referred to as condition monitoring or trending of test data, using various functional indicators that are specifically chosen for the particular component. This data base is further augmented with advanced information such as pattern recognition, statistical analysis, signature analysis, and human factors engineering. The result is a better understanding of equipment performance and earlier warning of developing problems due to aging or service wear, so that operations and maintenance planning is improved at an incipient stage.

A computer-based monitoring system is being implemented at Grand Gulf nuclear station (35) that utilizes process and vibration instrumentation to monitor the operational performance of 14 major pumps, 2 drive-turbines, 12 motors, 3 air compressors, the high and low pressure turbines, and the generator-exciter. The system monitors about 300 process variables and 200 vibration signals in each unit. The overall program addresses a wide spectrum of issues that affect the evaluation of machinery performance during all phases of the total plant cycle, including pre-operation, start up, power operation, and outages.

Other U.S. utilities have established computerized data bases or are in the process of doing so. Northeast Utilities Company (NU) developed a computer-based Preventive Maintenance Management System (PMMS) which provides equipment data including make, model, serial number, bill of material data and space for comments (36). The database is in a central computer that is accessible by terminals throughout the NU generation and staff facilities. Another example of the trend to computerization of nuclear plants is the Plant Information Management System (PIMS) which began development in 1983 by Pacific Gas and Electric Company (PG&E) in San Francisco. This system, which is nearing completion, will contain the following database:

- equipment
- commitment
- records management
- vendor lists
- warehouse stock
- equipment parts list
- bill of materials
- recurring tasks

- outage work breakdown structure
- technical specification procedures
- in-service inspection procedures
- preventive maintenance procedures
- surveillance test procedures.

The PIMS is installed on an IBM 4341 computer using the Multiple Virtual Storage (MVS) operating system and IBM compatible communication software, file structures, and COBOL programming (37).

Some utilities have installed Personal Computer (PC) databases for weak-link materials found in safety-related equipment. The data bases predict the amount of aging which has occurred in these materials for given environmental temperatures, and to keep track of changes made in the field to environmentally qualified equipment. With this system, one has a technical basis for extending the qualified lives of such equipment.

As licensees of the U.S. Nuclear Regulatory Commission, the utilities are required to perform regularly scheduled surveillance on certain safety-related instruments and equipment to insure that they are operating according to the technical specifications for the plant. There is some evidence to suggest that the stringent surveillance to which certain equipment is subjected results in improved availability (38). Nuclear utilities are beginning to recognize the advantages of equipment surveillance and are beginning to focus attention on this area (39). Also, it should be noted that in some cases, such as diesel generators, stringent surveillance (too many cold starts) can degrade equipment performance.

Nuclear utilities are currently searching for, and implementing more sophisticated surveillance techniques to improve equipment reliability. For example, some plants (e.g., Nine Mile Point #1, Oyster Creek Nuclear Generating Station), are obtaining signatures of the thrust and torque/limit switch actuation to diagnose degradation in MOVs, using MOVATS system. Manufacturers of test equipment are responding to the trend toward more sophisticated surveillance equipment. Some instrument companies are marketing an insulation analyzer for equipment such as motors, cables, etc. which uses newly developed algorithms in conjunction with microprocessor control to automatically select test voltage, gather data and calculate the true insulation resistance after a short, ten-minute test. An important feature of this instrument is its ability to discriminate among the three different components of the charging current (geometric capacitance current, absorption current, and conduction or leakage current (40). It is the conduction (or leakage) current which is generally sought in an insulation tests.

Surveillance tests to monitor the performance and mechanical operation of the valve motor operator can provide other data through interrelated aspects of valve stem thrust signature analysis and limit/torque switch performance, and may be obtained with the MOVATS system or the system being developed by ORNL in its phase 2 NPAR study on motor operated valves.

TABLE 5-3(a)

INDUSTRY STANDARDS FOR TESTING THREE PHASE INDUCTION MOTORS

Standard	Title	Tests	Acceptance Criteria[(a)]	Comments
ANSI/IEEE 4-1978	Standard Techniques for High Voltage Testing (Supersedes IEEE 29-1941 and ANSI/IEEE 322-1972).	Direct Voltage Rated Withstand Voltage Test Assured Disruptive Discharge Voltage Test Alternating Voltage Rated Withstand Voltage Test Assured Disruptive Discharge Voltage Test Lightning - Impulse Voltages Rated Withstand Voltage Tests 50 Percent Disruptive - Discharge - Voltage Tests Assured Disruptive - Discharge Voltage Tests Switching - Impulse Voltages (Same as for test with Lightning - Impulse Voltages) Impulse Currents	None	
ANSI/IEEE 43-1974	Recommended Practice for Testing Insulation Resistance of Rotating Machinery	Insulation Resistance	R_m J kV + 1 PI (Class A) J 1.5 PI (Class B) J 2.0 PI (Class F) J 2.0	
IEEE 85-1973 (Reaffirmed 1980)	Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery	Sound Power Levels Sound Pressure Levels	None None	
IEEE 95-1977	IEEE Recommended Practice for Insulation Testing of large AC Rotating Machinery with High Direct Voltage	Controlled Overvoltage Test	None	An abrupt change in slope of I vs V curve could mean failure is imminent. Any deviation from a smooth curve is a warning. Recommended ratio of direct voltage to power frequency voltage (rms) is 1.7 for acceptance and maintenance tests.

(a) Definitions of terms in equations are given in Table 2-3 (b).

Notes:

1. Formulas for calculating motor torque from acceleration and from the input power are also given in this standard.
2. 30 volts per turn is normal maximum value for motors.

TABLE 5-3(a)

INDUSTRY STANDARDS FOR TESTING THREE PHASE INDUCTION MOTORS
(continued)

Standard	Title	Tests	Acceptance Criteria[a]	Comments
IEEE 112-1983	Standard Test Procedure for Polyphase Induction Motors and Generators	o Current resistance in stator and rotor	None	Temperature correction: $R_s = R_t = (\frac{t_s + k}{t_t + k})$ ohms
		o Efficiency	None	
		o Losses	None	
		o Slip	None	Temperature correction: $S = s\,(\frac{t_s + k}{t_t + k})$
		o Power factor	None	$PF(3\phi) = \frac{\text{watts}}{\text{line volts x line amperes x 1.732}}$ or $PF(3\phi) = \frac{1}{1 \times 3\ (\frac{W_1 - W_2}{W_1 + W_2})^2}$
		o Tests with no load (current, loses)	None	
		o Tests with load (efficiency, power factor, speed, temperature rise)	None	
		o Tests with rotor locked (current, torque, power impedance, rotor voltage)	None	$T\ (\text{indirect}) = \frac{k(P_{SI} - P_{CU} - P_C)\ c_1}{n_s}$
		o Tests for speed-torque and speed-current	None	$T = \frac{k\ (P_{GO} + P_{GL})}{n}$ (See Note 1)
		o Motor temperature rise	None	$t_t = t_b + (\frac{R_t - R_b}{R_b})\ (t_b + k)$
		o Insulation resistance	None	No temperature correction for tests at < 3,300 feet and 10°C < R. T. 40°C
		o High potential test	None	
		o Winding resistance measurements	None	
		o Shaft/Current and bearing insulation	Deflection of voltmeter needle or "color" in a lamp filament is not satisfactory	

TABLE 5-3(a)

INDUSTRY STANDARDS FOR TESTING THREE PHASE INDUCTION MOTORS
(continued)

Standard	Title	Tests	Acceptance Criteria[a]	Comments
IEEE 112-1983 (Continued)		o Vibration	None	
		o Noise	None	
		o Overspeed	None	
ANSI/IEEE 117-1974 (Reaff. 1984)	Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random would AC Electric Machinery	Thermal aging	None	Acceptable methods for heating motors are; larger than normal air gaps, superimposing a dc current on the ac current, plug reversal, restricting ventilation, increasing surrounding air temperature.
ANSI/IEEE 286-1975 (Reaff. 1981)	Recommended Practice for Measurement of Power Factor Tip-Up of Rotating Machinery Stator Coil Insulation	Power Factor Tip-Up	None	
ANSI/IEEE 429-1972	Standard Test Procedure for the Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Stator Coils	Tests to simulate exposures of coil to temperature, vibration, humidity and water immersion.	None	
ANSI/IEEE 432-1976 (Reaff. 1982)	Guide for Insulation Maintenance for Rotating Electrical Machinery (5HP to less than 10,000 HP)	Tests to discern existing weakness		
		o Insulation resistance at low voltage	IEEE 43-1974	
		o Dielectric absorption (PI)	IEEE 43-1974	
		o Overvoltage (at 60 Hz, 0.1 Hz, dc)		
		o Interturn - Insulation	New Machine: 500 Vrms per turn Maintenance: 1/2 to 2/3 new coil test or 8 to 10 x normal operating (See Note 2)	
		o Slot discharge and corona - probe tests (Applicable to machines with operating voltages	None	

TABLE 5-3(a)

INDUSTRY STANDARDS FOR TESTING THREE PHASE INDUCTION MOTORS
(continued)

Standard	Title	Tests	Acceptance Criteria[a]	Comments
ANSI/IEEE 432-1976 (Continued)		> 6000 V)		
		o Rotor winding impedance	None	
		Tests to give indication of expected service reliability:		
		o Insulation power factor test (Applicable to machine with operating voltages > 6000 V)	None	
		o Controlled overvoltage test (dc)	None	
		Other special tests		
		o Stator core interlamination insulation test	None	
IEEE 522-1977 (Reaff. 1981)	Guide for Testing Turn-to-turn Insulation on Form Wound Stator Coils for AC Rotating Electric Machines	o Surge Testing	~10% or greater in magnitude or frequency of pulse waves indicates probable failure. $V_p = K_1 V_L$ V_p = minimum turn-to-turn proof test voltage as measured by the momentary peak test voltage across the coil. K_1 = empirical factor (1.0 suggested for trial use) V_L = rated rms line-to-line voltage	
No IEEE Std. Number Available	IEEE Recommended Practice for the Evaluation of the Impulse Voltage Capability of the Insulation System for Ac Electric Machinery Employing Form Wound Stator Coils. For Trail Use. (Draft)	Impulse Testing of aged formettes	$U_p = 4U_n + 5$	

TABLE 5-3 (b): DEFINITIONS OF TERMS USED IN TABLE 5-3 (a)

Rm	=	recommended minimum insulation resistance in megohms at 40°C of the entire machine winding
V	=	voltage
PI	=	polarization index
R_s	=	winding resistance, corrected to specified temperature t_s, ohms
R_t	=	test value of winding resistance, ohms
t_s	=	specified temperature, °C
t_t	=	temperature of winding when resistance was measured, °C
k	=	234.5 for pure copper, 225 for aluminum based on a volume conductivity of 62% (used in equations for R_s and S)
S	=	slip corrected to standardized stator temperature, t_s
s	=	specified temperature for resistance correction
PF	=	power factor
W_1	=	higher reading wattmeter
W_2	=	lower reading on wattmeter
T(indirect)	=	locked rotor torque not measured directly
P_{SI}	=	input power to stator, kW
P_{CU}	=	stator I^2R loss (a) in kilowatts at the test current
P_C	=	core loss in kilowatts at test voltage
n_s	=	synchronous speed, r/min
c_1	=	a reduction factor (varying between 0.9 and 1.0 to account for nonfundamental losses
k	=	9549 for T in N.m, 7043 for T in lb • ft. (used in equation for T)
P_{GO}	=	output of direct-current generator, kW
P_{GL}	=	losses of direct-current generator (including friction and windage), kW
n	=	test speed or motor, r/min
R_s	=	reference value of resistance previously measured at known temperature t_b, ohms
t_b	=	temperature of winding when reference value of resistance R_b was measured,°C
U_p	=	rated lightning impulse withstand voltage (peak) in kV.
U_n	=	rated voltage in kV

(a) At the temperature of the locked rotor test

5.4 Industry Standards for Motors

While industry standards for motors are not written specifically for field testing, there are IEEE standards that provide guidance for monitoring the condition of motors in the field. These tests are summarized in Table 5-3. Many of these tests are referenced in the NEMA MG1 set of standards for the performance, safety, testing, construction and manufacture of all types of motors.

Some of these standards, such as ANSI/IEEE Standard 43-1974 (for the minimum insulation resistance and polarization index), and ANSI/IEEE Standard 4-1978 (for interturn insulation resistance) provide acceptance criteria. Even though the standards lack the specificity that would make them more valuable for maintenance testing and condition monitoring, the guidance and acceptance criteria could be useful, in conjunction with industry experience, in providing a more standardized systematic approach to conducting maintenance and surveillance testing.

5.5 EPRI Survey on Motors

In response to the draft NPAR Phase II motor report, the EPRI Equipment Qualification Advisory Group (EQAG) conducted, March 1987, a Motor Maintenance/Surveillance Survey (MM/SS) of the 56 EQAG member utilities with operating plants (44). Twenty-six plant sites responded from 24 utilities and the results were analyzed to augment the BNL survey findings based on the four plant discussed earlier.

While the practices do vary among utilities, there exists no distinction in practices for safety related and non-safety related motors. The scope of the motor PM program appeared to be relatively independent of plant age. Although, there is good agreement with the BNL findings, the survey suggests extensive practices for large motors. Dielectric tests such as power factor, surge, partial discharge tests are not typically performed by the industry, nor are they believed to be useful. With exception to a few test frequencies, the survey responses support many of the recommended PM practices identified in the BNL draft report.

Dielectric Tests and Monitoring - Insulation resistance and polarization index testing are the dielectric tests performed most often on motors. The former test ratings decreased with motor size while the latter test is reserved primarily for large and intermediate size motors. Although trending of these parameters are recommended by a few, no assessment on the benefit of this activity with the aging condition of the insulation is provided. Other insulation tests including hipot, power factor, surge, and partial discharge are not considered as effective PM tests.

Monitoring of input voltage has no usefulness while the motor current data is largely used to determine if an excessive load is being placed on the motor during valve cycling, particularly during valve seating and unseating. The ratings of this parameter for continuous duty motors appear mixed but clearly favor the use of motor current for large motors. Use of winding temperature data is favored for large motors and is clearly not recommended for small motors and MOVs. Trending of this data is performed by 12 utilities for large and intermediate size motors.

<u>Bearing Tests and Monitoring</u> - Bearing tests include vibration tests and lubrication analysis. The vibration data is trended by 20 out of 26 respondents where a few trended bearing temperatures. Although the vibration trending has been proven beneficial, it is strongly recommended for large and intermediate size motors. The ratings are mixed for small motors excluding MOVs. Similar findings are reported for lubrication analysis and bearing temperature monitoring with a few utilities performing this test on strictly large and intermediate size motors.

Speed measurement is neither performed nor recommended as an effective PM activity. However, one respondent indicated that speed should be periodically measured for MOVs.

<u>Valve Stroke Timing</u> - All safety related MOVs are required to be valve stroke timing tested according to the plant technical specifications and ASME Section XI. Half of the respondents appear to be performing no such testing for non-safety MOVs. All suggested this test as an effective PM practice. However, the value of this test for monitoring the condition of the motor degradation, in addition to verifying valve operability, is not addressed by the survey.

<u>General Inspections</u> - Responses to this activity did not provide any recommendations or ratings. However, the use of periodic walkdowns as an aid in determining motor condition is encouraged. A few noted that general appearance and cleaning are incorporated into periodic maintenance activities.

5.6 Conclusions

Comprehensive survey of motor maintenance programs were conducted and the findings are summarized in Sections 5.2 and 5.5. A literature search on maintenance activities at nuclear utilities and a review of nuclear industry standards related to motors have resulted in the following observations:

Although there is a trend in the nuclear industry to improve motor preventive maintenance in power plants, the survey results indicate limited activities with regards to surveillance and periodic tests, and continuous monitoring programs. Important motors from the safety and cost stand-point are given a better inspection, with periodic replacement of bearing oil, checking dirt in the insulating systems as recommended by the motor manufacturer or based on the motor operating experience.

Safety motors, including valve operators, are maintained as included in the maintenance testing program, while some recently built plants have added certain tests or measurements to their plant tech specs or periodic tests. These include:

- periodic insulation resistance/polarization index test,
- periodic measurement of motor running current (for valves this involves both valve closing and opening running currents),
- bearing vibration tests on continuous duty motors using portable measuring instruments,
- winding inspections for any abnormal conditions,
- bearing inspections for wear, bindings, water damages, and checking oil level for sleeve bearings,
- stator-rotor clearance for any interference.

However, all physical parameters with exception to bearing vibrations are not generally monitored or trended for predicting the future condition. If any parameter indicates an abnormal conditions, the motor is immediately repaired, cleaned or parts replaced. In addition to the above, the following prescriptive equipment maintenance is done as a good maintenance practice,

- periodic replacement of bearing oil or grease,
- periodic replacement of gasket,
- cleaning (vacuuming or blowing) stator/rotor windings,
- tightening of loose bolts or nuts,
- cleaning the motor terminals,

Table 5-4 summarizes the current nuclear power plant motor PM programs.

With the exception of a few utilities identified in this section, there are only limited activities in condition monitoring or trending of any physical parameter for assessing the future state of the motor. The periodic tests on motors include the insulation resistance measurement only: the surveillance testing on safety motor-driven equipment include running current, bearing vibration and valve stroking. No industry standard, including ASME Section XI for pumps and valves, addresses any ISI/IST requirement for motors. Continuous monitoring on motors is limited to those of larger size driving pumps vital to plant availability. Both inspection and maintenance activities are performed as part of the good practices learned from operating experience.

In conclusion, there exists no uniform program within the industry to perform motor PM in nuclear power plants. Many of the existing PM activities are a result of operating experience, manufacturer's recommendations, a good industry practice or regulatory commitment. Motor operational readiness is assessed on insulation resistance or PI test. Running currents and winding temperatures are typically reserved for valve operators or intermediate to large motors. Bearing performance is maintained with periodic replacement of the grease or oil and sometimes in situ vibration measurements. Thus, one of the deficient areas that appear to exist in current industry practices is the testing, monitoring, and inspection activities specific to detect the effect of aging in the insulating system and bearing assemblies. Condition monitoring and/or trending of maintenance data is also not widely pursued to assess the present or the future state of the motor components. Periodic testing on insulations, while effective in detecting insulation contamination at the time of the test, does not provide sufficient information to monitor the age-related degradations.

Table 5-4: Current Nuclear Power Plant Motor PM Program

Motor PM Activities		Functional Indicators	Trending	Application
Periodic Testing		• Insulation Resistance	No	Motors Important to Safety and Plant Availability (Large & intermittent size)
		• Polarization Index		
		• Bearing Vibration	Yes	
Surveillance[1] Testing		N O N E		
Motor Performance Evaluation	Continuous[2] Monitoring	• Motor Running Current • Bearing Vibration • Winding Temperatures	No	Motors with appropriate instrumentation (Large & intermittent size)
Inspection		• Checking of Windings • Grease/Lube oil • Stator/Rotor Interference	No	Motors Important to Safety and Plant Availability
Motor Maintenance		• Change Oil/Grease • Change Gaskets/Seals • Cleaning Windings, Terminals • Tightening Bolts	-	Motors Important to Safety and Plant Availability or Manufacturer's Recommendations

Note: [1] Presently, there are no NRC requirements for motor testing in the technical specifications. However, some utilities monitor motor running current and bearing vibration during pump testing. During valve stroke time testing, some utilities are also monitoring motor peak and running currents.

[2] Some motors are equipped with permanent instrumentation which continuously provide information on certain functional indicators.

6. MOTOR MAINTENANCE PROGRAMS

The nuclear industry motor maintenance programs typically are based on performing preventive maintenance at prescribed intervals. If motor failure occurs prior to the scheduled time for PM, then corrective maintenance is carried out. PM is performed as scheduled, even if it is not required. The drawbacks to this philosophy are that untimely failures can occur causing a loss of availability, and unnecessarily high PM costs. A procedure to select a motor maintenance program for a nuclear power plant is described, which would enhance its reliability and hence, the safety of the plant. It includes an application of the procedure for the containment fan cooler motors and general discussions on application of certain motors.

The primary objective of this study is to provide recommendations for the development of a cost-effective preventive maintenance program and to as sure that the operational readiness of aged motors in a nuclear station is maintained throughout their design life. To achieve this goal, many factors must be considered that affect motor performance in a power plant, including design, manufacturing, construction, installation, operation, and maintenance testing. A properly implemented maintenance program as described here, can mitigate untimely motor failures, thus improving motor reliability. This, in turn, will improve plant safety and availability. Recommendations are provided on the application and frequency of these maintenance tests and activities for the four class of motors based on their sizes.

6.1 Preventive Maintenance Philosophy

The overall maintenance program includes performance evaluation of the component as well as maintenance activities. As discussed, performance evaluation contains four basic elements: surveillance testing, periodic testing, continuous monitoring, and inspection. Surveillance testing in the nuclear industry includes those mandatory tests obligated by the plant tech spec requirements. Periodic testing includes in situ tests performed at the equipment or associated controls at scheduled intervals to survey component degradations. Continuous monitoring, by definition, is the monitoring of certain functional indicators and hence, requires that data recording meters or other test equipment are permanently installed, to give continuous readings. Inspection of motors is defined as those activities which do not require any test equipment or tools but include listening to noise level, observing surface deteriorations, examining the mechanical/structural strength of component monitoring, etc.

Major emphasis is given to (1) a good inspection program which is applicable to any size and type of motor in a nuclear facility, and (2) a continuous monitoring program for those motors with monitoring devices. These two activities are recommended for all motors in a plant. However, the frequency of maintenance is dependent on the design function of the component and its importance to plant safety and availabilty. These programs, augmented with certain routine maintenance activities, based on the manufacturer recommendations and operating experience, should eliminate most of the motor failures due to age and service-wear.

For predicting the future health of equipment, the test and inspection data should be trended. Two tests have been performed to identify the functional indicators that are most suitable for condition monitoring (or trending) and the correlation between them in detecting incipient defects. The following recommended practices assume that certain motors in nuclear power plants are designed and qualified to withstand any design basis accident environments.

Since a power plant contains motors of various sizes and types located throughout the facility, it is difficult to generalize motor characteristics for all plant environments and applications. Appendix D provides a discussion on motor size, type, and specifications used in safety applications in typical PWR and BWR designs. The motor population present would help to estimate the maintenance effort for implementing the recommended practices for a particular class of motors.

6.2 Reliability Centered Maintenance (RCM)

To achieve a better balance between preventive maintenance and corrective maintenance, and to maintain a high level of motor reliability, it is prudent to establish a reliability centered maintenance program for motors (and for other important components).

RCM is a concept which uses an analytical methodology for establishing specific PM tasks for complex systems or equipment. Intrinsic to the concept is the identification of critical failure modes and degradation mechanisms through engineering analysis and field experience to determine the consequences and the most effective apportionment of maintenance activities. The phase I study on motors has provided these needs (7).

The initial step in the RCM decision logic is to determine the criticality (safety or availability importance) of the component in question, in this case, motors. This is typically achieved by a failure modes and effect analysis (FMEA) or some similar methodology. The criticality of a component is affected by its significance to plant safety and availability, and considers features such as the availability of redundant components. This step is plant specific and there are several publications which provide good treatment of the subject (41,42). The remainder of the steps in RCM decision logic are discussed here. These steps, illustrated in Figure 6.1, result in a decision to perform one of the following types of maintenance:

- Corrective Maintenance: Not all failures will have a safety or plant availability impact. If they are not more costly than PM, then the component can be allowed to fail and then taken out of service for repair or replacement.

- Indicative Preventive Maintenance: Periodic and/or surveillance tests, continuous monitoring, and inspection data of components are used to determine by condition monitoring (or trending) when a certain motor integrity has degraded to the point where repair or replacement is required.

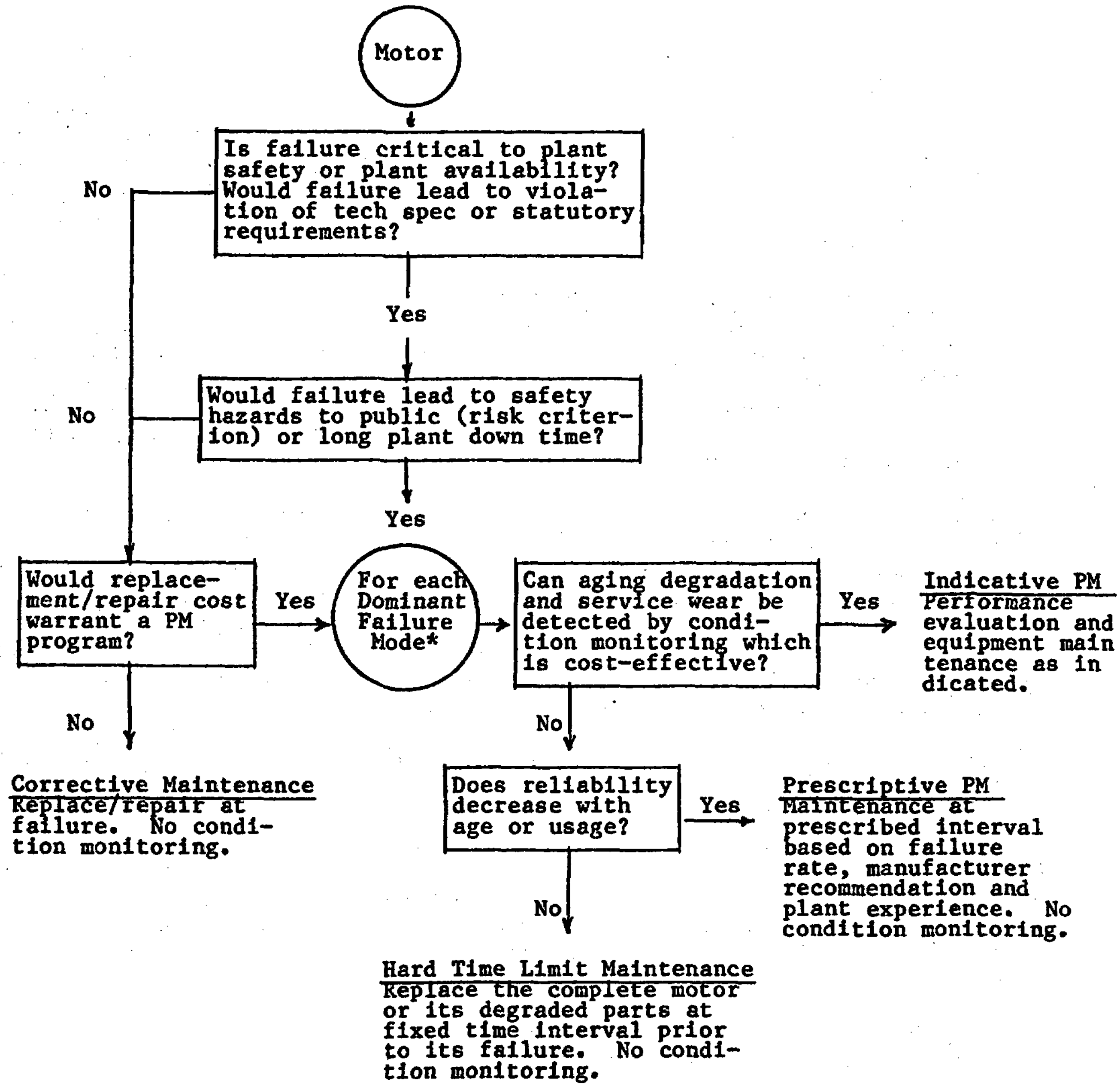

Figure 6-1: Reliability centered maintenance logic for nuclear power plant motors.

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*In case of motor, bearing and insulation failures are the two dominant failure modes.

- Prescriptive Preventive Maintenance: Certain motors do not warrant any sophisticated testing because of their minimal cost or unimportance to the plant safety and availability, or because condition monitoring techniques do not provide sufficient information to make PM decisions. The failure rate of such motors establishes these prescriptive maintenance intervals. No condition monitoring is required. This also includes recommended maintenance practice which require all scheduled activities, such as regreasing, oil changes.

- Hard Time Limit Preventive Maintenance: This is a prescribed PM program, where it is established that the reliability of the component remains unaffected by age or usage, and a PM program does not guarantee detection of the degradation at an incipient stage. Since the component is important for plant operation, the complete motor assembly or the degraded subcomponents are replaced at fixed time intervals prior to failure, based on the manufacturer recommendations or operating experience.

Thus, depending on the design requirements of the motor in plant operation, each nuclear plant motor can be assigned one of these maintenance programs. All important motors, which include all safety and intermediate to large non-safety motors, are considered for a PM program. The motors are filtered through the logic chart in Figure 6-1 to determine a cost effective PM program. If the cost of the PM program is prohibitive, then corrective maintenance is chosen. On the other hand, preventive maintenance is chosen if the motor is vital to plant operation and the costs of failure are prohibitive.

If any particular failure mode can be diagnosed with a cost-effective condition monitoring program, then the motor is considered for trending, using its functional indicators (FIs). Subsequent maintenance is performed as indicated by the FI trends. Where condition monitoring does not provide adequate information for PM decisions, but the motor reliability is affected with age, then it is subjected to prescriptive PM. Finally, if the particular failure mode does not affect the motor reliability, the aged subcomponents (or the complete motor assembly) contributing to this failure can be repaired or replaced at certain prior fixed time intervals.

Besides the design function and its importance to plant operation, other elements which govern the PM decision for nuclear power plant motors are:

- Location - Motors are located inside the containment and other high radiation areas, outside the containment, indoor/outdoor, and at elevations with difficult accessibility. Depending on this, the frequency and kind of testing should be optimized to limit personnel exposure, and remote monitoring should be considered.

- Environment - The aging process of motors is directly dependent on the type of environment to which they are exposed. All motors in a harsh environment are qualified for the lifetime of the plant and designed to operate in an accident. Motors in mild environment can be tested without too much difficulty. The outdoor motors that are exposed to hostile environment such as salty air, should be considered for condition monitoring.

- Operation - Motors are either operated under normal condition, in accident conditions, or in post-accident conditions for safe shutdown of the plant. Motors are used for continuous duty and standby operation, as in the case of safety motors. Valve motors are typically of the intermittent type. As is evident from the aging assessment, continuous duty motors experience a lesser degree of aging when compared to the others. Also, many times excessive testing on standby and intermediate duty motors induce accelerated aging, leading to premature failure.

- Failure modes - As evident from the preceeding study, bearing and insulation failures contribute to most motor failures. In some cases, the cause of a motor failure can be external, such as misapplication, misoperation, or the failure of the driven component. Hence, in establishing the failure modes for a particular motor, specific plant experience data on the subject operation should be taken into account.

One of the most important advantages of an RCM over other maintenance tools is that the decision tree helps change the maintenance intervals, depending on the past reliability of a particular component. If the motor has excellent reliability and the trended data indicates no subcomponent degradation, the maintenance intervals can be relaxed or optimized for future maintenance, and vice versa. This would also help in establishing the residual life of the component for plant extension, in case it is needed. To accomplish this, each plant must maintain a good data base for each component including its design and manufacturing specifications, qualification and installation documents, operating and maintenance histories, and maintenance data and their trends. With these elements in data base, the RCM decision tree can provide much useful information in detecting and mitigating degradation and failure.

6.3 RCM Logic Application for Containment Fan Cooler Motors

Containment fan cooler motors were chosen, due to their location in a radiation zone and the requirement that they remain operational in an accident environment. For certain designs, these fan coolers must operate up to a year in a post-accident humid and chemically contaminated environment. Since this environment is detrimental to the motor insulation and bearings, one study (4) has recommended hermeticlly sealed motors for this application.

A specific PWR was chosen for evaluation, which has five 225 hp fan cooler motors. Three of the five fan coolers are required to operate to manage accident loads, but less than three are sufficient if containment spray capability is available. Technical specification requirements are such that the plant is placed in an LCO (Limiting Condition for Operation) if one of the fan coolers is unavailable. These fan coolers require electric power and service water for proper operation.

A review of failure data from industry indicates that these motors are very reliable. There have been about 20 fan cooler motor failures reported industry-wide during the period 1976 to 1983: this is greater than one failure every one hundred years of operation. Approximately half of these are attributed to bearing failures and half to insulation winding burnouts. The root cause of these failures is presumably due to impingement from water cooler leaks. The probabilistic risk assessment for the subject plant in the case study used a motor failure rate of 3.23×10^{-3} per year, which means that one motor can be expected to fail after 300 years of operation, or for five motors, a failure can be expected every 60 years. If one thinks back to TMI (Three Mile Island), the fan cooler motors continued to operate during and after the accident.

With motors that are so reliable, a high activity, high frequency maintenance program is not required. On the other hand, one certainly would not want to have these motors in a degraded condition, such that they could not operate through a design basis accident. What is required is a maintenance program that provides information on the "health" of the motors.

The present tech spec requirements for operability on each group of containment cooling fans are:

a) at least once per 31 days:

- start each fan group from control room and verify that each fan group operates for at least 15 minutes.
- verify cooling water flow rate of greater than or equal to a specific number for each cooler

b) at least once per 18 months, verify that each fan group starts automatically on a particular test signal.

The tests do not provide any specific information on motor condition and there is no assurance of the operational readiness of these motors through the next test period. However, trending certain electrical or mechanical parameters taken from these tests could enhance the motor (hence the fan cooler) reliability.

To demonstrate the application of the recommended procedures outlined in Figure 6-1 logic diagram for containment fan cooler motors the following is presented:

- Is failure critical to plant safety and/or plant availability? Yes. The motors are safety related and one failure would place the plant in an LCO condition.
- Would failure lead to safety hazard to public (risk criteria) and/or long plant down time? A calculation performed with the PC based risk program "NSPKTR," indicated that for a failure of one fan cooler motor, there is no perceptible change in plant risk. This would seem to make the answer to the above question a No, and if the decision was based solely on reliability concerns, a No answer would be acceptable. However, in consideration of the tech spec LCO criteria and the inaccessibility of the motor during normal operation, a YES answer is selected.
- Would replacement/repair cost warrant a PM program? Yes. Given ALARA concerns and the potential for forced plant outages, and the opportunity to avoid costly equipment damage, it is presumed that a utility would prefer to repair or replace the motor under planned conditions such as refueling outage.

Based on the above, the motors in the subject plant should have a cost-effective PM program. The typical failure modes associated with these motors are bearing failures due to lack of lubrication, and the insulation burnout (primarily due to intrusion of water into the windings).

Other elements to be considered for this motor application are:

- Location - located inside containment and at an elevation not readily accessible.
- Environment - harsh environment. Should be designed to withstand post-accident environment with chemical and water spraying on motors.
- Operation - although not all motors run all the time, some motors function during normal operating conditions. They are designed to remain containment.
- Failure Modes - bearing and insulation failures.

Considering these factors, the following questions can be answered as follows:

	Bearing failure	Insulation failure
Can aging degradation and service wear be determined by condition monitoring which is cost-effective?	Yes	Yes

Maintenance Recommendations for Fan Cooler Motors

Perform preventive maintenance which includes (see Sections 6.4.1 - 6.4.4):

1) Performance evaluation:

   a) Inspection - Physical inspection of motors every refueling outage (see Appendix C.2).

b) Continuous monitoring - Since these motors require high reliability and are intermediate in size, line/phase current, winding temperatures (if any), and bearing temperatures should be continuously monitored. As a minimum, current and voltage can be monitored (see Appendix C.1).

c) Surveillance testing - There are no specific surveillance test requirements for these motors. However, recording the speed and winding temperatures every refueling outage would help monitor the bearing and insulation conditions (see Section B).

d) Periodic testing - Insulation resistance and polarization index at every month prior to fan start up testing should be performed to determine its dryness and accumulation of foreign particles. At the same time partial discharge (corona) testing as well as power factor testing should be performed to monitor any corona discharge inception and average condition of the insulation respectively. Vibration tests on bearings also should be performed each refueling outage or every other time. This infrequency is due to the low failure rate (see Appendix A).

e) Condition monitor - All of the above data should be trended and analyzed. Any adverse trends should be further analyzed for root cause and corrective maintenance performed as necessary (see Section 3).

2) Equipment maintenance:

This should include all corrective measures as indicated by the trends obtained from the above activities. Periodic cleaning of insulation, lube oil changes, and other good housekeeping measures should be performed as necessary to keep the motors in good operating condition. Measures should be taken to ensure that water leaks from the cooler do not impinge onto the motor components.

6.4 Summary of Maintenance Practices

The present preventive maintenance practices in nuclear power plants include scheduled inspections, line/phase current monitoring, and periodic tests such as insulation resistance and polarization index tests. Manufacturer- recommended maintenance includes periodic changes of oil or lubrication and carbon brush replacements. Vibration should be measured on certain safety class motors or motors (above 25 hp) important to power generation. Some utilities are installing on-line monitoring equipment to continuously monitor some functional indicators, such as bearing vibration and line/phase current or voltage on a selected number of motors important for plant operation and safety. Most of t he other test methods described in this report typically are used in the industry for detecting the location of faults in various motor sub-components as a part of the corrective maintenance program.

If a motor is operated without any maintenance, it will eventually fail. To resume operation it must be repaired or replaced (i.e. corrective maintenance). The total cost incurred as a result of availability/capacity losses due to motor failure and repair will be larger than the cost of a preventive maintenance program. Further, if a good preventive maintenance program is in effect, few unexpected failures should occur. Since the action is planned, it can be scheduled around plant operating conditions and therefore, will not impact plant availability. However, if the periodicity of PM activities is unnecessarily large, high costs will result as well as test-induced component degradations. The frequency of a good PM program lies somewhere in between the two extremes. A reliability-centered approach is recommended to establish the maintenance program for motors in nuclear facilities.

One element missing in the current industry PM activities is the capability to predict the future performance of motors. No industry standards or published documents are available identifying the FIs suitable for condition monitoring of motor performance. Thus, the overall preventive maintenance pro gram for motors is a collaborative effort of performance evaluation and certain equipment maintenance activities. Some of these maintenance activities may be routine, based on manufacturer's recommendations or operating experience while others may be as a result of an indication of abnormality in any of the FI trends obtained from tests or measurements. Specifically, many regular inspection schedules for evaluating the motor performance may be germane maintenance activities such as lube oil change, changing air filters or gaskets, replacing carbon brushes or parts with a finite life due to age or service wear, cleaning winding or commutator surfaces, readjusting components, and recalibrating instruments. The following is a summary of the recommended practices which could be included in a good PM program, to assure the operational readiness of any motor (including inside containment) designed to operate during normal as well as accident conditions. It should be noted that the recommended frequency of a particular activity is based on engineering judgement and a typical refueling outage schedule of 18 months for nuclear power plants. Not necessarily all recommended tests are required for monitoring a specific application motor. Suitable test methods should be considered for inclusion in the existing maintenance programs depending on the test intrusiveness, equipment accessibility, and operational requirements of the candidate motor.

6.4.1 Periodic Tests

Periodic tests described in Appendix A typically are used either subsequent to corrective maintenance on any motor or for routine testing on high voltage - intermediate to large size motors. Table 6-1 summarizes some of these test procedures for preventive maintenance. Some of the FIs included are suit able for trending in order to predict the future motor performance. Insulation resistance/polarization index tests, and surge tests may not suitable for condition monitoring. However, IR/PI tests are go/no-go type tests and important for pre- or post-maintenance operation of motors. PF/DF tests and partial discharge test are used to detect void growth and corona discharge activities in insulation. Use of voltage impulse/surge testing on motors provides instant voltage/current wave forms which are compared with those corresponding to good insulation.

Table 6-1. Periodic Tests on Motors (excluding fractionals)

Performance Evaluation Tests		Motor Size: Small, Valve Op.	Small, Cont. Duty	Intermediate	Large	Frequency (Months)	Trending	Remarks
Insulation Resistance/	Safety	X	X	X	X	12-18	No	IR/PI Tests are go/nogo tests. Indicates dryness of insulators.
Polarization Index	Non Safety	X	X	X	X	12-18	No	Should be used prior to energization for pre- and post-maintenance.
Ac/dc Leakage (hipot)[1]	Safety			X	X	36-60	No	Ac tests preferable for ac motors. Should be conducted in stepped
	Non Safety			X	X	36-60	No	voltages up to the max. rated voltage.
Power Factor/ Dissipation Factor[2]/ Capacitance	Safety		X	X	X	18-36	Yes	Used for high voltage machines. Power factor tip up plot provides
	Non Safety		X	X	X	18-36	Yes	void growth in insulations.
Voltage Impulse/ Surge	Safety	X	X			6-18	No	Comparison of wave forms with that of a good insulation
	Non Safety	X	X			6-18	No	provides conditon of insulation.
Partial Discharge	Safety			X	X	6-18	Yes	Used for large machines with
	Non Safety			X	X	6-18	Yes	voltage rating above 500 V.
Running Current[3,5]	Safety	X	X	X	X	12-24	Yes	No load, full load, rotor
	Non Safety			X	X	12-24	Yes	currents.
Motor Vibration[4,5]	Safety		X	X	X	6-18	Yes	Used to monitor structural and bear-
	Non Safety		X	X	X	6-18	Yes	ing interities, and end turn mvmts.
Lubrication/Oil Analysis	Safety			X	X	18-36	Yes	Specifically for sleeve/plate
	Non Safety			X	X	18-36	Yes	bearing degradations.
Nondestructive Testing	Safety				X	36-60	Yes	Ultrasonic tests for detecting
	Non Safety				X	36-60	Yes	cracks in metal components.

NOTES: (1) Hipot tests up to the allowable limits (greater than line voltage) are recommended for corrective maintenance only.
(2) Only applicable to motors, where conditions warrant for prevention maintenance.
(3) Also part of the surveillance testing on certain safety-motors.
(4) If built-in transducers are not available, portable units must be used.
(5) Can be used as on-line monitoring.

Table 6-2. Surveillance Tests[1] on Safety Motors

Performance Evaluation Tests	Motor Size					Frequency (Months)	Trending
	Fractional[3]	Small Value Op.	Small Cont. Duty	Intermediate	Large		
Running Current[2,5]		X	X	X	X	12-24	Yes
Speed[5]	X	X	X	X	X	12-24	Yes
Bearing Temperature[5]				X	X	12-24	Yes
Bearing Vibration[5]			X	X	X	6-18	Yes
Winding Temperature[5]				X	X	12-24	Yes
Valve Stroking[4]	X	X				6-18	Yes

NOTES: (1) It is assumed that surveillance tests are performed only on safety motors as required by plant tech spec requirements.
(2) Also part of periodic testing on certain motors.
(3) Except for value stroking, these measurements can be part of the inspection activities.
(4) This is applicable to valve motors only, which may be either fractional or small hp motors.
(5) Can be used as on-line monitoring.

Table 6-3. Continuous Monitoring Practices on Motors

Performance Evaluation		Motor Size: Fractional	Motor Size: Small	Motor Size: Intermediate	Motor Size: Large	Frequency (Months)	Trending
Line/Phase Current	Safety		X	X	X	3-6	Yes
	Non Safety				X	12-24	Yes
Winding Temperature	Safety			X	X	3-6	Yes
	Non Safety			X	X	12-18	Yes
Bearing Temperature	Safety			X	X	3-6	Yes
	Non Safety				X	3-6	Yes
Lubrication Oil Temperature	Safety			X	X	3-6	Yes
	Non Safety				X	12-18	Yes
Bearing Vibration	Safety		X	X	X	3-6	Yes
	Non Safety			X	X	12-18	Yes

NOTE: All functional indicators can also be used as on-line monitoring. Some of these indicators may already be included in periodic or surveillance test programs.

6.4.2 Surveillance Tests

No industry wide surveillance requirements on motors exist in the current plant tech specs. Appendix B describes some of the FIs either used, or which can be used , to survey motors in nuclear facilities. Table 6-2 summarizes these parameters with their suitability for inclusion in a plant PM program. Some of these evaluations are already being obtained in the nuclear industry for pumps and valves as components, including their drivers (i.e. motors). These include the motor running current and speed for pumps, and valve stroking for MOVs. Bearing and winding temperatures, and bearing vibration signatures are typically monitored for larger motors (above 50 hp). These indications are useful for surveying the insulating system and bearing conditions of motors. It is therefore recommended that these FIs be included in the present surveillance program and the data be analyzed for trending as a part of the plant PM program.

6.4.3 Continuous Monitoring

Table 6-3 summarizes the suitability of each of the continuous monitoring parameters described in Appendix C, and their recommended frequencies. Note that small safety motors should be periodically monitored for winding temperatures, voltage/current reading, and bearing vibration levels. If devices are not built into the motor components, portable test units must be used to obtain this information. It is assumed that intermediate and large size motors are equipped with devices to denote the recommended functional indicators directly on the display or dials.

6.4.4 Inspection

Figure 6-2 provides the "10-point" inspection checklist (see Appendix C) applicable to all sizes and types of motors utilized in nuclear power plant. Cleaning or other maintenance activities that may be performed along with the inspection depend on the condition of the motor and the need for such activities for good engineering practices. A 3-6 month inspection schedule for safety motors and 12-18 month for nonsafety motors are recommended. Trending of inspection FIs helps to predict future performance, and when compared with the previous inspection data, may help to diagnose any abnormality in motor performance history.

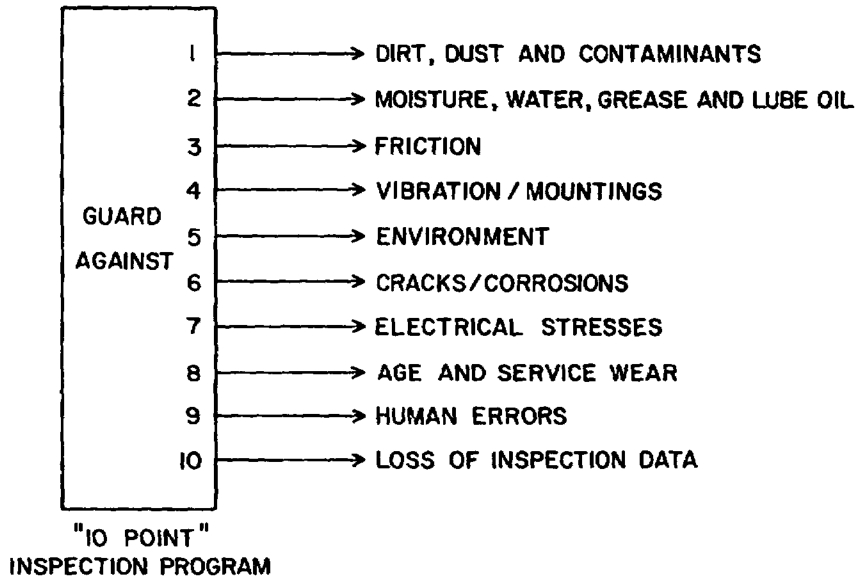

Figure 6-2: '10-point' Inspection Program for Motors

7. CONCLUSIONS AND UTILIZATION OF RESULTS

The insulating system and bearing assemblies were found to be the dominant failure modes accounting for almost seventy percent of the reported failures. A survey of four nuclear stations revealed that the current nuclear power plant motor preventive maintenance programs include insulation resistance and/or polarization index tests to monitor the dielectric integrity of motors. In certain motors, bearing vibration levels are measured to assess the rotational integrity. The plant technical specification does not include any specific tests f or motor performance checks, however, it includes the motor driven equipment overall performance tests. Motor operated valves are tested for valve stroking where pumps for speed and flow checks. Additionally, the current maintenance programs consider periodic oil/grease changes, winding cleaning, and tightening bolts as recommended by the manufacturers.

7.1 Conclusions

In conclusion, motors important to plant safety and availability to power generation should undergo cost-effective preventive maintenance programs. These include indicative, prescriptive, and hard time limit maintenance, depending o n their application and reliability as discussed in the report. Other nonsafety motors may be allowed to fail and corrective maintenance can be performed to r e store their design functions. The frequency of any activity can be optimized as the performance of a motor has improved.

For the performance evaluation of motor condition (after application of RCM logic), the preventive maintenance program should include the following tests and inspections:

- Periodic Testing: In addition to the current practices (i.e. insulation resistance and polarization index tests), smaller size motors with random wound coils should be considered for surge test to detect local defects in the insulation. Dissipation factor/capacitance test should be performed to monitor the average condition. Bearings for motors above 25 hp are candidates for periodic vibration testing. For intermediate to large motors, the partial discharge (or corona) test should be considered for hot spots or corona discharges where the power factor or dissipation factor test is suitable for monitoring average insulation condition.

- Surveillance Testing: Motor running current and motor bearing vibration should be measured and recorded during surveillance testing of the pumps, fans, and valves required by the present plant technical specifications. Provided the motor is equipped with measuring devices, the winding and bearing temperatures are good indicators for degraded components and should also be measured and trended during surveillance testing.

- Continuous Monitoring: All motors equipped with permanently installed devices should be monitored continuously or periodically. The data should be analyzed for condition monitoring and trending.

- Inspection: A comprehensive checklist for a good inspection programs has been recommended for implementation. The plant specific list should minimize any human errors in registering the data in the checklist.

- Condition Monitoring and Trending: Testing performed on those motors required for maintaining their operational readiness, should be trended. The future health until the next scheduled tests can be assessed by recording and analyzing the data each time a test is performed. There- fore, it is important that for each functional indicator a baseline parameter value should be developed first, prior to subjecting the motor to an in-service condition. If the motor is subjected to a particular test or inspection, then the data should be assessed comparing this with the previous set of test data or a baseline data for monitoring the present condition.

- Equipment Maintenance: Regular maintenance activities include greasing/oil change, gasket and seal replacement, periodic cleaning of windings and terminals, bolt tightening, and others recommended by manufacturers. The frequency of these activities, as well as certain specific maintenance activities should be developed based on the plant operating experience. Depending on the overall performance of a motor, the maintenance scheduling can be changed to optimize the maintenance program.

To develop a complete maintenance program, the frequency of the above activities should be determined after considering the following:

- accessibility to the motor or controls
- important to plant safety " test equipment and its intrusiveness
- cost versus benefits
- plant scheduling and outages
- system operating modes
- motor design and specifications

Precautionary measures should be taken to avoid any test induced degradation on motors. Certain maintenance tests can be performed at the motor control centers or switchgear. Some require the motor to be out of service, but not necessarily disconnected from power leads. For those cases when the disconnection of power leads are necessary, nuclear grade connectors (known as Elastomolds) are available to be installed inside the conduit box for motors up to 5,000 volts ratings. These connectors aid in providing electrical power to motór without disconnecting the leads.

7.2 Utilization of Results

The only guide available for motor maintenance is the IEEE-Std 432-1976 entitled "IEEE Guide for Insulation Maintenance for Rotating Electrical Machinery." This standard refers to the dielectric integrity of motors ranging in sizes from 5 hp to 10,000 hp. The guide contains a good description of the insulating system and the applicable inspection and test procedures. It discusses the applicability of various test methods which are typically used as a regular maintenance practice. No reference is made to preventive or corrective maintenance, except to the importance of service reliability. Effects of aging and service wear of other motor components are not included, nor is the condition monitoring of various FIs for predicting future health. Thus, the standard could be improved or a new standard may be developed as a result of the current Power Engineering Society (IEEE/NPEC) activities for motor maintenance practices. The emerging standard may address all the three integrities (dielectric, rotational, mechanical) and their testing and maintenance practices to mitigate age and service wear related failures.

Knowing the aging characteristics (7) of motor components, the impact of environmental and seismic effects (43) on the motor performance can include such effects in qualifying motors for nuclear applications. The standards and guides requiring updates are IEEE-Std 323, IEEE-Std 344, and Regulatory Guide 1.89. It should be noted that small induction motors with adequate qualification are rugged enough to withstand both design basis nuclear environment and seismic loads. Large motors, specifically vertical motors, with many additional protective and operational features require further studies to establish their aging/seismic correlation.

The present tech spec requirement written for any plant basically focuses on the driven component, rather than the driver itself. ASME Section XI, which addresses the in-service testing and monitoring procedure, needs to include other FIs suitable for motors.

Lastly, the research findings will help both nuclear power industry and the regulatory agency to resolve various safety concerns in reference to motors. Implementation of a good PM program, which will improve the plant safety and plant availability, can help to provide a reliable plant performance record. Hence, if any plant applies to have its operating license extended, the plant records will help the regulating agency in determining the extension.

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APPENDIX A

PERIODIC TESTING METHODS FOR MOTORS

A. PERIODIC TESTING METHODS FOR MOTORS

Periodic tests are in situ tests performed in the plant on the equipment or its associate controls at scheduled intervals to detect failures or degradations and verify operability. These tests require sophisticated test equipment to measure the performance parameters. A number of industry standards published by IEEE, ANSI, NEMA, and AFBMA describing these test procedures are available. This section describes the basic principles of these tests, discussing applicability, limitations, and sources of errors. The tests included are:

- Dc Resistance Tests
  - Insulation Resistance (IR) Measurement
  - Polarization Index (PI) Measurement
- Ac and Dc Insulation Leakage Test
- Dissipation Factor (Capacitance)/Power Factor/Tip-Up Tests
- Surge/Impulse Voltage Tests
- Partial Discharge Tests
- Motor Running Current Tests
- Bearing Lubrication Tests
- Additional Tests Performed by Manufacturers

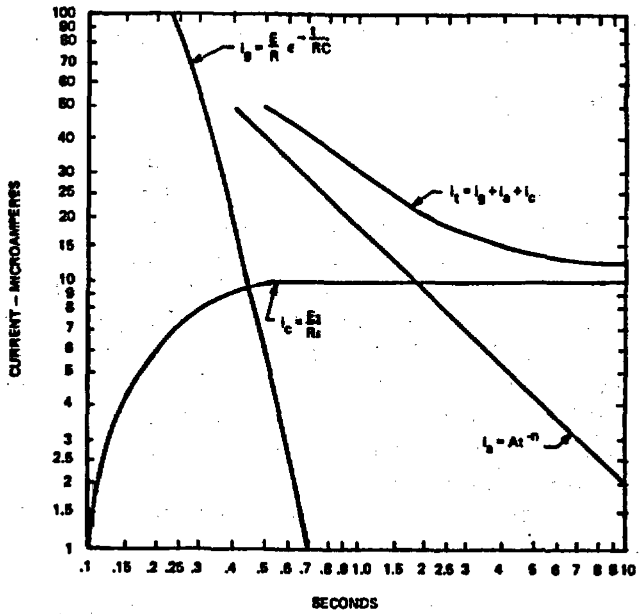
With the exception of the Lubrication Tests, all other tests are used to monitor the dielectric condition of winding insulations.

A.1 DC Resistance Tests

Insulation resistance is defined as the quotient of the applied direct test voltage when divided by the current through the insulation. When a dc voltage is applied across insulation the current that is recorded by a microammeter consists of three components (A1):

- Geometric Capacitance Current (i_g)
- Absorption Current (i_a)
- Leakage (Conduction) Current (i_c).

The geometric capacitance current is comparatively high in magnitude and of short duration: this component disappears so quickly that it does not affect the measurements. The absorption current decays at a decreasing rate from a comparatively high initial value to nearly zero. The resistance measured in the first few seconds of a test is largely determined by this component of the total current. Leakage current, which includes the conduction current and the surface leakage current, predominates after the absorption current has become insignificant. The leakage current, which is the electrical current that passes through the insulation, is of particular interest when evaluating the condition of the insulation. Figure A-1 illustrates the three components of the total current.



E = Open Circuit Voltage of the DC Source (volts)

R = Insulation Resistance (Ohms)

C = Insulation Capacitance (farads)

A = Constant

Figure A-1: Current components in the dc testing of electrical insulation (A1)

A.1.1 Insulation Resistance Measurement

Dc insulation testing, widely known as "meggering" (named after the test equipment used to measure the resistance) is commonly used in the nuclear industry to monitor the condition of the motor dielectric integrity of the stator and rotor windings. However, this particular test does not truly simulate the actual resistance and reactance components of the insulation of an ac motor since the applied potential is dc. Also it cannot detect the presence of 'bad' insulation when there is a layer of 'good' insulation in series with the 'bad'. Under this condition the dc tests will show 'infinity' or high insulation resistance (IR). The test is primarily used by maintenance personnel to determine insulation condition (go/nogo type) prior to application of an overvoltage test or motor startup. IEEE Standard 43 and IEEE Standard 432 contain a good description of this test procedure. The recommended minimum value of the insulation resistance is determined by the relation:

$$Rm = kV + 1$$

where

Rm = recommended minimum insulation resistance in megohms at 40°C

kV = rated machine terminal to terminal potential, in rms kilovolts.

A.1.2 Polarization Index Measurement

The polarization index (PI) is a dc insulation resistance test that is performed on both random wound and form wound motors and is a standard test used by many utilities in their maintenance programs. It is usually performed on the windings of a motor stator by taking insulation resistance readings at one minute intervals up to and including 10 minutes, using a 500, 1,000, 2,500 or 5,000 dc volt source such as a megger. The largest test voltage level is limited by 1.7 times the 125 to 150 percent of the rated terminal voltage of the motor being tested. The ratio of the 10 minute to 1 minute resistance readings gives the polarization index. It is assumed that a fairly steady value of the insulation resistance is reached in 10 to 20 minutes. This measurement is useful in appraising the winding dryness and its fitness to perform other high potential tests. The recommended minimum values of polarization index given in the IEEE standard 43 are:

For Class A insulation 1.5

For Class B insulation 2.0

For Class F insulation 2.0

For certain conditions when the charging current dissipates rapidly, the insulation resistance (IR) is above the basic minimum requirements, but the PI is below the recommended value. A very high PI value (>6) indicates the insulation condition to be brittle and dry, thereby indicating loss of mechanical strength. According to the IEEE Standard 43, motors rated at 10,000 kVA and less should have either a value of the PI or IR (at 40°C) above the minimum recommended values. The one minute IR reading should generally be above 1,000 megohms with good insulation. However, for motors rated above 10,000 kVA, both the PI and IR should be above the minimum recommended values.

There are many factors which can affect the measured insulation resistance during testing. They are:

Insulation Condition - Presence of moisture in the winding would lower the insulation resistance significantly, thus increasing the leakage current.

Test Potential Magnitude - The measurement of insulation resistance constitute a potential test, and must be kept within the rated voltages, particularly to low voltage motors and motors with imperfections or fractures in their insulating systems. Dc insulation tests often are begun at 500 volts to prevent stator damage that can be caused by moisture in the insulation. Retesting at 1,000 volts, 2,500, and 5,000 volts may then be safely performed. If the IR decreases significantly with an increase in applied potential, the insulation should be examined for dirt, moisture, or other contaminants.

Temperature - The insulation resistance increases with decreasing temperature. However, if significant heating in the winding occurs during the test, the results may erroneously indicate that the insulation is bad. For this reason, it is important to conduct the test at a relatively constant temperature, which is low enough so that rapid cooling does not occur but high enough (e.g. above the dew point) so that moisture which may have condensed on the insulation does not interfere with the results.

Temperature changes are an important consideration in the polarization index test, since they can be a source of error for reasons similar to those discussed for the IR test. That is why it is incorrect to perform the test immediately after the motor has been running and begins to cool. It is recommended that the test be performed when the motor windings have cooled to a suitable ambient temperature.

Insulation resistance readings may be corrected for temperature by using the relation:

$$R_c = K_t \times R_t$$

where

R_c = insulation resistance (in megohms) corrected to 40°C

R_t = measured insulation resistance (in megohms) at temperature t

K_t = insulation resistance temperature coefficient at temperature t.

Figure A.2 provides the insulation resistance coefficient, K_t plotted against the winding temperature.

Time Interval Between Voltage Steps - The error in calculating the leakage current from inadequate discharge time was discussed previously. The "megger" test equipment includes a discharge path which is actuated prior to disconnecting the equipment. If there is insufficient time between measurements, then the measurements will include negative components which had not discharged completely. These components will reduce the flow of charging current, resulting in an apparently higher insulation resistance.

Major source of errors for the insulation resistance and polarization index tests are:

a) Test readings not referenced to a given temperature level.

b) Poor connections and long cables. Readings should be taken at the motor terminals.

c) Megger is not calibrated.

d) Megger readings taken immediately after motor is shutdown and the winding temperature is dropping rapidly.

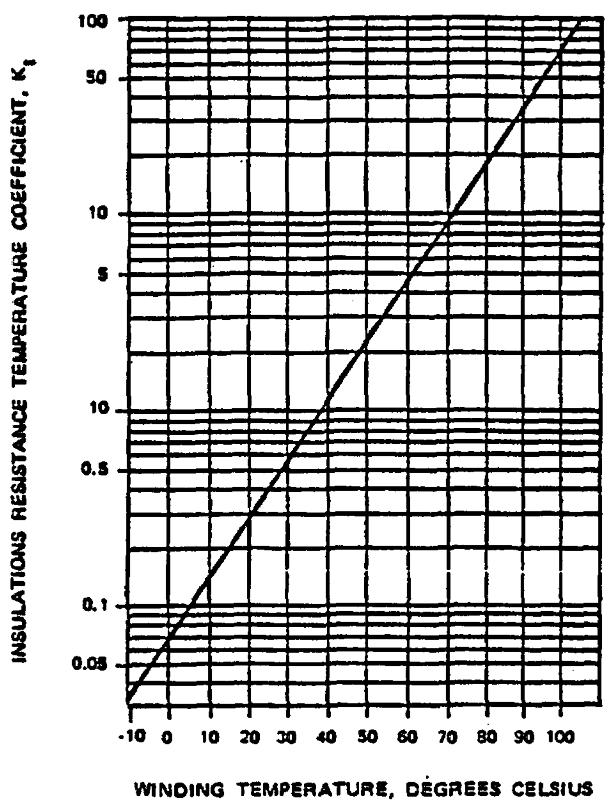


Figure A.2: Approximate insulation resistance variation with temperature for rotating machines

e) The winding must be completely discharged from all residual charges prior to the insulation testings.

A.2 Ac and Dc Insulation Leakage Tests

The cost and reliability of certain motor sizes warrant nondestructive tests to detect a localized fault in the insulation which has high capacitance. The insulating system is a large sheet of surface area separating the copper conductors on one side from the iron stator core on the other. Because of this arrangement, any measurement made when a test voltage is applied between copper and iron will be indicative of the average characteristics of the entire insulation. If there is excessive deterioration in a small portion of the insulation, the contribution of the deteriorated part to the total measurement would be so small that it might go undetected.

Ac and dc leakage tests are high-potential (hi pot) tests and have proved effective in finding localized faults in a high-capacitance test object (A2). However, the tests have several shortcomings. Since the voltage level and the time of application is entirely arbitrary, when an insulation has passed the test there always remains a question of whether it would have failed had the voltage been slightly higher or the duration of the test a few seconds longer.

When the insulation fails during a test, there is a problem in repairing the damage before the motor can be returned to service. Testing therefore is not recommended for regular use in preventive maintenance of all size motors. IEEE Standards 95, 432 and 433 contain good descriptions of this test procedure.

The distribution of the voltage gradients (electrical stresses) within the insulating material is not the same when a dc test voltage is applied compared to an ac voltage. Although service conditions are more closely duplicated when an ac voltage is applied to ac motors, the dc test equipment is small, compact, and provides a more economical test. For these reasons dc voltage testing of large motors is used more often after installation. The ac high voltage test usually is used to check test voltages with the windings connected to the test circuit to evaluate possible distortion or peaking of the voltage wave.

Both ac and dc tests generally are conducted on a withstand basis, with voltage applied for one minute. If no failure or sign of undue stress (e.g. rapid lowering of insulation resistance) is observed, the insulation is considered as having passed the test. Measurements of insulation characteristics (dielectric loss, power factor, leakage current, insulation resistance) can be made in conjunction with ac or dc hi pot tests. These values are helpful in interpreting the results of periodic tests. Some of these tests are discussed in the later sections.

Voltages for routine maintenance tests generally range from 125 to 150% rated terminal voltage for ac tests, and 1.7 times this value for dc tests. The 1.7 factor is an attempt to provide a direct potential corresponding, to the peak alternating value.

A.2.1 Ac Insulation Leakage Tests

The ac leakage test is a proof test in which a potential is placed across the insulation to insure a minimum dielectric strength. Because of the risk of destroying the insulation, the test voltages for hi-potting motors where the condition of the insulation is unknown should not exceed between 125 to 150 percent of the line to line voltage. Ac tests, in general, have a larger risk of causing permanent damage to the insulation. The degradation process from the ac test is rapid and is caused by the accumulated damage in the insulation from electrical discharges. The displacement of charges/dipoles in the insulation contributes to its deterioration by causing the temperature to rise. These degradation processes are directly related to the frequency of the applied voltage.

The ac high potential test is most commonly used in motor manufacturing and in service shops after rewinding or reconditioning stator windings. For rewound and new motors a test voltage is used of two times rated voltage plus 1,000 volts. For reconditioned motors, the high potential test voltage ranges from 66 to 75 percent of the test voltages. Ac high potential test equipment is available for test voltage from 1,000 volts and up; ac high potential tests are not used in maintenance because they are potentially destructive.

The ac test for observing the discharge leakage from corona uses special corona discharge test equipment. The test is used by manufacturers developing new insulation systems. In the following paragraphs, the procedures are discussed for ac insulation leakage tests used in the manufacturing of both random and form wound motors.

Random Wound Motors - After the stator is inserted and connected, but befor varnish treatment, the stator is hi-potted with an ac high potential tester. The motor is tested from the lead or leads to ground, and, as an example, a 2,500 volt ac source may be used for 460 volt motor.

After the stator varnish is treated and assembled, the motor is tested from a lead or leads to ground with a maximum voltage of two times rated voltage plus 1,000.

Form Wound Motors - After form wound coils are insulated, each coil can be ac high-pot tested. Some manufacturers do not hi-pot the coils at this point, while others test 100% of the coils. Another approach is to test a sample of the coils and then, if any failures are found, conduct a 100% inspection.

After the coils are inserted in the stator but not connected or treated with varnish, all the coils are hi-potted at a voltage below the value used on the coils individually and well above the final NEMA hi-pot test of two times rated voltage plus 1,000.

After the stator is connected and before varnish treatment, the stator is hi-potted from a lead or leads to ground at a voltage below that given in the above paragraph but above that for the final high potential test.

After the stator has been varnished and assembled in the complete motor, it is hi-potted from a lead or leads to ground at the NEMA rated votage of two times rated voltage plus 1,000.

A.2.2 Dc Insulation Leakage Tests

The current which is measured in the dc high voltage test circuit includes leakage or conduction current, and also the current necessary to charge the insulation to the desired test voltage. The source of the direct test voltage usually has appreciable resistance to reduce the risk of damage due to charging current. Sudden change in voltage produce larger charging or discharging currents as compared to the conduction current component. This current, also known as dielectric absorption current, becomes insignificant 10 to 20 minutes after the potential is applied.

The dc hi pot test is usually conducted on a withstand basis. However, it is prudent to record the resistance-versus-voltage or current-versus-voltage characteristics of motor insulation. Plots from this data serve as a reference for analysis of subsequent tests.

Current measurements made during a test with dc voltage will give an indication of impending breakdown, so that the test can be discontinued. However, other unpredicted breakdowns could occur and may not be detected from the current readings.

The high voltage dc step voltage test for insulation leakage is ordinarily performed on large motors, and is used in plant maintenance programs and by motor manufacturers when there is a special request by the customer. The test involves applying increasing dc voltage steps to a stator. The leakage currents at each step are recorded after waiting for the discharge currents to stop. The stable current is the leakage current through the insulation. Obtaining a steady current may take an excessively long time. Therefore, it may be necessary to use special test equipment or microprocessors that calculate the leakage currents, or to manually calculate the leakage currents by mathematical summation. The test is continued until the maximum test voltage level is reached. The leakage currents are plotted against the voltage to determine the tip-up (which is the difference between the final current reading and the initial current reading). The test is performed by using special step voltage testers which allow increasing voltage to be applied and the resulting current measured. The test procedure is discussed in detail in IEEE Standard 95 and IEEE Standard 432.

The major sources of in the error measurement are the same as those for the ac insulation test. Excessive voltages can increase the risk of damaging the insulation, just as with the ac insulation leakage test.

A.3 Dissipation Factor (and Capacitance)/Power Factor/Tip Up

When an ac potential is applied to a winding, alternating current flows through the stator and reaches a steady state value immediately after the application. Therefore, time is not considered as a factor in ac measurements and, unlike dc tests, measurements may be made very rapidly. Because of the alternating nature of the test voltage, the current that flows is largely charging current, which is a function of the capacitance of the insulation. However capacitance is not very sensitive to insulation condition, and degraded insulation usually is reflected in dielectric loss which is determined from the loss component of the total current measured (see in Figure A-3).

The power factor is a measure of the energy lost in the insulation (in watts) through I^2R (heat) losses and can be expressed as,

$$\text{Power Factor} = \frac{\text{Resistive Current}}{\text{Total Measured Charging Current}} .$$

The power factor is almost identical to the dissipation factor for low values and is related to it by the expression,

$$\text{Power Factor} = \frac{\text{Dissipation Factor}}{1+(\text{Dissipation Factor})^2} .$$

The power factor is a measure of the overall condition of the insulation and is usually performed on large, high voltage machines of 6kV, and higher. High power factors are generally indicative of high porosity, delamination, improperly or incompletely cured polymers. As the polymer ages and chemical degradation occurs (oxidation and loss of volatiles by ionization loss), voids form in the polymer which permit greater electrical leakage and the power factor will increase. The use of power factor to evaluate the condition of the insulation has the advantage that it is independent of the machine rating or dimension.

In a perfect insulation material, the power factor would be expected to remain constant with the increasing test voltage. However, all insulation has im-

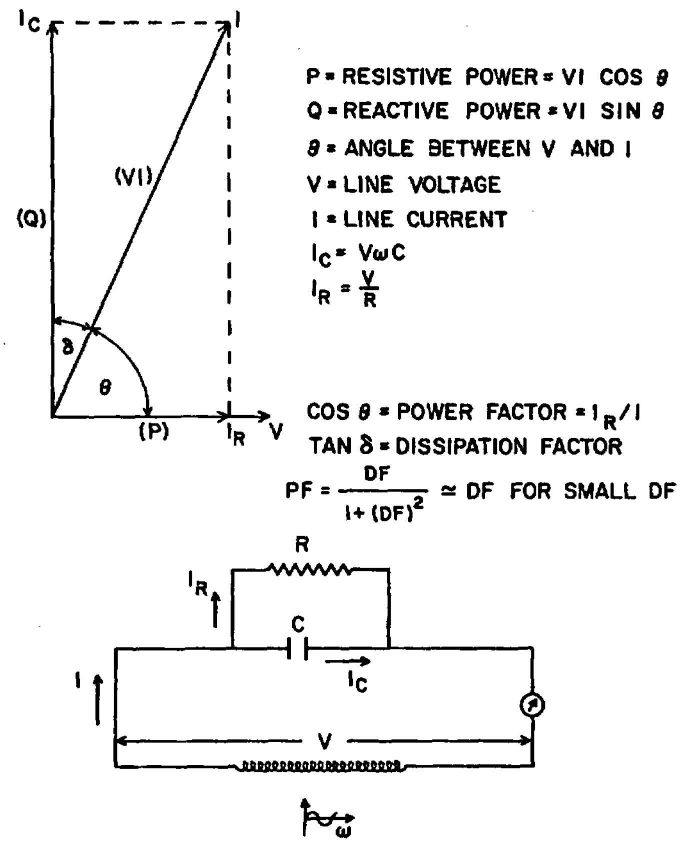


Figure A-3: Motor Insulation Equipment Circuit

perfections that are the source of current leakage paths which grow and cause the power factor to increase with increasing test voltage. An example is shown in Figure A-4 (A2).

The power-factor tip-up is obtained by subtracting the power factor measured at the lower test voltages (recommended as 25 percent of the operating phase-to-ground voltage) from the power factor at the higher test voltage (recommended as 100 percent of the operating phase-to-ground voltage). The important feature to monitor in power factor tip-up is the trend, not the absolute values. IEEE standard 286 provides the recommended practice for such testing applicable to rotating machinery.

A.3.1 Test Application

This test is performed most widely in the development of insulation systems, and is not normally used in maintenance programs or as a production test in manufacturing. The major source of error is improper use of the capacitor bridge, poor electrial connections and stray losses due to poor shielding and grounding.

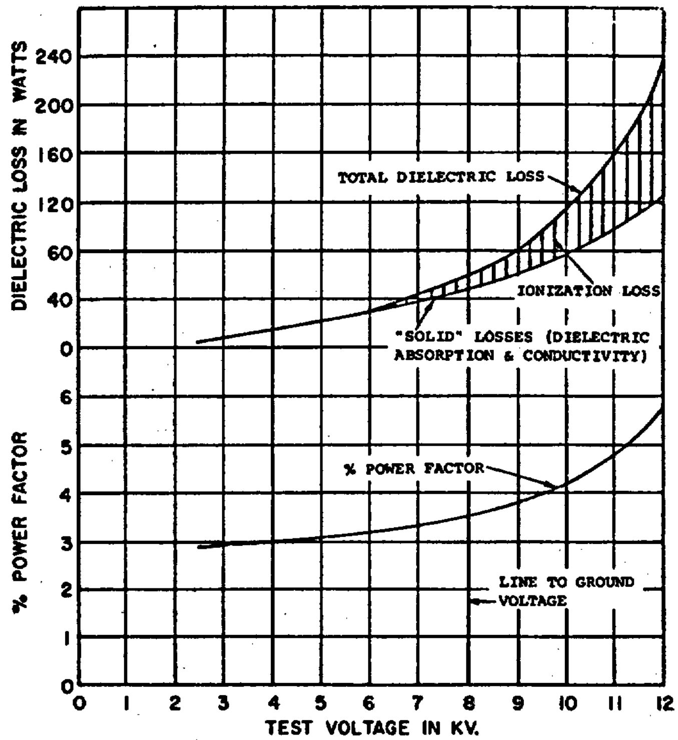


Figure A-4: Power-factor tip-up

Power factor testing of motor insulation is performed at several voltages up to 125% of line-to-neutral rating; charging current, dielectric loss and power factor are recorded, and the power-factor tip-up between 2 kV and line-to-neutral voltage is calculated. A good insulated winding may have surge factors ranging from 1% to 3%, depending upon the type of insulation and the degree of curing and/or dryness. Power-factor tip-up is generally less than 2%, again depending on the type of insulation, its age, and condition. It was found that coils which operated under severe ionization were in the poorest condition, and that the degree of internal deterioration was proportional to the "tip-up" measured.

A.4 Surge/Impulse Voltage Tests

Surge testing is used for evaluating the integrity of turn insulation in the stator winding and is conducted by transmitting electrical pulses from a capacitor, with very rapid rise times, into the motor windings of the stator. These pulses produce a damped, oscillating current which can be observed on an oscilloscope. Deterioration of the turn insulation will cause the shape of the damped signal to change. By superimposing on an oscilloscope screen the pulse signals transmitted through two motor leads (e.g. the lead to phase A and the lead to phase B) and assuming that the leads are from identical circuits, any differences between the two signals can be readily observed. A difference is usually interpreted as meaning that one of the coils has a weak spot or failure in the turn insulation. It should be understood that in a wye connected motor, each pair of leads is for two phases in series, and in the delta connected motor, each pair of leads is for a series - parallel arrangement of the phases. Examples of the wave shapes for different winding faults is shown in Figure A-5 (A3). IEEE Standard 522 provides the guide for testing on form-wound stator coils.

A.4.1 Test Application

Surge testing is performed on random wound and form wound motors during their manufacture to detect turn-to-turn failures and incorrect electrical connections. The test has been proposed for maintenance testing of motors, and it is gaining acceptance. The test voltage is the peak of the surge which is generated by applying the discharge of a capacitor across a resistor giving a pulse with a steep wave front. The result is a standing wave which distributes voltage equally across the turns of the coil. A comparison of the wave shapes of the voltage pulses between two windings or coils on an oscilloscope can reveal insulation failures in random wound and form wound motors, as discussed below.

Random Wound Motors - Surge testing of the windings is performed on random wound motors at two points in the manufacturing process. The first point is after the untreated coils are inserted into the stator core and connected. The second point is after the motor is assembled and varnished. This test compares surge voltage signatures in the winding between any pairs of leads (e.g. 1 to 2) to the winding between any other lead pair combinations (e.g. 2 to 3 or 1 to 3). For 460 volt motors the peak pulse test voltage will be on the order of 2,600 to 3,000 volts. Traces from the surges in the winding combinations between the two leads are superimposed on an oscilloscope; discontinuities and differences between the wave shapes may constitute winding failure. Six lead, independently connected motors can be surge tested by comparing one phase with another, while a complete surge test requires that all combinations of windings be tested. It is important to distinguish the reasons for the difference in wave shapes. For example, dissymmetries designed into the motor winding, such as phase coil placement in concentric windings and nonsymmetrical lap windings used in two pole motors may cause differences in the wave shapes that appear as failures.

Form Wound Motors - Surge testing of form wound motors is performed at two points in the manufacturing operation. The form wound coils are tested individually after they have been formed and insulated, by comparing the wave shapes from the surge tests from the different coils. A failure consists of differences between the wave shapes of the voltage pulses for the two coils. The surge test is repeated after the coils have been inserted in the stator but before they have been connected and treated with varnish. The applied voltage varies depending on the rating of the wire insulation used. The turn to turn insulation rating can vary from 500 volts for varnish film insulation to 1,500 volts per turn for film insulation that is covered with glass. The test voltage that is applied is the rated turn voltage times the number of turns. Damage to the motor can occur if the test voltage is too high.

The major sources of measurement error are:

a) Misinterpretation of the discontinuities and differences in wave shapes which may be caused by winding dissymmetries in the design of the motor.

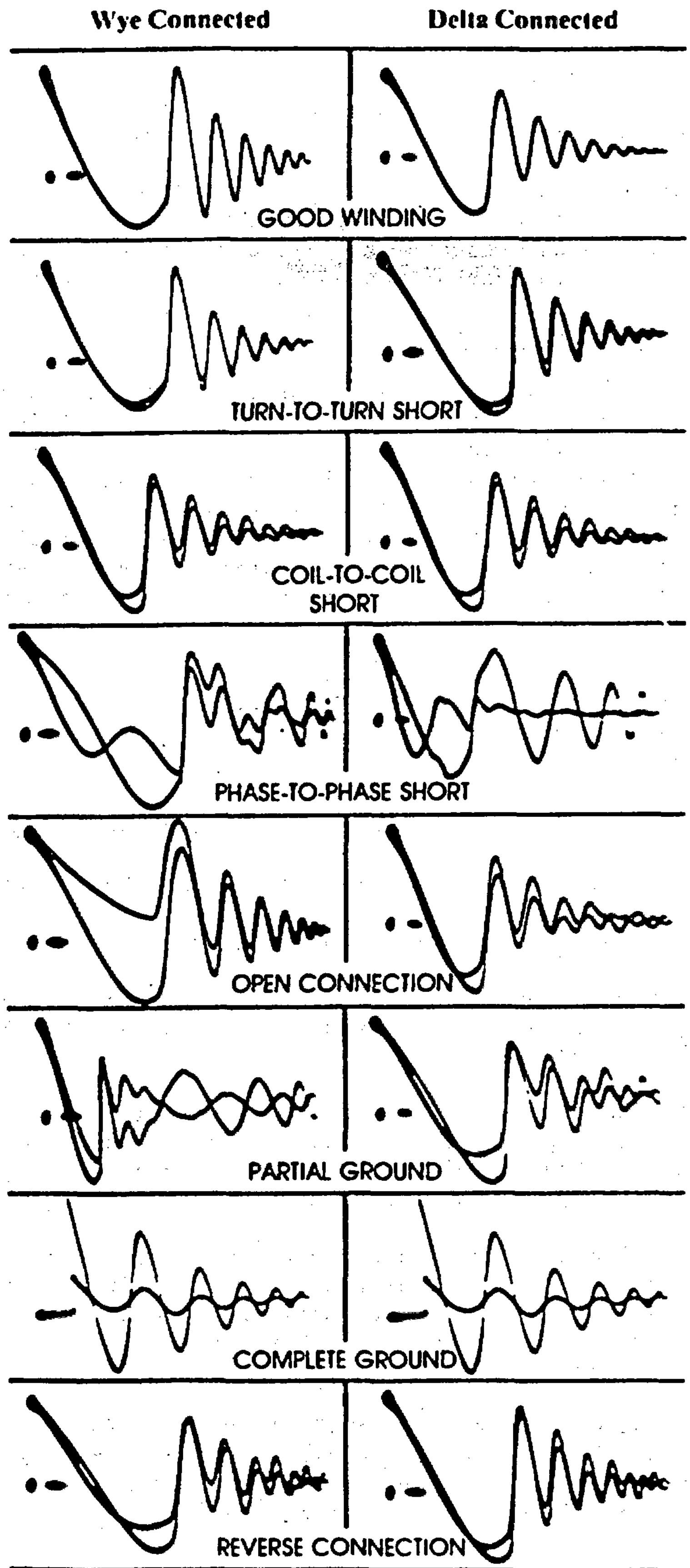


Figure A-5: Wave shapes for typical winding faults in wye connected and delta connected windings (A3)

b) Tester out of calibration.

c) Improper measurement of output voltage.

For surge testers that obtain the output surge voltage from measuring the input voltage to the tester, erroneous, lower output voltage readings may result from saturation in the transformer. To correct this condition, direct measurement of the output voltage with a voltage meter is necessary.

A.5 Partial Discharge Tests

The electrical breakdown of insulation material occurs from 500 to 5,000 volts per mil, yet the stress level for most equipment is in the range of 40 to 50 volts per mil. With such a factor of safety one would not expect to observe electrical breakdown (as a corona discharge) in the insulation of low voltage electrical machinery. However, corona discharge does occur and is commonly seen in the slot between the ground wall and the insulation because of the multiplying effect on the voltage potential across the gap from the dielectric constant of the insulation. This multiplying effect can be expressed by:

$$\frac{E_{air}}{E_{ins}} = K_{ins}$$

where:

E_{air} = voltage potential across the air gap

E_{ins} = voltage potential across the insulation

K_{ins} = dielectric constant of the insulation.

The dielectric constant of a material is the capacitance of the material, divided by the ratio of the area under a pair of electrodes to the thickness between the electrodes.

From the above expression, if the dielectric constant of the insulation is 5, then the voltage potential (or dielectric stress) across the air (E_{air}) is five times the voltage gradient across the insulation (E_{ins}). When the stress is high enough to breakdown air, then a corona discharge will occur.

Electrical breakdown of air can occur at very small voltages, depending on the air pressure and the size of the gap. The critical voltage at which breakdown in the gas occurs is a function of the product of the pressure of the gas (p) and spacing (d) described by Paschen's Law. The critical voltages for the breakdown of several gases are plotted in Figure A-6.

When these discharges are small, they are referred to as "partial discharges" and their detection requires very sensitive equipment. The discharge can occur in air at approximately 300 volts; however, at this voltage discharges are almost impossible to detect because they are so small in magnitude.

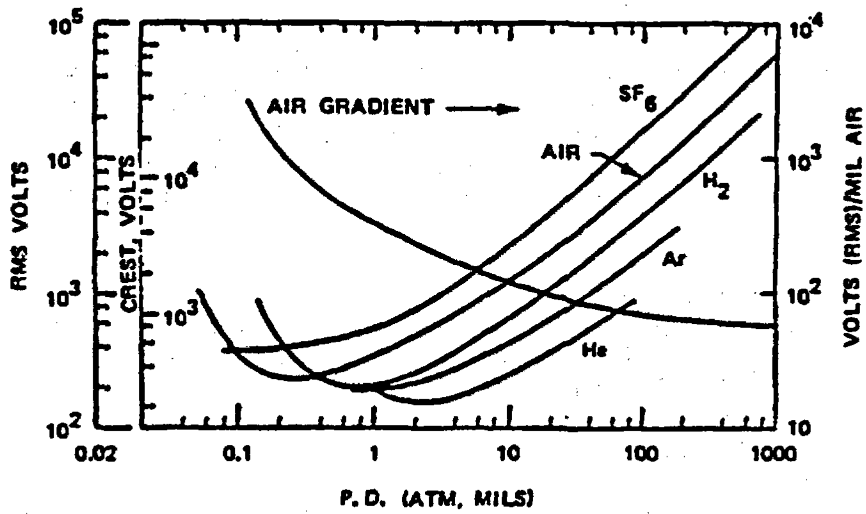


Figure A-6: Pressure-spacing dependence of the dielectric strength of gases

The effect of discharging in the insulation is to increase the leakage current with increasing test voltage so that the leakage increases more rapidly at the higher voltages (and therefore does not obey Ohm's law). This effect can be measured with the power factor "tip-up" test. This test is ordinarily performed at levels in the kilovolts range, where partial discharges millivolts in magnitude can be observed. Below this test voltage, it is very difficult to observe partial discharging because of the small magnitude of the partial discharge and the small signal-to-noise ratio.

There is some evidence to show that the maximum pulse height of the partial discharge increases with insulation age in power generators (A4). Diagnostic tests over an eight year period on a 13.8 kV hydroelectric generator demonstrated tht the maximum pulse height increased from approximately 75 mv in 1975 to 150 mv in 1977 when delivering the rated load. The increase in partial discharge magnitude is thought to be associated with the growth of voids in the insulation.

A.5.1 Test Application

Partial discharge testing is being developed and used for maintenance testing of large equipment, such as turbine generators and high voltage cables, in which partial discharge signals occur with greater magnitude and frequency. Ontario Hydro, Canada sucessfully used this test for monitoring the condition of the insulation in its hydroelectric generators. The high cost of the test equipment (which can begin at approximately $10,000) and the lack of experience and historical test data have been drawbacks in the spread of its use.

Other applications for partial discharge testing are for Quality Assurance acceptance in the manufacturing of electrical components such as capacitors, transformers and cables. Many of these applications are in the low voltage range (e.g. 110 volts). Some instrument companies claim to have between 400 and 500 of their testers in the field, mostly being used for QA acceptance of electrical components.

A.6 Motor Running Current Tests

An increase in the motor running current can be caused by excessive loads on the motor (e.g., from tightly packed stem packing, worn bearings, bent valve stem), by unbalanced voltage in the phase windings and from deterioration of the winding insulation and low full-load voltage. The result increases in such currents can be a rise in temperature of the motor and accelerated thermal degradation of the winding insulation.

Motor running currents normally should be below the service factor, which can be 1.15, or 15 per cent above the rated value. All large motors (greater than 500 hp) and totally enclosed motors normally have a unity service factor. Recording and trending the motor running current can be useful in confirming other test results, in assessing the condition of the motor and predicting whether it will remain functional.

The terminal voltage should be measured to help to diagnose the reason for any changes in the motor running current, specifically, whether an increase results from a reduction in the input voltage or from unbalanced motor phase voltages.

Both the no-load and the load currents are measured during manufacturing and on the assembled motor. The test also is performed in the maintenance programs at the utilities for checking the load and balance of phase currents. The no load test is performed on the assembled motor in conjunction with the impedance test and open rotor bar test. The no load current test and impedance test are part of the National Electrical Manufacturers Association (NEMA) commercial test in NEMA MG-1, "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators."

The no load test is performed at the rated voltage to obtain the motor current and current balance in the phases. The impedance current of the motor is measured at one quarter of the rated voltage with the rotor locked. The open bar test is performed with a single phase voltage applied to the motor and open bars are detected by irregular current readings on the unlocked rotor when the rotor is slowly turned by hand. These tests are described in IEEE Standard 112.

A.7 Bearing Lubrication Tests

When the motor is assembled, the bearings are lubricated either with grease or oil. During shipping, the oil is removed from the motor and must be replaced before the motor is stored or installed. During operation the lubricant should be replaced in intervals recommended by the manufacturer. Grease life depends on the bearing size, speed, load and temperature. An equation for bearing grease life is (A5):

$$\log L = -2.60 + 4{,}420/(460 + T) - 0.301S$$

where:

L = time at which 10% of greased bearings fail (hours)

T = bearing temperature (°F)

S = half-life reduction factor and is the sum of the reduction factors for grease type, bearing speed (S_N) and bearing load (S_W).

The grease type reduction factor can be determined from a rating given by Booser (A5). This factor varies between 0 for long-life petroleum and silicone greases to 2.9 for diester, low-temperature greases.

The bearing speed reduction factor, S_N can be calculated from the expression:

$$S_N = 0.86DN/(DN)_L$$

where:

D = shaft diameter at bearing seat (mm)

N = speed (rpm)

$(DN)_L$ = limiting DN for a particular bearing type (mm-rpm)

The bearing load reduction factor, S_W can be calculated from the expression:

$$S_W = 0.61DNW/C^2$$

where:

W = radial load (lb)

C = specific dynamic capacity (lb) which is the bearing load that produced fatigue failure in 10% of the bearings after 1 million revolutions.

Generally, regreasing should be done at or before the calculated 10% grease life (L). Large motors that use oil for lubrications should be tested periodically for metal wear and oil contaminations in the bearings, thus preventing any catastrophic failures.

Oil Analysis - The three significant lubrication variables affecting gear (or bearing) life are: viscosity, acid number (pH) and antioxidant concentration. These can be evaluated with the following standards: ASTM D88-53 (A6), ASTM D974-53T (A7), and D664-52 and ASTM D943-53T (A8), respectively.

Visual inspection of the oil for particulates (e.g. metal shavings, etc.) and identification of the metal to localize the source of wear can provide some measure of bearing degradation.

A.8 Additional Motor Tests Performed by Manufacturers

A.8.1 Winding Resistance Tests

The winding resistance test is used in the maintenance, manufacturing and rewinding of motors. The test is performed after the stator is wound and connected but it is being varnished.

This test determines electrical unbalance in the windings and if the windings have the proper resistance. Improper resistance can result from the incorrect values for the number of turns, pitch, wire size and connection (e.g. wye or delta). The test is normally performed with a resistance bridge to measure the resistance of the winding between leads (e.g. between lead 1 and lead 2, lead 2 and lead 3 and lead 1 and lead 3); the measurement then is compared with the design limits.

The winding resistance balance between phases can be inspected only on six-lead motors by measuring the resistance between each pair of leads (e.g. lead 1 and lead 4, lead 2 and lead 5, etc.).

Winding resistance is measured on random wound and form wound motors during manufacturing and during maintenance. However, the winding resistance of form wound motors is much smaller than of random wound motors (because of the larger cross-section of the form wound coils) and the small number of turns.

The major sources of error in measurement are due to the resistance bridge being out of calibration and poor electrical connections between the coil leads and test set.

A.8.2 Load Tests

These tests determine the efficiency, power factor, temperature rise, line currents and watts at different loads to verify the motor design parameter and are described in IEEE Standard 112-1978. These tests also can be used to evaluate the performance of driven equipment by comparing the equipment performance (e.g. flow rate for a pump) with the electrical load on the motor. In many applications only the load current is monitored.

A.8.3 Torque Testing Including Start and Maximum Torque

This test measures the motor torque and current to verify the motor design parameters. The tests are discussed in IEEE Standard 112-1978.

A.8.4 Motorette Tests

This test is for determining the insulation life for random wound motors using models of the insulation system called motorettes. The test is conducted as IEEE Standard 117-1974, "Test Procedure for Evaluation of Systems of Insulating Materials for Random Wound Electric Machinery." The motorettes are cycled to failure by repeatedly heating them in an oven to age them and by subjecting them to vibration and humidity stresses. The criterion of failure is a short circuit from failure in the turn-to-turn, phase-to-phase or phase-to-ground insulation. Using of IEEE Standard 101, "IEEE Guide to Statistical Analysis of Thermal Life Test Data," the data from the test can be plotted and analyzed.

A.8.5 Formette Testing

This test is for determining the insulation life for form wound motors using models of the insulation system called formettes. The test is conducted per IEEE 275-1966, "Test Procedures for Evaluating of Systems of Insulating Materials for AC Electrical Machinery Employing Form Wound Preinsulated Stator Coils." This test is conducted in a manner similiar to that given in IEEE Standard 117-1974 and the test data is plotted and analyzed as described in IEEE Standard 100.

A.8.6 Sealed Winding Testing

This test is conducted per IEEE Standard 429-1972, "IEEE Standard Test Procedure Evaluation of Sealed Insulation Systems for AC Electrical Machinery Employing Form Wound Stator Coils." It is similar to the test in IEEE Standard 275-1966 except an underwater submergence test is used in place of the humidity test. The results are plotted and analyzed as discussed above for the IEEE standards.

A.8.7 High Frequency Life Testing

This test determines insulation life generally in form wound motors. It requires that the accelerated aging of the motors be performed while applying voltages on the order of 3,000 cycles per second.

A.8.8 Plug Reverse Life Testing, Holding Temperature Constant

In this test the motor is started in one direction, run for a period of seconds and then the leads are interchanged (e.g. the lead for phase A becomes the lead for phase B, etc.), reversing the rotation of the motor. The process is repeated until motor failure occurs. In this way the motor is thermally and operationally aged. The test is conducted to determine the adequacy of the motor winding bracing system over the life of the motor, and can be combined with a 100% relative humidity test to determine the life of sealed winding motors.

A.8.9 Miscellaneous Tests

The twisted wire test is an easy but not very functional way for screening and classifying insulated magnet wire according to its temperature class. The test consists of subjecting pairs of insulated magnet wires to voltage stressing and thermal aging cycles and conducting insulation tests to determine when insulation failure occurs.

The twisted wire test was originally described in IEEE Standard 57 which no longer exists and is presently described in ASTM D2307, "Test for Relative Thermal Endurance of Film Insulated Magnet Wire." IEEE Standard 117, "Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electrical Machinery" is a more functional test than the twisted wire test. The twisted wire test, ASTMD2307 is referred to in Underwriters Laboratory Standard UL 1446, "Systems of Insulating Materials". Another standard that references the twisted wire test is ANSI/NEMA Standard MW1000, "Magnet Wire," in which the procedures for preparing the specimens are given and minimum acceptable test values are specified.

The humidity test is conducted on motor stators or models of stators by selected tests (e.g. current leakage, phase balance, dissipation factor and capacitance measurements and corona starting voltage) after exposure to moisture. The test is described in IEEE Standard 117 as one which includes thermal aging and mechanical stress. The humidity test also is part of the military specification, MIL-M-17060E (SH).

The sealed tube test is used to measure the compatibility of components in an insulation materials system by placing samples of the materials in glass tubes, sealing them and heating the glass tubes. For the hydrolysis test, the tube is sealed with water at a temperature above 100°C to create an environment with greater than 95% relative humidity. For the Underwriters Laboratory Standard UL 1446, Section 14, in which water is not added, the test temperature is 25°C above the rated temperature for the particular insulation system.

The effects of hydrolysis on the polymers is evaluated by measuring the hardness and weight gain at room temperature after the tube is opened at the end of the test.

A.9 References

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(A3) Bergstrom, A., Smith, G.W., "An Inroduction to the Testing of Insulation Systems in Electrical Apparatus," pp. 1-16, issued by Baker Instrument Company, Ft. Collins, CO.

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(A5) Booser, E.R., "When to Grease Bearings," Machine Design, pp. 70-73, August 21, 1975.

(A6) "Method for Testing Visocity of Lubricants," American Society for Testing of Materials Standard ASTM D88-53.

(A7) "Methods for Measuring the Acidity of Lubricants," American Society for Testing of Materials Standard ASTM D974-53T.

(A8) "Methods for Measuring Antioxidant Concentrations in Lubricants," American Society for Testing of Materials Standard ASTM D943-53T.

APPENDIX B

SURVEILLANCE/IN-SERVICE TESTING (IST) METHODS

B. SURVEILLANCE/IN-SERVICE TESTING (IST) METHODS

Nuclear plant equipment and systems undergo periodic surveillance tests, calibrations, and inspections to ensure that the plant meets the requirements of the technical specifications (tech specs). There are several hundred surveillance procedures for a single plant which determine the degree of compliance. In nuclear applications, the term "surveillance requirements" is defined in 10CFR50.36 as "... requirements relating to test, calibration, or inspection to assure that the necessary quality of systems and components is maintained, that facility operation will be within the safety-limits, and that the limiting conditions for operation (LCO) will be met." To preserve the meaning of surveillance tests, this section discusses some of the test and mandatory procedures applicable to motors, which can be used to monitor motor performance.

For motors, there are no specific tech specs that require surveillance testing to be performed. However, the motor driven components such as pumps, valves, fans, chillers are the subject of such requirements. Of course, for each of these driven components the motor is an integral part of the equipment. ASME Section XI, in-service testing procedures, governs the reference values of test quantities as measured or observed when the equipment is known to be operating acceptably. The in-service tests are not designed to establish complete equipment performance, but provide information through measurement or observation of the equipment operational readiness. This does not include routine servicing, which involves planned preventive maintenance of the equipment without disassembling it or replacement of parts such as changing the oil, flushing the cooling system, adjusting packing, adding packing rings, or maintenance of mechanical seals.

Test quantities considered for pumps and valves are given in Table B-1 as required by ASME, Section XI. Reference values for each piece of equipment are determined from the results of an in-service test which may be run during preoperational testing or power operation. Depending on the system design, each pump or valve is subjected to a set of tech spec requirements. Nominally, every 3 months during normal plant operation each pump or valve undergoes in-service testing

TABLE B-1: SURVEILLANCE TEST QUANTITIES FOR PUMPS AND VALVES

Quantity	Measure	Observe
Pump		
Speed N (If Variable Speed)	X	
Inlet Pressure P_i (Startup & During Test)	X	
Differential Pressure ΔP	X	
Flow Rate Q	X	
Vibration Amplitude V	X	
Proper Lubricant Level or Pressure		X
Bearing Temperature T_b	X	
Valve		
Valve Exercising Test - Stroking	X	
Valve Leak Rate Test	X	

The test quantities used in surveillance or pumps and valves include vibration amplitudes, temperatures, stroke time for MOVs and speed and flow for pumps. These parameters are also suitable for motor surveillance and are discussed here. Vibration and noise analysis can be applied to motor mountings, as well as the bearings. The temperature measurements include the winding system, the bearings and the lubricating oil for large motors, specifically for those with sleeve bearings. Valve stroking and pump speeds which can be translated to the motor speed also are discussed. A subsection is devoted on MOV testing which measures several key parameter suitable for inclusion in the plant surveillance testing program.

B.1 Vibration/Noise Analysis

Unusual vibration and noise may occur from different sources in a motor, such as worn bearings, rotor misalignment, and loose parts. Shorted turns in the winding may induce vibrations in the motor that are out of phase with the 60 Hz ac load.

Unusual noise may result from worn bearings, baffles for the cooling air which have become detached, and loose mechanical parts. Some noise may be the result of the motor design, such as a noisy circuit, or because of an unusual ducting of air. The discussion below treats the vibration and noise caused by bearings, in more detail.

The objective is to discuss potential test methods for monitoring vibration and noise in the bearings of running motors to detect incipient failures. These tests would be performed on continuous duty large pump motors.

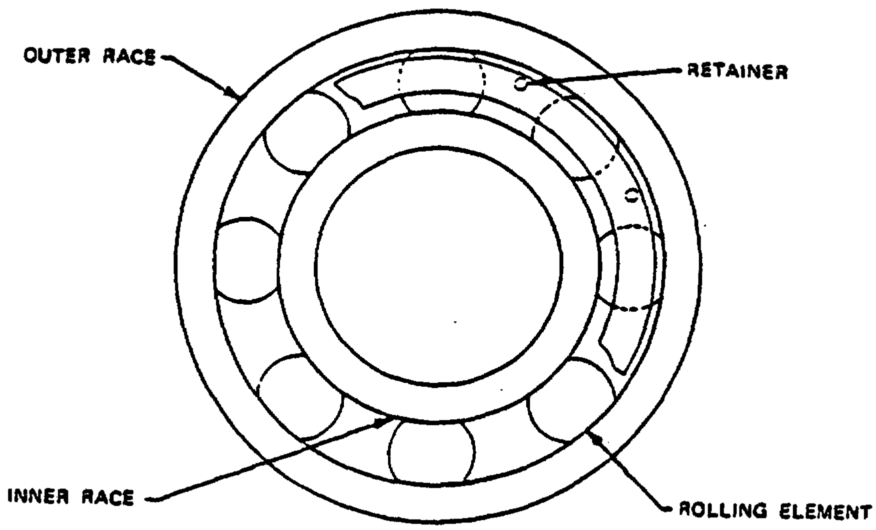
Bearing degradation generally manifests itself by a deterioration of contact surfaces. The repeated application of high alternating stresses which occur just below the surface can produce small voids. Cracks grow from the voids to the surface, resulting in pitting. Surface defects also may arise from small oscillations of the balls in the bearings ("false brinelling") during shipment. These defects may occur in the inner race, outer race, rollers or balls.

Other possible degradation mechanisms include broken cages, loss of grease resulting in inadequate lubrication, and brinelling of the bearing from excessive loading (permanent deformation of the bearing). Excessive clearances from loosened lock nuts and excessive bushing shaft seat wear from abrasives in the lubricant are mechanisms that cause bearing degradation.

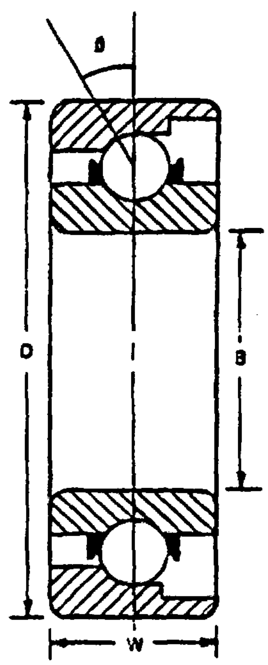
Degradation can be detected in a variety of ways. Each method captures some form of energy produced by the defective action on the dynamics of the rotating bearing.

B.1.1 Vibration Measurements

As the shaft rotates, various elements of the bearing pass repeatedly over the surface defects causing in vibration. Figure B-1(a) and (b) show the parts in a cross section of a representative angular contact bearing. By knowing the vibration signature of the bearing, degradation may be detected as the defect grows and the problem becomes more severe.



(a) Drawing of angular contact bearing



(b) Cross section of ball bearing showing the contact angle

Figure B-1: Angular contact ball bearing

Vibration frequencies for bearing dynamics are:

Ball Pass Frequency (BPF): Occurs due to the ball or roller passing over a surface defect.

Ball Spin Frequency (BSF): Occurs when a defect on the ball strikes the raceway or when the cage is broken or when the balls are thrusting against the cage.

Fundamental Train Frequency (FTF): Occurs when a defect affects the rotation of the train.

Rotating Unit Frequency (RPS): Occurs by residual imbalances and/or eccentricity in the rotating unit.

These frequencies are given mathematically by:

$$RPS = RPM/60$$ rotating unit frequency

$$FTF = \frac{1}{2}\left(1 - \frac{Bd}{Pd}\cos\phi\right) RPS$$ fundamental train frequency

$$BPFI = \frac{Nb}{2}\left(1 + \frac{Bd}{Pd}\cos\phi\right) RPS$$ ball pass frequency - inner race

$$BPFO = \frac{Nb}{2}\left(1 - \frac{Bd}{Pd}\cos\phi\right) RPS$$ ball pass frequency - outer race

$$BSF = \frac{Pd}{Bd}\left(1 - \left(\frac{Bd}{Pd}\right)^2 \cos^2\phi\right) RPS$$ ball spin frequency - ball defect

where:

Bd = diameter of ball or roller

Pd = bearing pitch diameter (diameter from ball center to ball center)

Nb = number of balls or rollers

ϕ = contact angle from the center of the balls to the point of contact on inner race.

RPM = revolutions per minute

RPS = revolutions per second

Monitoring the spectral density of the power or the amplitude spectrum of the vibration for changes in amplitude or modulation of these frequencies can be used to diagnose the occurrence of a defect and degradation of bearings.

Defects in bearing raceways would show up as narrow band spikes at the BPFI or BPFO. As the size of the defect increases, the band width of the spectrum increases and may become modulated by the RPS, i.e., a wide band spectrum with narrow band spikes at BPF and BPF ± RPS where RPS << BPF.

Ball or roller surface defects produce narrow band spikes at the BSF. One ball with a defect would appear as a spike at the BSF; multiple defects would appear at Nb x BSF. Should the defects become large, the FTF would also be excited. A damaged or defective cage also would show up in the BSF, with a severely damaged cage exhibiting frequency shifts.

Excessive internal looseness appears in the RPS plus multiples of the RPS. A bearing turning on the shaft or in the housing results in low amplitude, broad-band random noise. Inadequate lubrication usually shows as an increase in the amplitude of peaks in the range of higher frequencies. The locations of these peaks are dependent on the geometry and RPS of the bearing, and are typically experimentally determined.

Most bearings have some characteristics at each of these frequencies and their spectra are complex as the basic frequencies. Essentially, detection occurs through identification of the peak amplitudes, and subsequent monitoring of the changes in these amplitudes with time.

Transducers for vibration measurements fall into three classes: accelerometers, velocity pick-ups, and displacement probes. Typically, displacement probes are non-contact measuring devices whose outputs are proportional to the distance between their tip and the surface of the specimen. Crucial cosniderations are the suitable placement of the probe and accessibility of a usable surface (flatness relative to probe tip diameter).

Velocity pick-ups and accelerometers are mounted directly on the surface. In all cases, a suitable surface for vibration measurement must be available; this generally is so for current designs of many motors and motor-operated valves.

The non-contact probe provides the only alternative if the surface is rotating. Eccentricity and out-of-balance conditions in the shaft as well as the surface conditions under the probe tip will appear in the displacement spectra usually at the RPS. Surface conditions are less of a concern provided the test location is precisely identified and suffers no variations, i.e., it is not marred after the baseline.

Directly attached transducers are preferrable to the noncontact probes in that they are more easily placed on surfaces since they are smaller and require less space for installation. These transducers come in various sizes and may be permanently attached via a mounting stud or attached temporarily with beeswax or epoxy.

Acceleration or velocity transducers are more often recommended than noncontact probes because they are easier to setup and provide maximum flexibility in location on the valve surfaces.

Transformation of the time signals produced during a test into frequency domain spectra requires a spectrum analyzer for the performance of a Fast Fourier Transform (FFT) on digitized data.

B.1.2 Acoustic Emission

Acoustic emission is a disturbance from the rapid release of energy that is generated by a transient elastic wave within a material. Plastic deformation, initiation and growth of cracks from fatigue or corrosion all give rise to acoustic emission signals which propagate throughout the structure. They are detected through a piezoelectric transducer mounted on the surface. The signal is then preamplified and put in to an analysis unit. Analysis includes count analyses and amplitude distribution similar to that used by vibration transducers, but at higher band widths.

Applicability of acoustic emission to valve operator monitoring is more limited than that afforded by accelerometers or velocity pick-ups because a baseline characterization of the acoustic emissions from the material is needed. This is often not available. Further, analysis of the vibration spectral content yields relatively straightforward diagnostic methods and techniques to localize the source of the problem within the bearings themselves, so eliminating the necessity for additional analysis.

B.1.3 Spike Energy

Analysis of the vibration signals can also take place in the time domain. Energy released due to the impacts of components on defecting sites produce spikes spaced at periods of time. This period is related to the frequencies discussed in this section as reciprocals, i.e., $T = 1/F$. More importantly, the spike amplitude and width is a function of the energy of the defects dynamics. As a defect worsens, the energy in the spike increases, usually manifesting itself as an increase in amplitude. Spike width can also indicate degradation.

Output from the vibration transducers would be input to an oscilloscope rather than a spectrum analyzer. The area under the spike or pulse then becomes the spike energy.

B.1.4 Vibration/Noise Measurements

Vibration tests are conducted to detect mechanical problems with the motor, such as worn bearings and loose motor parts. The vibration limits for a motor are generally available from the instruction manual. Typical test equipment for measuring vibration is the vibration analyzer available from several manufacturers, which can be used with a hand-held probe or an accelerometer attached to the motor.

Measurements of noise are commonly made with noise analyzers before shipping the motor and may also be used for surveillance testing if the background noise is not unacceptably loud. The procedure and acceptance limits for this test are in NEMA MG-1 and IEEE Standard 85-1973, "IEEE Test Procedures for Airborne Sound Measurements on Rotating Electric Machinery."

Local monitors which are commonly used for vibration and noise analysis range in capability and sophistication from simple meters to small computer-driven data acquisition systems. Selection of the system is highly dependent upon the consequences of not detecting failure in advance, the cost of the monitor and the criticality of the equipment to the operation of the plant.

At the most fundamental and least expensive level of sophistication are alarm/alert monitors, which monitor the total root-mean-square (rms) content of the signal and/or peak-to-peak levels. Based on pre-selected limits, the monitor provides either an indicator for an alert condition or an indicator for an alarm condition. Generally, there is no provision for actions by the monitor. Monitors can come in a number of channel configurations of two, four, six or more. Limitations are based on the number of monitoring sites and their proximity to the location of the monitor with its input channels.

Spectral analyzers provide the basis for comparisons in the frequency domain. Expense increases with higher numbers of input channels, but costs are relatively low for the two channel configurations. Limitations are the two channels for monitoring signals.

The advent of the personal computer and its attendant signal analysis software packages provides a relatively low cost solution, allowing higher numbers of channels and performing similar levels of frequency analysis. There are many vendors supplying hardware and software that can be added to the IBM PC, Apple IIEs, and HP personal computers, which can perform frequency analyses of 12 channels and more at, fairly economic rates. Additionally, the PC-based monitoring system provides detailed analytical capability for comparisons of baseline with on-line data. Information can be stored for later, more detailed analysis or processed on the spot for "instant" diagnosis.

B.2 Temperature Measurements

Temperature readings as well as the rise in temperature of certain motor parts are many times indicative of the presence of high leakage or eddy current flow, excessive friction and wear of rubbing surfaces, or blocking of cooling air or water flow passages. Temperature detectors are typically used in motor windings, bearing housings or lubricating oil to detect any existing abnormalities. A large flow of current in the winding or failure of the cooling system could increase the winding temperature, leading to hot spots. Failure of rollers or balls in the bearing assembly, insufficient or excessive lubrication, and high friction caused by rotor imbalance could lead to higher bearing temperatures. In case of sleeve bearings, the lubricating oil temperature is very critical to maintain proper viscosity and lubricity between the surfaces in contact.

Temperature measurements on larger motors are made periodically or continuously at the motor controllers or at the control room. Since the pump and valve tech specs include component temperatures as a part of routine surveillance, they are considered to be a good practice for periodic measurement and hence included in the surveillance testing.

The discussion in this section is derived from the description provided in IEEE Standard 112-1978, "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators." Four methods of measuring temperatures in motors and their applications are described and include:

- Embedded Detector (thermocouple or RTD)

  Used for:

  Standard Windings

  Bearings (probe type or embedded detectors used)

- Winding Resistance

  Used for:

  Stator Windings (or rotor windings for a wound rotor motor)

- Local Temperature Detector

  Used for:

  Local temperatures of winding and core laminations which are not accessible to thermometers but can be measured by detectors (e.g. thermocouples, resistance temperature detectors or thermistors) that are installed as permanent parts of the machine.

- Thermometer Method

  Used for:

  Stator Coils

  Stator Core

  Ambient

  Discharge Air or Discharge Coolant.

The most commonly used temperature measuring devices for motors are the thermocouple (T/C), and resistance temperature detector (RTD). The thermistor (a temperature-sensitive semiconductor) is used as a protective device that can be set to activate an alarm or relay at a predetermined temperature. It is difficult to use when accuracy is important (because of the non-linearity of its resistance vs temperature curve), however, it is satisfactory as an alarm. The most accurate readings are achieved with RTDs which can have an order of magnitude better accuracy than the T/C.

The temperature of the copper winding can be determined by measuring the resistance of the winding at a known temperature, T_B (e.g. room temperature) and at the temperature of interest, T_T. Substitution of these values and the values for the resistances at T_B (R_B) and at T_T (R_T) into the equation gives (from IEEE Standard 112-1978):

$$T_T = T_B + \left(\frac{R_T - R_B}{R_B}\right)(T_B + k)$$

where k = 234.5 for pure copper and K = 225 for aluminum, based on a volume conductivity of 62 percent. For copper, which has an average temperature coefficient of resistance of approximately .004 ahm/ohm-°C, the difference, $R_T - R_B$, for 200°C is approximately 0.8 ohms (B1). Since the resistance of the winding is at least an order of magnitude greater than this, achieving an accurate value for T_T is difficult because of the error resulting from small differences from large numbers.

B.2.1 Bearing Temperature

Bearing temperatures are measured on large motors as part of the plant surveillance testing program. This measurement is particularly important for special bearings where the temperature is critical, such as oil lubricated sleeve bearings, spherical roller bearings and plate bearings. Thermocouples or resistance temperature detectors are installed on the motor so that they contact the bearings and can easily detect the temperature changes. These instruments are connected to alarm relays and often can shut the motor off should the temperature exceed predetermined limits.

B.2.2 Winding Temperatures

Most large, high voltage form wound motors above 300 hp and voltages of 4,000 volts and greater, have resistance temperature detectors or thermocouples embedded between the coils in the stator slots. These sensors measure the winding hot spot temperatures that, together with the ambient, give the total winding temperature. Examples of total allowable temperatures are 130°C for motors with Class B insulation and 155°C for Class F insulation (given in NEMA MG-1). Winding temperature is a function of various factors including motor load (current), efficiency, ambient temperature, and motor cleanliness.

Sometimes the temperature sensors are mounted on the end turns of the motor or in the stator slots where they are used to monitor the winding temperature during heat runs, in which the motor is run under a series of different loads. Often, these sensors are used to transmit a signal to a device having an alarm or circuit relay to protect the motor if the temperature exceeds a predetermined limit.

B.2.3 Oil Temperature

Large motors with sleeve bearings have oil reservoirs supplying continuous oil to the bearing. Depending on the condition of the bearing, the oil gets warmer by acquiring heat from the friction produced at the bearing's contact surfaces. In some cases, the temperature of the oil is measured by a thermocouple or some other device to indicate the condition of the bearing.

B.3 Stroke Time (MOV)/Speed (Pump) Test

The stroke time test is necessary for valves that have performance criteria governed by the plant technical specifications. The test consists of opening (closing) the valve until the indicator light shows it to be fully opened (closed). The test can be conducted in the control room by using a calibrated stop-watch which is started when the valve is actuated, and stopped when the light goes on to show that the end of the valve stroke has been reached. The data from the check list obtained from stroke-time tests can be reviewed for trends in the stroke time. An increasing time may result from poor maintenance or buildup of crud on seats that is causing overloading of the motor, or because of deterioration of the motor, itself. For example, improperly set limit/torque switches or stem packing that is excessively tightened, can force the motor in the operator to work harder, leading to higher than normal motor temperatures and more rapid aging of the insulation.

Rotating speed of shaft driven pumps, fans or other rotating components can be measured directly to monitor the condition of the motor, coupling, or the driven equipment itself. For components directly coupled to motors of either synchronous or the induction type, the speed need not be measured per ASME Section XI. However, it is a good practice to monitor the speed of such equipment and compare it with the normal speed for operability.

B.4 Motor Operated Valve Testing

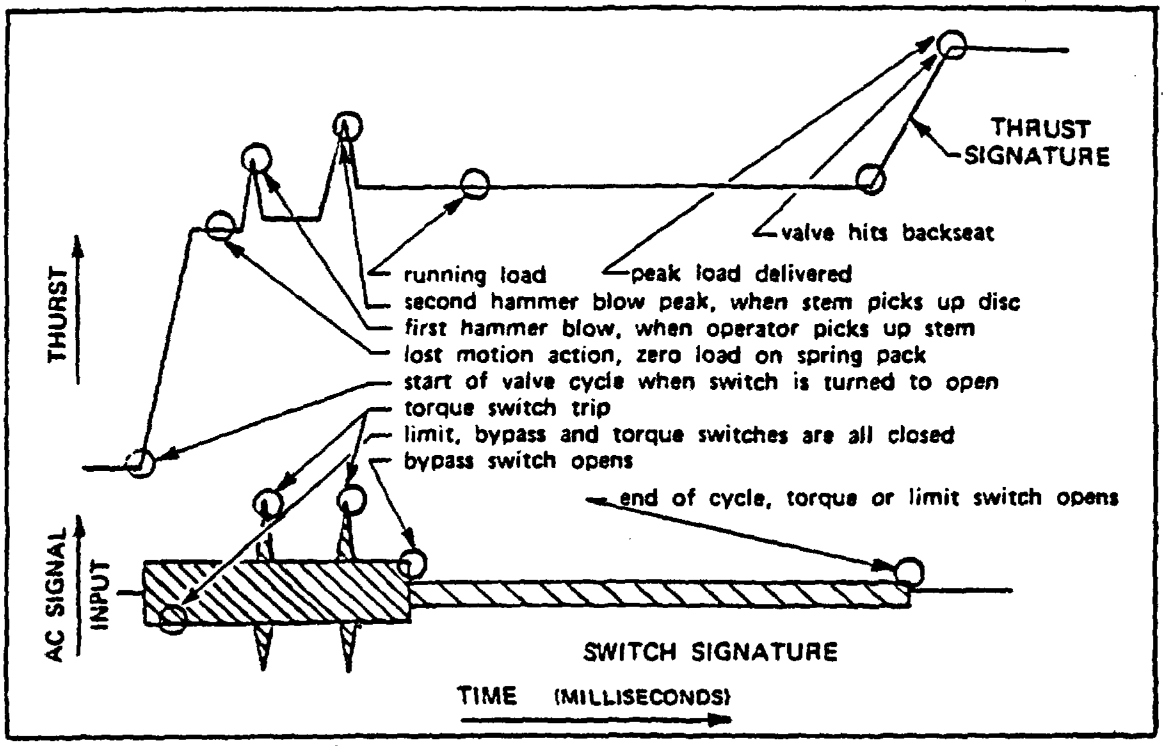
The NPAR study (B2,B3) on MOVs at Oak Ridge National Laboratory (ORNL) is developing a testing device which will measure the following parameters:

- motor current
- valve stem position
- valve stem velocity
- valve stem strain
- torque and limit switch actuations
- internal and external motor temperature
- MOV acceleration
- torque switch shaft rotation

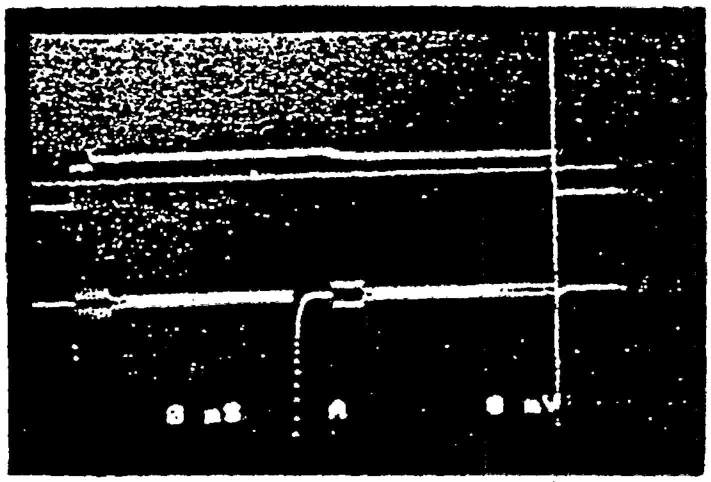
This testing provides the time dependent plots for each of the above parameters. Evaluation of the current motor operational readiness can be obtained by comparing the test data with the baseline (reference) plots.

The MOVATS* System is available from industry, which provides similar results. The MOVATS test system simultaneously measures the stem load, the motor current, and control switch points. It assesses the electrical and mechanical MOV condition with a patented thrust measuring device and switch monitoring circuit. The system can display on a CRT screen the signatures for

*MOVATS is a Motor Operated Valve Analysis Test System for diagnosing mechanical and electrical degradations. It is manufactured by MOVATS, Inc., Marietta, GA .



(a) Diagram of typical thrust and switch signatures during a close to open cycle



(b) Picture of the stem thrust and switch signatures of a "healthy" operated valve

Figure B-2: Displays for the MOVATS system

(a) stem thrust, (b) control switch, and (c) motor current and store them in a computer or plot them. Two signatures can be displayed and stored simultaneously, as shown in Figure B-2 (a). A picture of an actual trace on a CRT screen is shown in Figure B-2 (b). The manufacturer claims that the following parameters in an MOV can be determined:

- Load to unseat valve (hammerblow)
- Running load
- Load at torque switch trip
- Available load (final load minus running load)
- Valve cycle time
- Time of hammerblow
- Time at which close to open bypass switch opens
- Operator inertia induced stem load
- Final load
- Starting motor current
- Running motor current
- Final motor current.

B.5 Reference

(B1) Kerlin, T.W. and Shepard, R.L., "Industrial Temperature Measurement," published by The Instrument Society of America (1982).

(B2) Greenstreet, W.L., et al., "Aging and Service Wear of Electric Motor-Operated Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants," NUREG/CR-4234, June 1985.

(B3) Crowley, J.L. and Eissenberg, D.M., "Evaluation of the Motor-Operated Valve Analysis and Test System (MOVATS) to Detect Degradation, Incorrect Adjustments, and Other Abnormalities in Motor-Operated Valves," NUREG/CR-4380, January 1986.

APPENDIX C

CONTINUOUS MONITORING AND INSPECTION PROGRAMS

C. CONTINUOUS MONITORING AND INSPECTION PROGRAMS

The preceding two appendices have described various testing methods for evaluating the conditions of motor insulation and bearing assemblies. The two other activities, continuous monitoring and inspection of motor conditions, provide the other functional indicators to assess the condition of the motor performance. The following discussions include the procedures and the applicability for these two maintenance activities to various motor applications and sizes.

C.1 Continuous Monitoring of Motors

Continuous monitoring of motors can be done without the aid of any sophisticated equipment or tools. In fact, most of the measuring devices are permanently installed either at the installation or at the controller for the motor. These devices include ammeters, voltmeters, temperature indicators, and vibration sensors. Since they are not supplied with all motors, this particular activity is applicable only to those motors having the instruments for such readouts.

Since most readings can be taken at the controllers which are generally located in a milder environment than are their motors, a more frequent monitoring schedule is possible without too much inconvenience of personnel exposure. Some parameters for very large motors important to plant safety can be read by the control room operators. It is recommended that these parameters are logged on an individual motor performance sheet while making the scheduled inspection checks.

Parameters which are typically monitored continuously include line/phase current or voltage, winding and bearing temperatures, lubricating oil temperatures and bearing vibration signals. Depending on the motor size, the winding and bearing temperatures are measured at several locations in the winding/bearing housings. Vibration transducers usually are mounted on bearing housings on intermediate to large size motors, since failure of bearing may lead to damages to the insulation which are expensive to repair.

Small motors used for driving safety components or valves are often equipped to indicate winding and bearing temperatures, line and phase currents/voltages; some have bearing vibration monitors. Intermediate and large size motors also have instruments to provide readings for the above parameters. Some specially designed large motors, with heat exchangers for bearing cooling, have indicators to monitor oil temperatures, so providing valuable data for bearing condition, specifically for sleeve or plate bearings where oil plays an important role in their life span.

Certain continuous monitoring parameters can be used in the on-line monitoring system which logs data electronically and helps in trending them to assess motor condition. Some of these parameters, such as motor running currents, are included in some plant technical specification as part of their surveillance testing.

C.2 Inspection of Motors

Motors, regardless of their sizes and types, should have a periodic inspection to evaluate their condition. Such inspection requires listening to the noise level, observing any surface degradation, applying hand forces to assess structural integrity and electrical connections, etc. It is prudent to perform some of the regular maintenance activities (which include regreasing, cleaning, replacing parts) at the same time. Motors critical to plant safety and availability should have a more frequent schedule (such as quarterly to half yearly) than those are classified as less critical. However, it is recommended that these motors should be inspected at least once per operating cycle to ensure their overall reliability and operational readiness.

Individual motor maintenance manuals present the manufacturer's recommended practices. The utility company modifies the recommendations, based on usage and environment, by selecting the important activities for the particular motor applications. Based on these recommendations, following is a "10-point" motor inspection program to protect the motor against various detrimental elements. Precautionary measures for human health and safety prior to or after the inspection for a motor application are not included. Most of the recommended items can be done without any sophisticated testing or tools.

These recommendations are applicable to all size and type of motors. Certain motors, especially large motors furnished with special features may require an added checklist to address important subcomponents, such as coolers or protective relays.

(1) Guard Against Dirt, Dust, and Contaminants

Although nuclear facilities are very clean when compared with some other industries, the insulating system and mechanical parts of the motor can accumulate dust. A visual inspection of the condition should be made periodically, especially for motors with open enclosures and exposed to a hostile environment. Dust, dirt and foreign particles that are free from oil or grease may be removed by wiping clean with a dry cloth, or preferably, by suction. Compressed air at a recommended pressure limit can be used to reach objects in inaccessible areas. Low-pressure steam cleaning with a mild, neutral, and non-conducting detergent may be used to remove stubborn dirt from windings and other parts of motors. It is important that the windings be thoroughly dried after the steam cleaning operation. When grease or oil is present, wipe with a cloth moistened with a recommended petroleum solvent of a 'safety-type.'

(2) Guard Against Moisture, Water, Grease or Lube Oil

Moisture intrusion into motor components significantly increases the probability of motor failure. A wet insulating system can burn the windings, moisture in the air could short electrical connections, water in the bearing assembly could alter the lubricity of the lubricating agent, and moisture in chemical reaction with air or oxygen could corrode mechanical parts made out of metals. Motors should always be guarded against the accidental intrusion of water from splatter or splashing, leakage from coolers, condensation from moisture inside the motor or intrusion of moisture from the environment. Space heaters or other heating devices should be used to thoroughly dry the motor before it returns to service.

Leakage of oil or grease from the bearing assembly onto motor parts will help the deposition of foreign particles on the motor or winding surfaces. Visual inspection of such leaks, combined with good preventive measure could eliminate many contact or insulation problems.

(3) Guard Against Friction

Visual inspection, higher temperatures, and an abnormal level of sound during running may indicate excessive friction or overheating of bearings and is usually traced to one of the following causes: (a) excessive belt tension, (b) poor alignment causing excessive vibration or binding, (c) bent shaft, (d) excessive end or side thrust due to gearing, flexible coupling, and (e) damaged bearings.

(4) Guard Against Vibration

Excessive winding vibration could be caused from loose rotor bars or end rings, phase imbalance in the winding currents, jammed or frozen balls, low lubrication level, and nonuniform clearances between stator and rotor windings or a misaligned rotor shaft. Unusual bearing vibration level or noise level is an indication of low or excessive lube oil or grease, vibration transmitted from the driven component, degraded bearings, frozen or jammed balls or rollers, and excessive load or thrust in bearings. Overall motor vibrations are caused by the foundation settling or heavy floor loading, loose mounting bolts, base fixtures or shims, excessive drive on the components, high electrical noise, etc. Since all of the above vibrations are observed or heard while the motor is running, standby and intermittent motors should be inspected when they are in running condition.

(5) Guard Against Adverse Environment

Humidity, temperature, radiation, and chemical spray affect the age and performance of motor components. Therefore, motors required to run during times after an accident for safety functions that are exposed to a harsher environment, should be shielded from these hostile conditions. A check should be made to see if any of the above environmental parameters have exceeded the allowed limiting conditions. In addition, visual inspection for dislodged objects hanging around the motor should eliminate any possibility of mechanical damage during a seismic or dynamic event.

(6) Guard Against Cracks/Corrosion

Surface corrosion or cracks on motor components can be detected by thorough visual inspection. The sources of corrosion include metallic components exposed to humid atmosphere where cracks may develop from an existing flaw in the metal during manufacturing. High frequency vibrations in loads initiate cracks or voids at high stress regions. Corroded or cracked rotor bars and end rings could affect the motor dielectric life significantly. All the corroded regions should be scraped and cleaned, and then an anti-corrosion chemical or paint used to keep these surfaces away from humid atmospheres. Many times cracked surfaces can be detected by just hearing the sound of the reflected soundwaves from these locations. If it is found that they have reached their critical length so that complete failure is possible, then they should be repaired or replaced immediately. Otherwise, close monitoring of the crack propagation must be instituted in future inspections.

(7) Guard Against Electrical Stresses

Electrical stresses are caused by high voltages, high leakage currents, broken wires or shorts, etc. Without performing any electrical testing, a good inspection on insulation surfaces for corona discharges (white and grey deposits), burn marks, visible voids and cracks, and on bearing insulations can avoid much expensive maintenance. Shorts, burned and poor electrical connection of wirings within the motor can be checked for possible disconnection during running.

(8) Guard Against Age and Service Wear

There are some components in a motor which have a finite life because of their age and service wear. These components include seals, bearings, insulating systems, gaskets, carbon brushes and brush holders for dc or synchronous motors. Periodic checking on their conditions, as well as replacement at the end of their specified life is an important aspect of the inspection program. Any service wear and mechanical component distortion due to cyclic thermal and mechanical aging should be checked periodically. Carbon deposits on contact points where sparking occurs while starting or running and on the commutator surface for dc machines should be cleaned and wiped at frequent intervals with a clean canvas cloth free from lint. If the commutator develops growing eccentricity, high bar or mica, the armature should be removed and the surface should be ground, polished and beveled as instructed by the manufacturers. Regreasing bearings at regular intervals is also a part of a good maintenance practice. A typical life for bearings in small motors is 10-12 years.

(9) Guard Against Human Errors

Dedicated crews inspecting motors as well as performing maintenance súch as regreasing bearings, cleaning contacts, replacing carbon brushes, gaskets, and seals, air blasting, can eliminate most of the problems created by humans. Good planning and scheduling will cover the motors at regular intervals, in accordance with their importance to plant safety and availability. A comprehensive inspection checklist should be developed for each size and type of motor to guard against its omission. An independent inspection by a qualified individual should insure that the activities were performed correctly and the motor is left in an operationally ready state.

(10) Guard Against Loss of Inspection Data

Although a motor inspection does not provide any data which can be used to predicting future performance, logging all the inspection activities describing the condition of motor on a log sheet, such as spare part/grease type identifications and other relevant information will help monitor the motor and may provide insight into environmental conditions which could impact its performance. A computerized system can effectively enhance the data management and the data stored can be used for root cause analysis when a motor fails.

APPENDIX D

MOTORS IN NUCLEAR POWER PLANTS

D. MOTORS IN NUCLEAR POWER PLANTS

This appendix discusses the various elements one would consider in specifying a motor for an application. Since plants are designed by many different architectural engineering (AE) and nuclear steam supply system (NSSS) firms, motor specifications for a particular application vary, but not significantly so.

The typical nuclear power motor populatin is presented according to size and type of environment.

D.1 Motor Auxilliaries Design and Specifications

The design and specification requirements for selecting a motor for any particular application were discussed in the phase I report (7). This section discusses other auxilliary equipment needed for motor operation, including switching devices or control equipment, and protection devices.

When specifying motor switching or control equipment the following must be considered:

- starting frequency or application (continuous duty or intermittent, such as valve operators)
- multispeed and reversing operation capability
- motor size (hp)
- motor supply voltage
- motor short-circuit current.

For complete motor protection, these data must be available:

- full load current
- service factor
- locked rotor current at minimum and rated starting voltages
- starting method employed
- acceleration time (starting time) at minimum voltage and rated starting voltage
- operating duty cycle such as frequency of starts, duration and degree of overloading
- safe stall time at minimum voltage, starting voltage, ambient temperature and operating temperature
- power supply data such as voltage variation, unbalance, etc.

The following subsections contain discussions of other details which must be considered when specifying motor auxilliaries.

D.1.1 Enclosures

Motors for indoor service generally are put in open dripproof enclosures, while for outdoor service they are totally enclosed in fan-cooled (TEFC) weather protected enclosures. Both of these enclosures have drains. Nuclear power plants located near salt water or in environments with hostile atmospheric conditions should consider the TEFC enclosure for indoor applications. When totally enclosed water to air cooled motors (TEWAC) are used, the design of coolers should be such that water from leaks in the tube do not affect the dielectric integrity of motors.

D.1.2 Grounding

Each motor has means for grounding the frame. For integral motors, many times there exist two grounding means located in diametrically opposite corners of the motor. These are non-corrosion pads, welded or brazed to the motor frame: one is generally sited on the main lead conduit box side of the motor.

D.1.3 Bearing Protection

Motors up to about 250 hp usually are furnished with antifriction ball or roller bearings. Horizontal motors above 250 hp are equipped with sleeve bearings. Large vertical motors have antifriction (ball, roller or spherical roller) and plate type thrust bearings up to 4000 hp. Motors with antifriction bearings are equipped with oil or grease fittings, so that a lubricant can be forced through the bearing housing without disassembling the motor. Sleeve bearings are often of the ring-oiled type except where pressurized oiling is provided. In this case, bearings have split-type housing and split-end shields arranged in such a way that the bearing may be inspected and replaced without too much difficulty. Some antifriction bearings, especially those for valve operators, are sealed units requiring no regular maintenance and are replaced at the end of their life, as recommended by the manufacturer. Bearing lubricants should be the ones recommended by the manufacturers.

Protective devices for bearings are responsive to one or more of the following conditions, which can lead to bearing failure:

- lack of or too much lubricant
- low oil level in reservoir
- low oil pressure
- reduced oil flow
- high bearing or oil temperature
- rate of temperature rise
- vibrations.

Some special large size motors are equipped with Resistance Temperature Detectors (RTDs) in place of thermocouples to monitor bearing or oil temperature, because RTDs offer faster response and are more accurate. Vibration transducers are also mounted on the bearing housing to monitor abnormalities.

D.1.4 Thermal Protection

Thermal detectors are utilized to detect the motor winding temperature during normal and abnormal conditions. Abnormal conditions which can cause overheating include:

- overload
- restricted motor ventilation
- reduced speed operation
- frequent starting
- low line voltage
- high line voltage, with or without low line frequency (over-excitation)
- mechanical failure of the motor bearing, of the driven equipment or of the coupling between the motor shaft and the driven equipment

- improper installation
- unbalanced line voltages, including single phasing.

Thermal detectors which can be embedded in the stator windings include thermocouples, RTDs, thermal protectors such as GE Thermo-Tectors and thermisters (nonlinear RTDs). Thermocouples often are installed in random wound stator coils, whereas RTDs are used in form-wound coils. Generally, 6 RTDs are installed in large motors above 1500 hp (two per phase) and 3 RTDs are put into motors less than 1250 hp (one per phase). RTDs may be connected to initiate an alarm or to shut off the motor.

D.1.5 Phase Overcurrent Protection

Small motors are equipped with overcurrent relays with one instantaneous unit and one long-time delay unit to protect against severe overloads, locked rotor, and line faults. On large motors, the use of overcurrent relays with two instantaneous units is preferred, one with normal dropout and the other with high dropout and a timer. This arrangement limits iron damage and bus voltage disturbances due to faults resulting in a current just above the locked rotor current.

D.1.6 Differential Protection

When the locked rotor current exceeds 5 percent of the symmetrical 3-phase fault current available at the switchgear, differential relay protection is used with the instantaneous overcurrent relays. These devices respond to fault currents which are limited by the fault impedence to a current level lower than the load current. It is reasonable to assume that most multiphase faults begin as a low-level current and gradually build up to a high level. Thus, the differential relay can prevent a great deal of burning damage.

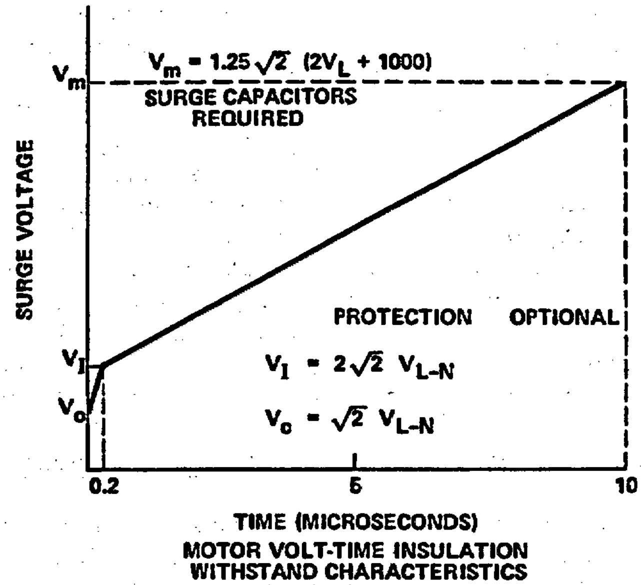
D.1.7 Surge Protection

Figure D-1 illustrates the surge limits which a motor can withstand and still provide satisfactory service. Damaging surges may be caused by switching, including switching the motor itself, and other breaker contact problems. It is generally recommended to provide protection with surge capacitors for certain motors. These devices must be mounted in the motor conduit box to be effective.

D.1.8 Additional Motor Protection Considerations

Other design considerations to protect motors from degradation or failure are:

- flexible couplings between motor and the driven equipment
- mounting and doweling
- drainage for water accumulation inside the motor
- insulation material damage other than heating
- operating environment of motor
- noise level of motor
- leads and terminals
- instrumentation and control



V_o: Normal Operating Voltage

V_I: Surge Voltage (initial step)

V_{L-N}: Normal Line-to-Neutral Voltage

V_m: Maximum Surge Voltage

V_L: Line-to-line Voltage

Figure D-1: Surge limits for a motor

- accessories such as space heater, terminal boxes and terminal blocks, means for lifting
- spare parts and special tools
- cleanliness
- barrier or baffle to separate motor bearing assembly from moisture/contaminant intrusion.

D.2 Motor Population and Applications

Motors in the power industry are basically used for two different applications: continuous and intermittent duty. Valve operator motors are the intermittent type and run for short durations to actuate the valve from the open position to the closed position, or vice versa. Continuous duty motors are those used to drive pumps, fans, generators, dampers, chillers and other components, where the motors run at steady state conditions for long periods of time after having passed through the startup transients. Some of these motors are used continuously during normal plant operation, while others remain as standby to run in some abnormal (emergency) condition. However, with exception of periods of testing, these motors run continuously while delivering their intended services. When testing, safe shutdown conditions should be achieved before terminating the test.

This section discusses different nuclear power plant (NPP) systems that contain electric motors. The terms safety-related and nonsafety-related are used to indicate those systems and motors most important to ensuring plant and public safety. At a NPP the term safety-related is well defined and designates those systems and components agreed upon by the NRC and the utility as ncessary to prevent or mitigate the consequences of Final Safety-Analysis Report (FSAR) assumed accidents. These components and systems are usually contained on a Quality or Q list at the plant. Other components and systems which also contribute to safe plant operation but to a lesser extent are sometimes referred to as important to safety. There is much discussion in the industry about these components. This report will stay primarily with the safety-related groupings. However, some of the recommendations made for safety-related motors could be applied to a larger class of motors.

B.2.1 Critical Motors for Plant Safety and Plant Availability

It is imperative that safety motors remain capable of functioning throughout their life. Large non-safety motors which have a high cost impact, both for replacement and their importance to plant availability must also be highly reliable. Hence, these motors require more rigorous maintenance and surveillance to maintain them in good operating condition.

Since each plant system design is different, it is difficult to identify all systems in the above category. The following is a list of some of the important systems:

- Emergency Core Cooling Systems (ECCS) which include
  - Residual Heat Removal (RHR)/Low Pressure Coolant Injection (LPCI)
  - Core Spray (CS)
  - High Pressure Coolant Injection (HPCI)
  - High Pressure Core Spray (HPCS)
  - Reactor Core Isolation Coolant (RCIC)
  - Safety Injection (SI)
  - Charging System
  - Decay Heat Removal
- Containment Heat Removal (CHR)
- Chemical and Volume Control System (CVCS)
- Emergency Power System.

From a plant risk standpoint, studies (e.g. probabilistic risk assessment) have shown that failure of certain support systems such as service water or component cooling water, can significantly impact frontline systems. In the past, these key support systems may not have received adequate attention, but increased attention is crucial to ensure plant safety. For example, component cooling water and service water systems are required for proper functioning of safety components and systems such as reactor coolant pump seals, diesels, control room HVAC, containment coolers, emergency diesel generators, RHR heat exchangers and RHR pumps. Some other support systems are:

- Gas Radiation Waste Management
- Heating, Ventilation and Air Conditioning (HVAC)
- Containment Isolation System

* Containment Gas Control
* Fire Protection
* Radiation Monitoring
* Condensate and Feedwater.

As previously mentioned, some large non-safety motors require good maintenance because of their replacement cost. The reactor coolant pump motors in the case of a PWR system and the recirculation pump motors for BWR systems are non-safety related, but very important for plant availability. Other motors which can be considered in this category are:

* circulating water
* condensate
* condensate booster
* main feed water
* turbine building cooling water
* control rod drive
* reactor water cleanup.

D.2.2 Motors in Boiling Water Reactor (BWR) Plants

The motor population in a BWR station is directly proportional to the number of systems existing. The earliest BWR plants had a drywell and torus containment arrangement, designated as a Mark I. The Mark I had fewer systems, both safety and non-safety related, when compared with the later BWR designs, primarily the Mark II, or the most recent Mark III. Both the Mark II and Mark III design contain about the same number and type of fluid systems and hence, the motor population does not differ significantly. Table D-1 illustrates the motor population breakdown compiled from selected plants of each design type*.

BWR designs have two recirculation loops connected to the reactor vessel with two recirculation pumps located inside the contaminant in a high radiation zone. These two motors are large three-phase vertical induction motors of approximately 5,000 hp. Although these motors are classified as non-safety, they are important because of their impact on plant availability. Corrective maintenance is expensive due to the location of the motor and its size.

Environmental conditions at various plant locations are also important factors for considering motor age-related degradation rates. Table D-2 provides these parameters for inside and outside the primary containment. High radiation zones are: inside the primary contaminant where the recirculation motors are located, main steam/feed water tunnel, reactor water clean-up pump area. Other areas inside the secondary containment and outside the primary containment with lower radiation levels are: control rod drive hydraulic unit areas, RHR and core spray pump area, HPCI and RCIC pump area, fuel pool clean-up pumps, and containment fan cooler. Motors outside the containment area in the turbine building can experience high radiation. These areas include the reactor feed pump area, condenser area, and main turbine area. Other buildings, except for radwaste, have no significant radiation, but could experience high humidity and temperature conditions.

*Compiled by Ebasco Services, Inc. under contract to BNL.

Table D-1: APPROXIMATE MOTOR POPULATION[a] IN A BWR PLANT

	SAFETY-RELATED MOTORS						NONSAFETY-RELATED MOTORS						TOTAL MOTORS		
	INSIDE CONTAINMENT			OUTSIDE CONTAINMENT			INSIDE CONTAINMENT			OUTSIDE CONTAINMENT					
	Mark I	Mark II	Mark III	Mark I	Mark II	Mark III	Mark I	Mark II	Mark III	Mark I	Mark II	Mark III	Mark I	Mark II	Mark III
Continuous Duty Motors															
AC POWER															
≥300 hp	0	0	0	<10	15	15	2[b]	2[b]	2[b]	<15	15	15	<27	32	32
125-250 hp	0	0	5	10	70	90	0	0	0	10	35	35	255	525	565
1-100 hp	10	20	25	15			5	10	10	205	390	400			
Fractional hp[c]	0	0	0	<5	15	20	0	0	0	15	50	65	<20	65	85
DC Power	0	0	0	<10	10	10	0	0	0	10	10	10	<20	20	20
Sub-Total:	10	20	30	<50	110	135	7	12	12	255	500	525	322	642	702
Motor Operated Valve Motors															
AC Power	20	20	15[d]	45	215	180[d]	0	15	10	75	235	190[d]	140	485	395[d]
DC Power	0	0	0	<10	15	10	0	0	0	0	0	0	<10	15	10
Total:	30	40	45	<105	340	325[d]	7	27	22	<330	735	715[d]	<472	1,142	1,107[d]

Notes:
(a) Auxiliary motors supplied as part of other equipment such as blowers, transformer fans, cabinet fans, lube oil motor, etc., are not normally recorded separately and therefore their totals may not be reflected in the table.
(b) One recirculation motor for each loop and are important for plant availability.
(c) Most safety fractional hp motors are part of electrohydraulic valve operations. Control room motors for strip charts and other control applications are not included.
(d) These quantities were estimated based on judgement and comparison with other reference plant data. In a real plant design, these numbers may be as high as that for a Mark II design.

TABLE D-2: ENVIRONMENTAL CONDITIONS FOR A TYPICAL BWR PLANT

Environmental Paramenters	Inside Primary Containment (outside the sacrificial shield wall	Outside Primary Containment
Normal Operating Pressure	-0.5 psig to 2 psig	- .25" of water gauge
Design Pressure	-2.0 psig to 45 psig	-0.33" of water gauge
Test Pressure	52 psig	not applicable
Normal Operating Temperture	135°F average 150°F maximum	70°F average 104 F maximum
Design Temperature (Accident)		
3 hours	340°F	212°F
next 3 hours	320°F	212°F
next 18 hours	250°F	150°F
up to 100 days	200°F	150°F
Relative Humidity (Normal)	40 - 55% - 90% (maximum)	40% 90% (maximum)
Relative Humidity (LOCA)	100% (all steam)	100% (all steam)
Radiation		
gamma (normal operating)	50 rads/hr.	not applicable
neutron (normal operating)	1.4×10^{5} neutrons/cm^{2}/sec (inside the sacrificed shield wall)	
integrated (40 years) gamma dose (normal operating)	1.8×10^{7} rads	
integrated (40 years) neutron dose (normal operating)	1.8×10^{14} neutrons/cm^{2}	"
Integrated (over 6 mos.) gamma dose (accident conditions)	2.6×10^{7} rads	"
LOCA gamma dose	1.3×10^{6} rads/hr.	"
Chemical	not applicable	"

Among safety systems, many large motors are 4 Kv, 3 phase vertical induction motors with plate or ball bearings. They must operate during accident conditions to accomplish their safety function, and therefore must be capable of operating in both mild and harsh environments. The motors responsible for such functions are typically reactor heat removal, core spray, and fan cooler motors.

Intermediate size safety motors include the service water pumps, reactor building cooling water pump and control rod drive water pump. These motors are located indoors, have antifriction bearings, 3 Φ, induction motors and are exposed to both harsh and mild environments. Continuous duty small integral and fractional motors are used all over the plant, both inside the reactor building and in other auxiliary structures. They are generally fed from the 460 v bus lines and have antifriction bearings. The typical safety systems include containment HVAC, standby liquid or gas control, emergency diesel generator, chilled water, and support systems for safe shutdown of the reactor. Some small dc motors are used as back ups for small ac pump motors in the event of a station blackout or loss of offsite power.

Intermittent motors, a class of motors which are typically fractional or small integral, are used in valve operators. These motors are designed to have high starting torque, and have weather proof, explosion proof or submersible enclosures, with grease-sealed ball bearings. They can be either ac or dc, with the ac motors being of the squirrel cage design and the dc motors being compound wound. The ac power supply is from 110 v to 460 v bus lines and the dc voltage is 125 v or 250 v. Most important inside containment valves belong to the RHR, nuclear steam supply shutoff (containment isolation) and reactor recirculation systems. Outside primary containment motors include RHR, Core Spray, HPCI, RCIC, CRD, and Component Water (CCW) and are classified to be exposed to mild environment with the exception of those valves located in areas where high energy piping is routed. These valves are generally designed for the environment resulting from a high energy line break (HELB).

D.2.3 Motors in Pressurized Water Reactor (PWR) Plants

Unlike BWR plants where General Electric is the sole supplier of the nuclear steam supply (NSSS) system, three companies (Westinghouse, Combustion Engineering and Babcock & Wilcox) are principal NSSS suppliers. The balance-of-plant (BOP) design is done by any one of several architectural engineering firms. Since the motor population is a strong function of the plant design, there exists quite a variation in the number and size of motors at PWR facilities. However, the variation is not wide enough to warrant considering each plant design separately. This section identifies safety and non-safety related motors based on a PWR plant design. An approximate motor population in a typical PWR plant is given in Table D-3.

A PWR facility consists of a reactor building, turbine building, and associated auxiliary buildings. The PWR primary systems and steam generators are completely enclosed inside the reactor building. Because of this arrangement, a larger number of motors are located inside the reactor building (or primary containment) than in the primary containment of a BWR. Table D-4 provides the normal and accident environmental parameters for inside and outside the containment shell. Some of the auxiliary buildings of the PWR which house equipment driven by electric motors may not be exposed to significant radiation, but

Table D-3: APPROXIMATE MOTOR POPULATION[a] IN A PWR PLANT

	SAFETY-RELATED MOTORS		NONSAFETY-RELATED MOTORS		TOTAL MOTORS
	INSIDE CONTAINMENT	OUTSIDE CONTAINMENT	INSIDE CONTAINMENT	OUTSIDE CONTAINMENT	
Continuous Duty Motors					
AC POWER					
≥300 hp	0	20	4[b]	15	39
125-250 hp	10	0	0	20	30
1-100 hp	<10	150	<10	270	<440
Fractional hp[c]	0	15	0	20	35
DC Power	0	<10	0	5	<15
Sub-Total:	<20	<195	<14	330	<559
Motor Operated Valve Motors					
AC Power	30[d]	<250[d]	0	<260[d]	<540[d]
DC Power	0	<10	0	0	<10
Total:	<50	<455	<14	590	<1,109

Notes:
(a) Auxiliary motors supplied as part of other equipment such as blowers, transformer fans, cabinet fans, lube oil motor, etc., are not normally recorded separately and therefore their totals may not be reflected in the table.
(b) One reactor coolant pump (RCP) motor for each loop and are important for plant availability.
(c) Control room motors for strip charts and other control applications are not included.
(d) These quantities were estimated based on judgement and comparison with other reference plant data. In a real plant design, these numbers may vary.

TABLE D-4: CONTAINMENT ENVIRONMENTAL CONDITIONS FOR A PWR PLANT

1. Continuous Normal Operation During Forty (40) Years:

Parameter	Inside Steel Containment	Inside Annulus	Outside Concrete Shell
Temperature	60-120F	60-120F	30-110 F
Pressure	0 psig	0 psig	0 psig
Relative Humidity	0-100%	0-100%	0-100%
Radiation	1 R/hr	100 mR/hr	0.1 mR/hr

2. Zero to Two Hours Accident Environment:

Parameter	Inside Steel Containment	Inside Annulus	Outside Concrete Shell
Temperature	267 F	170 F	30-110 F
Pressure	44 psig	± 1 psig	0 psig
Relative Humidity	100%	0-100%	0-100%
Radiation	2×10^6 R/hr	2×10^6 Rhr	25 R/hr
Chemical Spray	1700 ppm Boron as Boric Acid (Inside steel containment)		

3. Two Hour to 24 Hour Accident Environment:

Parameter	Inside Steel Containment	Inside Annulus	Outside Concrete Shell
Temperature	240 F	200 F	30-110 F
Pressure	25 psig	± 1 psig	0 psig
Relative Humidity	100%	0-100%	0-100%
Radiation	1×10^6 R/hr	1×10^6 Rhr	9 R/hr
Chemical Spray	1700 ppm Boron as Boric Acid (Inside steel containment)		

4. 24 Hours to 1 Year Post Accident Environment:

Parameter	Inside Steel Containment	Inside Annulus	Outside Concrete Shell
Temperature	190 F*	190 F*	30-110 F
Pressure	15 psig	± 10 in. Wg	0 psig
Relative Humidity	100%	0-100%	0-100%
Radiation	250×10^3R/hr	250×10^3R/hr	100 mR/hr
Chemical Spray	1700 ppm Boron as Boric Acid (Inside steel containment)		

*Temperature gradually decreases to approximately 120 F

other hostile environmental parameters, such as humidity and temperature conditions are detrimental to motors.

As with BWRs, most older PWR plants built during the late sixties and early seventies have fewer systems as compared to the most recent designs. Hence, these plants might have fewer motors than presented in Table D-3, which represents a recently built PWR facility. Also, since a PWR system contains additional systems, such as the Chemical Volume and Control System (CVCS), the motor population is larger as compared to a similar size BWR unit, especially those motors located inside the containment building.

The PWR design consists of two to four primary coolant loops. Each loop has a reactor coolant pump which is driven by a large induction, ac, 3 Φ, 6.6 or 13.2 kv, 10,000 hp vertical motor with plate bearings. These motors are classified as non-safety, but are vital for plant availability. Since these units are located inside the containment, they are exposed to high radiation levels which contributes to a higher maintenance expense. Other non-safety motors large enough to warrant good maintenance from the standpoint of replacement cost, include circulating water (4,000 hp), heater drain pumps (800 hp), feedwater and condensate pumps (4,000 hp). Most of these motors are 6.6 kv, ac, 3 Φ vertical motors with plate or sleeve bearings.

Large safety-related motors are generally 4 kv, 3 Φ, induction, horizontal motors with sleeve bearings, of less than 1,000 hp. The systems with such large motors include chilled water, component cooling water, containment spray, safety injection, and HVAC. These motors are primarily installed indoors.

Containment fan cooler motors are of intermediate size, 3 Φ, 460 v, ac units, with antifriction bearings. They are located inside the containment as a part of the HVAC system. Some of the containment fans are belt-driven which makes the motor bearings susceptible to failures due to the asymmetrical load placed on them. These motors are safety-related and are required after an accident to maintain the reactor environment within specifications. The post-accident conditions are very harsh, consisting of a steam and alkaline boron spray environment (4). According to 10 CFR 50.49, containment coolers must be qualified for their environment/service condition.

Safety-related small and fractional motors exist all over the plant in almost every safety system. Except for a few dc motors that are used for backup equipment in case of complete ac power loss or station blackout, most motors in this classification are ac, 3 ϕ, induction motors with antifriction bearings and are fed from a 110 v to 480 v power supply. These motors primarily drive small pumps for coolers, dampers and other smaller components. With the exception of those located inside the containment building, motors are exposed to a mild environment under normal operating conditions.

The valve motors which exist in PWR safety systems are small induction type, pipe mounted motors, similar to those in a BWR plant. Since a comparable size PWR unit contains some additional safety systems, such as the CVCS which is also a very large system, the valve motor population is larger than that of a BWR plant. The PWR safety injection system has some safety valves inside the containment stemming from the primary loops. These valve motors are exposed to harsh environment and are vital to plant safety.

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This report constitutes the first of the three volumes under this NUREG. The report presents recommendations for developing a cost-effective program for performance evaluation and maintenance of electric motors in nuclear power plants. These recommendations are based on current industry practices, available techniques for monitoring degradation in motor components, manufacturer's recommendations, operating experience, and results from two laboratory tests on aged motors. Two laboratory test reports on a small and a large motor are presented in separate volumes of this NUREG. These provide the basis for the various functional indicators recommended for maintenance programs in this report.

Implementation of the information provided in this report, will improve motor reliability in nuclear power plants. The study indicates the kinds of tests to conduct how and when to conduct them, and to which motors the tests should be applied. It should be noted that the recommendations and conclusions provided in this report are based on research findings, and as such should not be construed as regulatory or statutory requirements for motors in nuclear power plants.

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