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Aging Assessment of Large Electric Motors in Nuclear Power Plants

Prepared by
M. Villaran, M. Subudhi

Brookhaven National Laboratory

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Prepared by
M. Villaran, M. Subudhi

Brookhaven National Laboratory
Upton, NY 11973

S. K. Aggarwal, NRC Program Manager
J. E. Jackson, NRC Program Manager

Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
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ABSTRACT

Large electric motors serve as the prime movers to drive high capacity pumps, fans, compressors, and generators in a variety of nuclear plant systems. This study examined the stressors that cause degradation and aging in large electric motors operating in various plant locations and environments. The operating history of these machines in nuclear plant service was studied by review and analysis of failure reports in the NPRDS and LER databases. This was supplemented by a review of motor designs, and their nuclear and balance of plant applications, in order to characterize the failure mechanisms that cause degradation, aging, and failure in large electric motors. A generic failure modes and effects analysis for large squirrel cage induction motors was performed to identify the degradation and aging mechanisms affecting various components of these large motors, the failure modes that result, and their effects upon the function of the motor. The effects of large motor failures upon the systems in which they are operating, and on the plant as a whole, were analyzed from failure reports in the databases. The effectiveness of the industry's large motor maintenance programs was assessed based upon the failure reports in the databases and reviews of plant maintenance procedures and programs.

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EXECUTIVE SUMMARY

An assessment of aging in large electric motors was conducted under the auspices of the US NRC Nuclear Plant Aging Research Program (NPAR). The objectives of the NPAR program are to resolve issues relating to the aging and service wear of equipment and systems at operating reactor facilities and to assess the impact that they may have on safety.

Electric motors rated at more than 500 hp serve as the prime movers to drive high capacity pumps, fans, compressors, and generators in a variety of nuclear plant systems. Based upon a systems review and a review of failure events, the majority of these large electric motors were used as drivers for pumps. Their applications include both safety-related and nonsafety-related nuclear process systems and balance of plant systems. By virtue of their large size, these motors play important roles in the safe and reliable operation of a nuclear plant.

This study examined the stressors that cause degradation and aging in large electric motors operating in various plant locations and environments. The operating history of large motors in nuclear plant service was studied by review and analysis of failure reports in the NPRDS and LER databases. This was supplemented by a review of motor designs, and their nuclear and balance of plant applications, in order to characterize the mechanisms that cause degradation, aging, and failures in large electric motors.

The review of large ac motor populations in nuclear plants found that the squirrel cage induction motor was the most widely used prime mover in the nuclear industry. Squirrel cage induction motors accounted for nearly 97% of the large motor applications in PWR plants, and almost 94% of those in BWRs. A generic failure modes and effects analysis for large squirrel cage induction motors was performed to identify the degradation and aging mechanisms affecting various components of these large motors, the failure modes that result, and their effects upon the function of the motor.

The effects of large motor failures upon the systems in which they are operating, and on the plant as a whole, were analyzed from failure reports in the NPRDS and LER databases. The effects of large motor failures on the different types of plant systems, including safety systems, nonsafety systems, and balance of plant systems, were compared and analyzed.

A review of maintenance, monitoring, and surveillance activities was performed, and the effectiveness of the industry's large motor maintenance programs was assessed based upon the failure reports in the databases and reviews of plant maintenance procedures and programs.

Significant Observations and Conclusions

The following observations and conclusions were made based upon review and analysis of the operating history data, review of plant procedures, specifications, and system descriptions, discussions with manufacturers, vendors, researchers, and plant personnel, and review of research literature:

- Both the NPRDS and LER data indicated that a significant portion of the reported failures were attributed to normal aging degradation of the motors, subcomponents, support equipment, and materials.

- The components that most often contributed to large motor failures, in order of importance, were found to be: bearings and bearing related components (lubrication, lubrication systems, cooling water), stator windings and insulation, terminations and motor leads, shaft and coupling, and motor mounts.

- In PWR plants, the systems most often experiencing large motor problems are: RCS, Condensate, Service Water, Main Feedwater, and Safety Injection. The plant systems most often experiencing large motor problems in BWR plants are: Reactor Recirculation, RHR/LPCI, Condensate, Service Water, and Core Spray.

- Problems with the large pump motors in the RCS in PWRs and the pump motors and MG set motors in the reactor recirculation system in BWRs can have a greater effect on plant operation than the large Class 1E pump motors on safety-related systems.

- Problems with the large pump motors in BOP systems such as Main Feedwater, Condensate, and Circulating Water in PWR plants, and Condensate and Circulating Water in BWR plants can have a greater effect on plant operation than many of the large Class 1E pump motors on safety-related systems.

- Failures in the large pump motor support equipment, such as circuit breakers, instrumentation, controls, and protective relaying, cooling water, and room/area cooling, account for as much of the large pump motor unavailability as failures within the large motor itself.

- Maintenance programs in the nuclear plants generally follow the motor manufacturers' recommendations. The types of failures observed in the operating data, and their severity, however, indicate that there is room for improvement in detecting incipient failures before they have degraded into more severe in-service failures that trip large pump motors or require immediate shutdown.

- The additional maintenance, monitoring and surveillance received by Class 1E pump motors on safety-related systems have had a positive effect on the operating performance of this equipment.

- The more severe operating conditions experienced by large motors inside containment, specifically, higher temperatures, humidity, and radiation, contribute to accelerated degradation and aging processes in these machines. These are partially compensated for by enhanced design features. Limited accessibility during operation, however, is the major factor that prevents timely detection of degradation and incipient failures before they progressed to a more severe level.

- The most difficult part of preventive maintenance monitoring for large electric motors is quantitatively assessing electrical insulation condition. The most effective approach is to establish a machine specific program combining consistent, periodic monitoring and testing of operating parameters, visual inspection, together with trending and analysis of the changes in the monitored operating and test parameters over time. Periodic review and evaluation of data from all these sources by experienced personnel will then provide the best indication of machine condition and the need for repairs.

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ABBREVIATIONS

AC	Alternating Current
AFW	Auxiliary Feedwater System for a PWR
ASME	American Society of Mechanical Engineers
Aux	Auxiliary
B&W	Babcock & Wilcox Company
Bldg	Building
BOP	Balance of Plant
BWR	Boiling Water Reactor
CCW	Component Cooling Water
CE	Combustion Engineering Company
CFR	Code of Federal Regulations
CRD	Control Rod Drive System for a BWR
CS	Core Spray System for a BWR
CT	Current Transformer
CVCS	Chemical and Volume Control System
DBA	Design Basis Accident
DBE	Design Basis Event
ECCS	Emergency Core Cooling Systems
EPRI	Electric Power Research Institute
ESF	Engineered Safety Features
FFT	Fast Fourier Transform
FMEA	Failure Modes and Effects Analysis
FSAR	Final Safety Analysis Report
GE	General Electric Company
HELB	High Energy Line Break
HHSI	High Head Safety Injection
HPCS	High Pressure Core Spray for a BWR
HPSI	High Pressure Safety Injection or Safety Injection for a PWR
HVAC	Heating, Ventilation, and Air Conditioning
Hz	Hertz, cycles per second
I&C	Instrumentation and Controls
IAS	Industry Applications Society of the IEEE
IEEE	Institute of Electrical and Electronics Engineers
INPO	Institute of Nuclear Power Operations
IR	Insulation Resistance
IR Radiation	Infrared Radiation
ISI/IST	Inservice Inspection/Inservice Testing per ASME Section XI
ITP	Inservice Testing Program per ASME Section XI

ABBREVIATIONS (Cont'd.)

KV	Kilovolt
LCO	Limiting Condition for Operation in plant Technical Specifications
LER	Licensee Event Report
LOCA	Loss-of-Coolant Accident
LOOP	Loss of Offsite Power
LPCI	Low Pressure Coolant Injection mode of a BWR RHR system
LPCS	Low Pressure Cooling System
LPSI	Low Pressure Safety Injection
Lube Oil	Lubricating Oil
MCA	Motor Circuit Analysis
MCSA	Motor Current Signature Analysis
MG Set	Motor-Generator Set
MOV	Motor Operated Valve
NEMA	National Electrical Manufacturers Association
NPAR	Nuclear Plant Aging Research
NPEC	Nuclear Power Engineering Committee of the IEEE
NPRDS	Nuclear Plant Reliability Data System
OBE	Operating Basis Earthquake
PI	Polarization Index
PT	Potential Transformer
PWR	Pressurized Water Reactor
QA	Quality Assurance
RCM	Reliability Centered Maintenance
RCP	Reactor Coolant Pump for a PWR
RCS	Reactor Coolant System for a PWR
RHR	Residual Heat Removal
RS	Recirculation Spray for a PWR
RTD	Resistance Temperature Detector
Rx	Reactor
RWCU	Reactor Water Cleanup System for a BWR
SCSS	Sequence Code Search System
SI	PWR Safety Injection System
SR	Surveillance requirement in nuclear plant Technical Specifications
SSE	Safe Shutdown Earthquake
SW	Service Water System
US NRC	United States Nuclear Regulatory Commission

ABBREVIATIONS (Cont'd.)

Vac	Volts, alternating current (ac)
VARs	Volt-Amperes, Reactive
VPI	Vacuum Pressure Impregnated

1. INTRODUCTION

Large electric motors, typically rated above 500 hp, are used in nuclear power plants to drive large pumps, compressors, and fan coolers. With the exception of a few Emergency Core Cooling System (ECCS) pumps and fan coolers, most of these motors are classified as nonsafety-related equipment. Recirculation (Recirc) pumps in Boiling Water Reactors (BWRs) and the reactor coolant pumps in Pressurized Water Reactors (PWRs) use very large motors (> 5000 hp) and are installed inside the primary containment. Failure of these pump motors may lead to a small LOCA or other transient. Other large pump motors include Core Spray, Residual Heat Removal (RHR), and High Pressure Core Spray (HPCS) in BWRs, and reactor containment fan coolers, High Pressure Safety Injection (HPSI), Low Pressure Safety Injection (LPSI), and containment spray pumps in PWRs.

Because of their differences in operation, environment, design, accessibility for maintenance, and construction, the aging characteristics of large electric motors serving systems that interact with reactor containment, or are located inside reactor containment, can contrast with motors of smaller size. This study will examine the degradation and aging of large electric motors in order to identify and evaluate the methods that can be used to mitigate their effects.

1.1 Background

Electric motors are used as the prime movers in nearly every system in a nuclear power plant. Electric motors in sizes ranging from fractional horsepower to more than ten thousand horsepower are used to drive pumps, fans, compressors, valves, conveyors, generators and various other applications. Large electric motors, defined for this study as motors of approximately 500 horsepower and greater, are important because they can have a significant effect on the continuous operation of the plant simply by virtue of their large size. Any problems or interruptions affecting such a large prime mover, whether it is on a safety system or a nonsafety system, can often cause a correspondingly large transient in the operation of the plant. Trips of large motors driving pumps, fans, and generators in nonsafety nuclear steam supply systems (NSSS), such as the BWR reactor recirculation system and the PWR reactor coolant system, as well as in balance of plant (BOP) systems, such as the condensate and feedwater systems, can initiate large process operating transients that challenge safety systems and cause reactor scrams.

Depending upon their application, large motors and other electrical equipment used in nuclear power plants are qualified to the requirements of various regulations and standards. These include the environmental qualification requirements as set forth in 10 CFR 50.49 (Ref. 1) and Regulatory Guide 1.89 (Ref. 2), and the Class 1E electrical equipment qualification requirements governed by IEEE standards (e.g., IEEE Stds. 323-1974 (Ref. 3) and 334-1974 (Ref. 4)). These qualification requirements are intended to ensure that the electrical equipment that is relied upon to maintain the integrity of the reactor coolant pressure boundary, to shut down the reactor, to keep the reactor safely shutdown, to mitigate the consequences of accidents, and to monitor certain post-accident conditions, will remain functional during and following design basis events, at any time over the life of the plant. The qualification requirements consider the extremes of the environmental conditions that electrical equipment will encounter during and following design basis events, including seismic, temperature, pressure, humidity, chemical sprays, radiation, vibration, submergence, and synergistic effects.

Although large motors are constructed, tested, and qualified to rigorous standards, failures of large electric motors in nuclear power plants continue to occur. Operating anomalies, failures of other equipment, and other unforeseen circumstances can all contribute to aging degradation in motors. Recent studies regarding the operating experience of electric motors (Ref. 5) and the effects of aging on electrical equipment in nuclear power plants (Refs. 6 and 7) have indicated that many electric motor failures can be attributed to the aging and degradation of insulating materials and bearings caused by high temperature, vibration, moisture and other stressors.

Large electric motors operating both inside and outside of the reactor building at a nuclear power plant are exposed to special environmental conditions of radiation, elevated temperatures, and high humidity. During design basis events, these conditions can reach the extremes postulated during environmental qualification type testing. Large motors may also then be exposed to high vibration, containment spray, moisture impingement and/or submersion, high pressure, and other environmental stresses.

Large motors in balance of plant (BOP) locations may also face unique operating environments. Condensate pump and feedwater pump motors, for example, may be exposed to high temperature and humidity, water or chemical spray impingement, submergence, and vibration during operation. These environmental factors may reach extreme levels during operating transient conditions. Service water pumps and circulating water pumps are located in intake structures adjacent to rivers or the ocean. They can be exposed to humid and salt-laden atmosphere throughout their service life, and the possibility of submergence exists in these locations.

1.2 Scope and Objectives

The objectives of this study are: 1) to examine the operating experience the nuclear industry has had with large electric motors, 2) to analyze the failures that have been reported in order to identify the environmental, operational, and design basis event-related stressors and associated aging mechanisms, 3) to assess the effects of aging degradation on large electric motor performance and reliability, and 4) to evaluate the methods currently available to monitor, repair, and mitigate aging degradation.

For the purposes of this study, the large electric motors that will be covered are ac machines of approximately 500 horsepower and greater. High torque applications, such as valve operators, are excluded since they use motors smaller than 500 hp, and have already been the subject of an NPAR study (Ref. 8).

The boundaries of the study with respect to the large motor and its subcomponents, its support systems and subsystems, and associated equipment are shown in Figure 1.1. The large motor will include the stator, rotor, frame, shaft, load coupling, bearings, motor housing, motor mounting, cooling air fans and filters, lubricating oil system, bearing cooling, stator and rotor cooling, terminations, component cooling lines at the machine, heaters, and instrumentation sensors, Components unique to wound rotor induction motors or synchronous motors such as the field windings, brushes, slip rings, or rotating type brushless exciters are also included. Support equipment, such as the electric power distribution system, motor starters and controls, indicating instrumentation, protective relaying, voltage regulators, station lightning and surge arrestors, room coolers and fans, service water system, and component cooling water supply system are considered outside the boundaries of the study. Associated equipment, i.e. the driven mechanical loads are also considered outside of the study boundaries. However, support equipment and associated equipment will be noted in the analysis to the extent that the operating experience data, engineering judgement, and risk analyses indicate that they can influence or directly contribute to large motor failure.

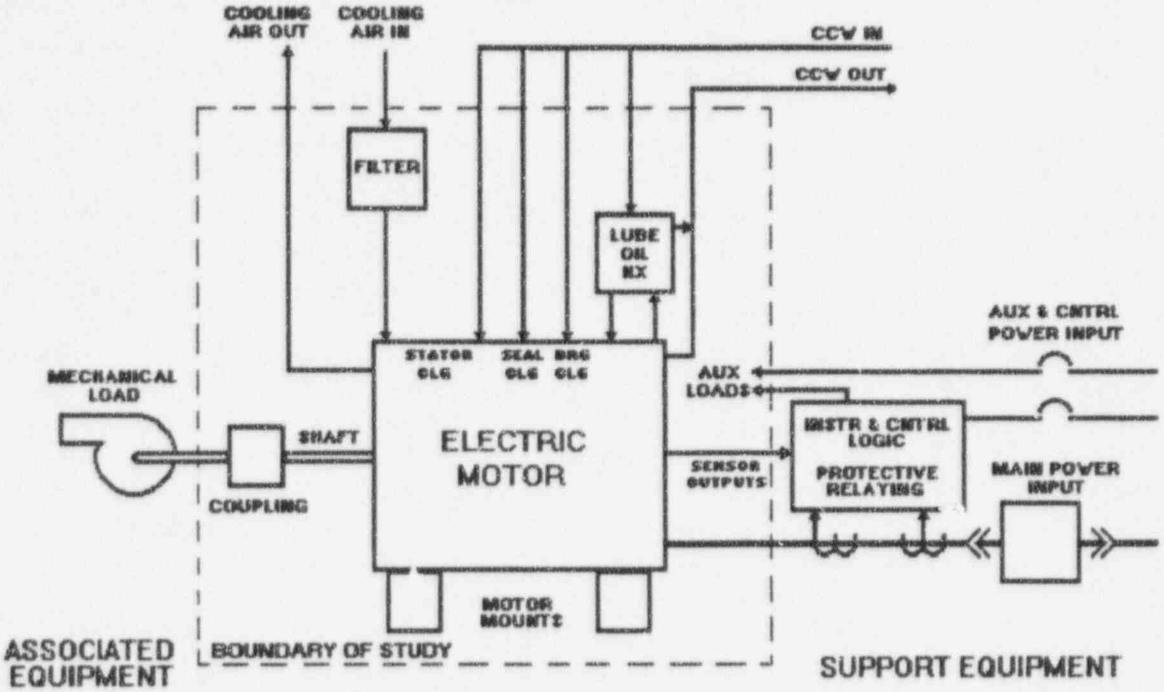


Figure 1.1 Large electric motor study boundaries

Environmental, operational, and design basis event-related stresses acting on the motor, its subcomponents, and direct support systems are considered for evaluation. The environmental stressors will include ambient temperature, pressure, humidity, airborne salts, dust and particulates, radiation, and chemical sprays. Other factors that are considered are mechanical overloading, voltage imbalances, single-phase operation, surge voltages, ventilation restrictions, improper lubrication, actual service factor, short cycling (excessive starting frequency), vibration, moisture intrusion or impingement, faulty or degraded electrical connections, and poor system voltage regulation. Seismic considerations are not included, since these have been addressed in detail in an earlier study (Ref. 5).

The large electric motor failure database developed for the evaluation of the industry operating experience was drawn primarily from two main sources: the Nuclear Plant Reliability Data System (NPRDS) and Licensee Event Reports (LERs). These data were reviewed and analyzed to determine whether the event was aging related or not. The aging related failures were then analyzed further to identify failure modes, failure mechanisms, root causes and proximate causes for failure, severity of the failure, and the effects on the motor, the system, and the plant.

Additional information that was used to supplement the data base included descriptive literature, technical documents, and maintenance recommendations from the manufacturers, expert knowledge and opinion, in-service inspection reports, plant procedures, motor purchase specifications, NRC plant and vendor inspection findings, and technical journals.

1.3 Report Organization

The first section of the report sets forth the origins of this study including background information on the application of large electric motors in nuclear power plants, where they are used, the special environmental conditions to which they are exposed, and their significance in plant safety. The objectives of the study are given, along with the sources used to develop the failure database and evaluate industry surveillance and maintenance practices. The boundaries of the machines as they apply to this study are also identified. Section 2 identifies the two main types of large ac motors, and provides basic descriptions of their designs, mounting, and application. The design considerations and features of large motors in nuclear service environments are highlighted. Various subcomponents and support systems in the machine are discussed. Section 2 also covers the systems that utilize large ac motors in BWRs and PWRs, and discusses the basic design enhancements incorporated into the large motors used in various plant locations. Section 3 describes the environment under which the motors operate, during normal conditions, and in design basis events. Some of the potentially severe conditions that may be encountered inside containment, in the reactor building, in the auxiliary building, and in various other BOP locations, and the effects that they could have on the reliability and performance of large electric motors, are discussed. A failure modes and effects analysis for large squirrel cage induction motors is developed. The industry operating experience review is provided in Section 4, with a description of failure data bases developed from LERs and the NPRDS, and analysis of the failures reported. A summary of the aging mechanisms affecting large electric motors, surveillance that can detect them, and maintenance activities that can help to mitigate their effects is found in Section 5. The findings of the study and other insights are summarized in Section 6. The conclusions regarding aging and degradation of large electric motors are given, along with methods for monitoring and mitigating the effects of aging.

2. BASIC DESIGN AND APPLICATION

This section of the report will cover two topics: the basic design characteristics of large ac motors, and the nuclear plant systems in which they are used. For the purposes of this study, the large electric motors that will be covered are ac machines, of approximately 500 horsepower and greater, that are used in continuous operation applications such as prime mover for pumps, fans, and compressors. The systems using these machines are identified and described briefly for BWRs and PWRs. The role of the large electric motor in each of these applications is summarized, along with the important operating characteristics. Finally, some of the basic design enhancements that may be incorporated into large motors used in various plant locations will be discussed.

2.1 Basic Design and Construction

The large ac motors used as prime movers in nuclear power plants will be of two basic types: induction motors and synchronous motors. There are two types of induction machines, characterized by the type of rotor used: the wound rotor induction motor and the squirrel cage induction motor. The synchronous motors may also be classified by the two distinctive types of rotor construction: the cylindrical pole rotor found on high speed motors consisting of two or four poles, or the salient pole rotor found on lower speed machines (less than 1800 rpm) which is designed with a large number of poles. Table 2.1 lists these principle large motor types, along with some of the typical driver applications in which they are found in nuclear power plants.

The induction motor is the main driver found in nuclear power plants, not only in large motor applications, but also in small motor applications. A survey of large motor population data, as reported to the Nuclear Plant Reliability Data System (NPRDS), was made to determine the distribution of each motor type among the various nuclear plants. Figure 2.1 presents the results of this survey, grouped by the four major reactor system suppliers. Squirrel cage induction motors are seen to be, by far, the workhorse of the industry, making up nearly 97% of the large motor applications in PWR plants, and nearly 94% of those in BWRs. When wound rotor induction motors are included, these totals grow to 98% and 96% for PWRs and BWRs, respectively.

The major features of large motor designs are described in the following sections.

2.1.1 Induction Motors

The most commonly used motor in nuclear power stations, and all of industry in general, is the three-phase induction motor. The induction motor is an synchronous machine, running at 1% to 10% below synchronous speed, depending on design specifications and load torque. As in all electric motors, the induction motor contains two major parts: a stator and a rotor.

<u>Stator</u> - The stator is a cylindrical-shaped, stationary component within which the rotor rotates. It is made up of a three-phase winding around an iron core formed from laminated steel punchings. The stator core and windings are mounted in, and enclosed by, the motor frame. The three phase stator windings, physically located in slots in the stator core laminations, are spatially arranged and distributed to produce a rotating magnetic field when the three phase voltages are applied. Figure 2.2 illustrates a typical stator showing the arrangement of the three phase stator windings, winding connections, the stator core, and the enclosing housing.

Table 2.1 Large AC Motor Types and Applications

MOTOR TYPE	ROTOR TYPE	TYPICAL NUCLEAR PLANT PUMP/FAN/COMPRESSOR APPLICATIONS	
		PWR	BWR
INDUCTION	Wound Rotor	Component Cooling Water (CCW) Condensate Service Water	Condensate/Condensate Booster Recirculation Pump MG Set Motor Service Water High Pressure Core Spray (HPCS) Low Pressure Core Spray
	Squirrel Cage	Reactor Coolant Condensate Auxiliary Feedwater Compressed Air Containment Spray Safety Injection Main Feedwater RHR Charging Pump/HHSI Circulating Water Condensate Booster CCW Containment Cooling Fans	Reactor Recirc Condensate Compressed Air Main Feedwater RHR/LPCI Core Spray Circulating Water HPCS Condensate Booster Service Water Recirculation Pump MG Set Motor
SYNCHRONOUS	Cylindrical	Reactor Coolant Condensate Condensate Booster	Condensate/Condensate Booster RHR/LPCI Core Spray Recirculation Pump MG Set Motor
	Salient Pole	Circulating Water Service Water	Circulating Water Service Water Condensate/Condensate Booster

Rotor - The rotor design of the three-phase induction motor, in particular, the rotor winding, is the major characteristic distinguishing the two major types of induction motors described above and in Table 2.1. The major elements of all induction motor rotors are: the iron core (formed from slotted, laminated steel punchings); the rotor shaft that supports the iron core, windings, bearing surfaces, and slip rings (if applicable); and the rotor winding, either wound rotor type or squirrel cage type.

The wound rotor has a three-phase coil winding similar to that in the stator and is wound for the same number of poles as the stator winding. The slots in the laminated iron rotor core are located near the outer surface of the core. The coils of the wound rotor are located in the slots in the iron core. The rotor windings terminate in slip rings mounted on the rotor shaft. Brushes ride on the slip rings, and during starting each of the three phases is connected to an external resistor that is short circuited in one or more steps as the motor accelerates. Both the slip and torque of an induction motor are affected by the rotor design, varying with the resistance of the rotor electrical circuit. Slip and torque may therefore be controlled to a certain extent by varying the externally connected resistance. Wound rotor induction motors are applied in situations where limited speed control is required or torque must be controlled. These include cranes, conveyors, and some pumping applications.

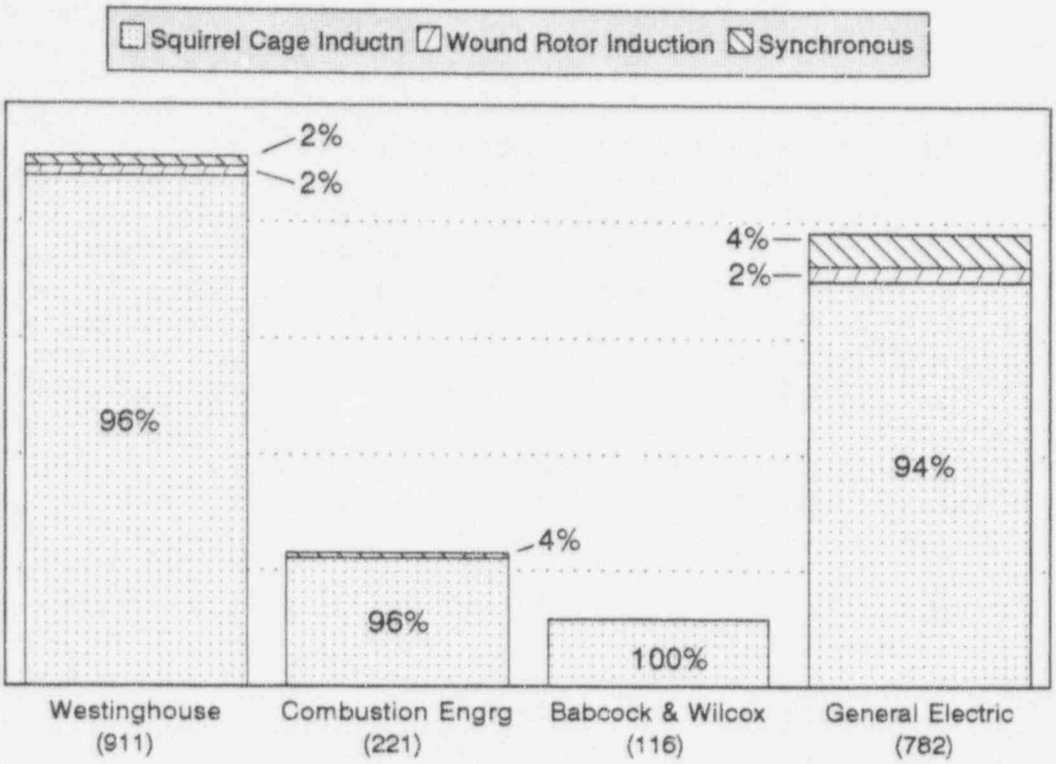


Figure 2.1 Large electric motor populations, grouped by NSSS supplier (NPRDS)

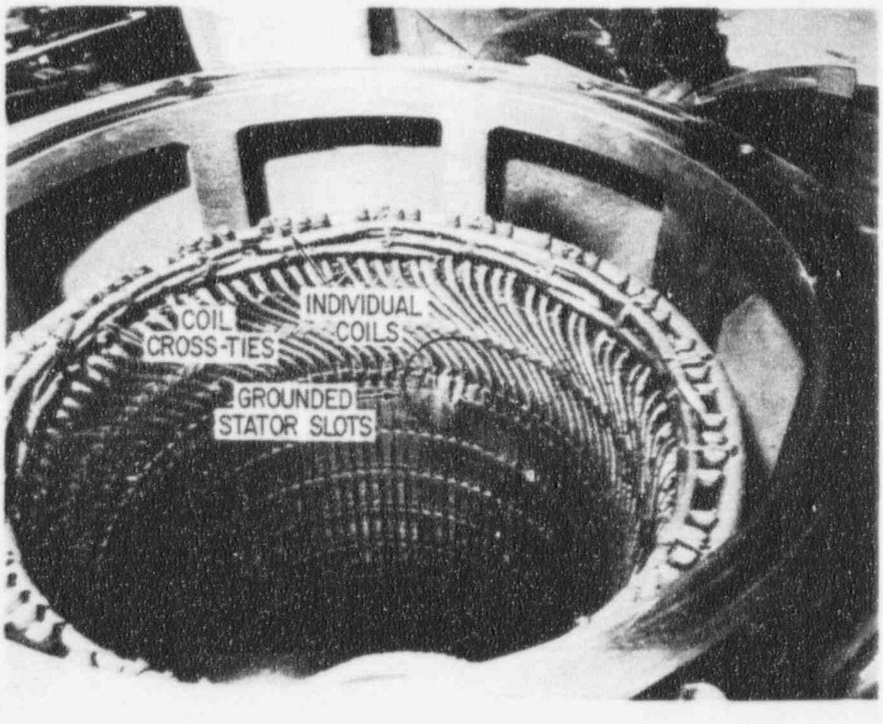


Figure 2.2 Stator with three phase winding

In the squirrel cage induction motor, instead of a coil winding, the electrical circuit of the rotor consists of highly conductive copper, copper alloy, or aluminum alloy bars located in the slots of the rotor core. The bars are connected at each end of the rotor by a heavy, annular-shaped, conductive end ring. The resulting appearance of the rotor electrical circuit, shown in a simplified form in Figure 2.3, is reminiscent of the rotating exercise cages commonly used for small rodents, hence lending its descriptive name to the squirrel cage induction motor. The rotor construction generally will be one of two types: brazed rotors or die cast rotors. In the former, the bars are pressed into the slots of the rotor core, joined to the centrifugally cast end ring by high frequency induction brazing (to insure the mechanical strength and electrical conductivity of the joints), and then swaging the bars into the slots to assure a tight fit with no movement. In the die cast rotor, the laminated iron rotor core is placed in a die casting into which a molten conductor metal, such as aluminum, is injected. In this manner, the rotor bars and end rings are formed as one piece, which is tightly held in the rotor slots in which they had been cast. Fins may often be cast into the end ring of the rotor to provide additional forced air flow through the motor for cooling. Figure 2.4 is a photograph of the squirrel cage rotor for a large induction motor. Rotor cooling air is driven by the integral fan seen at the left, and aided by the cooling fins cast into the rotor assembly at either end. The squirrel cage bars, that make up the electrical circuit of the rotor, can be seen running horizontally in the photograph. They are parallel to the rotor shaft that runs through the center of the rotor assembly, and is partially visible at the right. The stacked magnetic core of the rotor, assembled from insulated iron laminations fastened by through-rods, can be seen in the center of Figure 2.4. Spacers are installed between the packets of the core laminations in this rotor to provide five slots for the passage of cooling air through the rotor core.

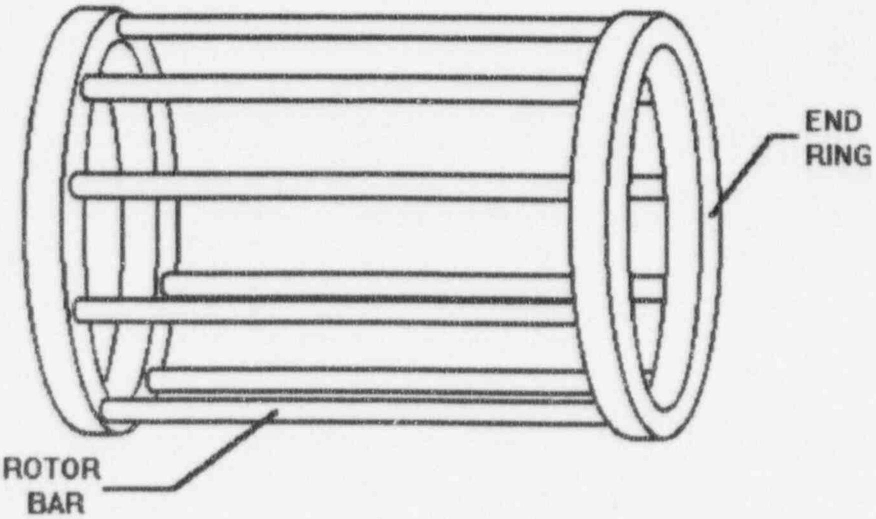


Figure 2.3 Simplified squirrel cage for an induction motor

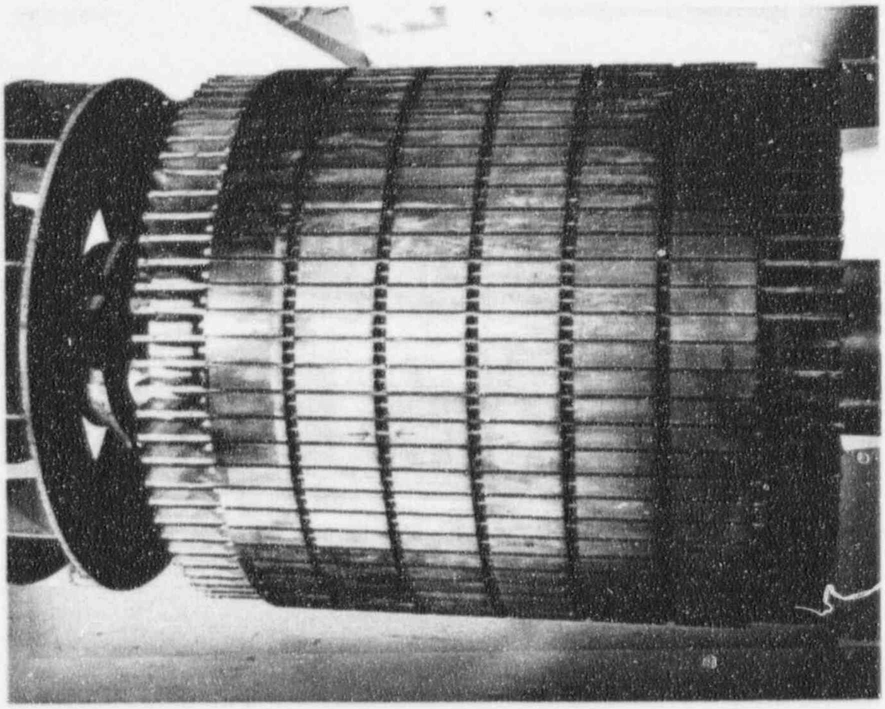


Figure 2.4 Squirrel cage rotor for a large induction motor

2.1.2 Synchronous Motors

The synchronous motor requires both ac and dc power input to operate. The stator is energized by three-phase ac power, and the rotor field windings are energized by dc power either through slip rings on the shaft or directly via a shaft-mounted alternator with rectifying circuitry. One important operating characteristic of the ac synchronous motor is that it always runs at synchronous speed, $n_{synch} = 120f/p$, where f is the operating frequency in Hertz and p is the number of poles. It will run exactly at synchronous speed from no load to full load, making it ideal for continuous, slow-speed applications. The most important and useful characteristic is the ability of the synchronous motor to improve power factor while driving its assigned load. By adjusting field excitation within the thermal design limits of the field and armature windings, the machine can supply negative (leading) VARs to the system to correct a lagging power factor. The two principal components of the synchronous motor, the stator and the rotor, are discussed below.

Stator - The stator for the synchronous motor is nearly identical to that in the induction motor (Figure 2.2). It is made up of a three-phase winding around an iron core formed from laminated steel punchings. The stator core and windings are mounted in, and enclosed by, the motor frame. The three phase stator windings, physically located in slots in the stator core laminations, are spatially arranged and distributed to produce a rotating magnetic field when the three ac phase voltages are applied.

Rotor - The rotor of the synchronous motor may be of the cylindrical type or the salient pole type. The laminated steel rotor poles will contain the main rotor field windings that are excited by dc power during operation. In addition, the rotor will have embedded starter windings known as damper, or amortisseur windings. These may be in the form of imbedded bars terminated at short-circuiting end rings, a squirrel cage winding, or even a wound rotor winding where high starting torques are required. These windings allow the synchronous motor to be started as a three-phase induction motor, to provide the necessary starting torque to accelerate the machine and its connected mechanical load nearly to synchronous speed. When excitation is then applied to the field, the synchronous motor can develop sufficient pull-in torque to pull-in to synchronous speed when connected to its driven mechanical load. The damper windings will also help to stabilize speed oscillations that result from pulsating load torque.

The cylindrical rotor is found mainly in two and four pole machines operating at higher speeds (3600 rpm and 1800 rpm, respectively, for a 60 Hz system). The smooth, compact design of the cylindrical rotor is better suited to withstand the high rotating forces in a large machine, produces lower windage losses, and allows the use of a narrower air gap.

The salient pole synchronous motor typically has four or more field poles arranged radially around a central rotor yoke. Since the salient pole machine has a large number of field poles, it operates at a lower synchronous speed ($n_{synch} = 120f/p$) than the cylindrical rotor, making it ideal for low speed applications such as fans, circulating water pumps, and other direct-connected loads. This type of motor is generally less expensive to manufacture than an equivalent cylindrical rotor machine.

In addition to the stator and the rotor, an essential component of the ac synchronous motor is the rotor field excitation system. The dc power to excite the rotor field windings may be brought to the rotor either from a dc source mounted on the motor shaft, or from a source external to the motor, via brushes riding on slip rings. More commonly used is the brushless exciter, in which the output of a shaft-mounted alternator is converted to dc in a solid-state rectifier circuit, also mounted on the motor shaft, and then output to the field windings.

2.2 Large Motor Bearings

Operating experience data and industry surveys (Refs. 9, 10, 11) have shown that bearings and bearing lubrication problems are a major cause of failures in large electric motors. The major types of bearings are described to provide a better understanding of this important motor component.

Anti-friction Bearings - The anti-friction bearing consists of caged rolling elements operating in a raceway. The rolling elements may be spherical balls (as in the ball bearing), or rollers (cylindrical, spherical, needle, or tapered). Ball bearings are usually found in smaller (less than 200 hp) horizontal motor applications and belt-driven applications, such as fans, compressors, and conveyors. Cylindrical, spherical, or tapered roller bearings are typically used in horizontal belt-driven applications and in vertical applications because roller bearings can manage axial thrust loads better than ball bearings. Anti-friction bearings can be found in larger motors (up to 1500 hp or more) depending upon the particular application, but the larger motors will most often employ hydrodynamic journal bearings. Anti-friction bearings may be grease or oil lubricated, especially in the larger motors operating at higher speeds.

Hydrodynamic Bearings - This is a cylindrical journal bearing consisting of an oil-lubricated, babbitt-lined bearing. Oil rings and grooves help to distribute the lubricating oil onto the journal and bearing surfaces.

Hydrodynamic, oil-lubricated journal bearings are the type most often used on larger electric motors and generators.

Thrust Bearings - Thrust bearings are used in large motors where large axial thrust loads are found in horizontal applications, and in vertically mounted applications, such as reactor recirculating water pumps, circulating water pumps, and service water pumps. They may be of two basic types: anti-friction (similar in principle to those described above) and Kingsbury type, a pivoted segmental thrust bearing.

2.3 Additional Subcomponents, Auxiliary, and Support Equipment

Large Motor Subcomponents - The major subcomponents of the electric motor, i.e., the stator, rotor, and bearings, have been described in the previous section. Other important subcomponents and equipment of the electric motor proper include the motor frame, shaft, mechanical couplings (to the driven load), motor housing, motor mounting, cooling air fans, filters, and heat exchangers, lubricating oil system, bearing cooling, stator and rotor cooling, electrical terminations, component cooling water lines at the machine, heaters, and instrumentation sensors. The lubricating oil system for a large motor typically will include a pump, auxiliary pump, reservoir, screen and/or filter, heat exchanger, and piping. Instrumentation will include CTs for motor current, PTs for bus voltage, vibration monitoring and recording, and RTDs for monitoring winding temperature, lubricating oil temperature, and bearing temperature. Components unique to wound rotor induction motors or synchronous motors are the field windings, brushes, slip rings, or rotating type brushless exciters.

Support Equipment - In addition to the electric motor itself, a variety of support equipment and systems are essential for the starting and continued operation of the large motor. These include motor starters or circuit breakers and their associated controls, indicating and automatic monitoring instrumentation, protective relaying, control logic circuits, voltage regulators, surge arrestors, service water, and component cooling water supply systems. Ventilation systems or room coolers are necessary to maintain temperature below maximum design levels in the area or room in which the motor is operating.

The plant electrical distribution system, obviously, is necessary to provide electric power to the large motor at the required voltage for operation. The electric power system, which itself has been the subject of an aging study (Ref. 12), is considered outside the scope of this study. In the special case of the reactor recirculation pumps for a BWR, the variable frequency power used to drive the recirculation pump motors is obtained from a motor-generator (MG) set. The motor driving the recirc MG set generator, through an adjustable fluid coupling, is a very large motor that is considered as a part of this study.

Associated Equipment - In this aging study, associated equipment is defined as the motor-driven mechanical loads and any other equipment that can affect the driven load. The most common large electric motor loads in a nuclear power plant are pumps, fans, and compressors. In a BWR recirc MG set, the variable frequency ac generator and its mechanical fluid coupling are the driven load.

Other associated components and equipment that can affect a large motor are pump discharge and suction valves, ventilation inlet and discharge dampers, valve and damper motor operators, pump suction screens, pump and fan bearings and seals, pump shafts and impellers, fan blades, and their associated controls, instrumentation, and power feeds. Failures of this associated equipment can lead directly to large motor trips, either as a mechanical failure, or as part of the starting and control logic for the large motor. An associated equipment failure can also lead to a large motor trip when it results in a condition that exceeds an allowable parameter in the large motor operating logic. Examples of this are room cooling ventilation fan and damper failures, low suction pressure due to failed valve operators or strainers, or failed discharge valves.

2.4 Large Motor Applications and Systems

A design review of several representative nuclear plants from each of the four major NSSS suppliers was conducted based upon the plant Final Safety Analysis Reports (FSARs) and surveys of large motor populations reported to the NPRDS. The systems and applications utilizing large electric motors were identified, along with the typical plant locations for these motors.

2.4.1 BWR Plants

Table 2.2 summarizes the large electric motors typically found in General Electric BWR power plants. All of the entries listed in the table are pumping applications with the exception of the drive motors for the Reactor Recirculation Pump Motor/Generator Sets.

Table 2.2 Typical Large Electric Motors at BWR Plants

SYSTEM/APPLICATION	TYPICAL QTY MOTORS	TYPICAL HP RANGE	VOLTAGE CLASS	SAFETY CLASS	TYPICAL PLANT LOCATION
Reactor Recirculation (Rx Recirc)	2	5700-8900	4 kv	2	Primary Containment
Rx Recirc MG Set Motor	2	7000-9000	4 kv	2	Control Bldg
RHR/Low Pressure Coolant Injection (LPCI)	4	800-2000	4 kv	1E	Reactor Bldg
Feedwater (Reactor Feed Pump)	2-3	9000	4 kv	4	Turbine Bldg
Condensate Pump	2-4	1500-3500	4 kv	4	Turbine Bldg
Condensate Booster Pump	2-4	1750-3500	4 kv	4	Turbine Bldg
Control Rod Drive	2	250-300	4 kv	1E	Reactor Bldg
Low Pressure Core Spray (LPCS)	2	1250-1500	4 kv	1E	Reactor Bldg
High Pressure Core Spray (HPCS)	1	3000	4 kv	1E	Reactor Bldg
Rx Bldg Closed Loop Cooling Water	3	100-500	4 kv	1E	Reactor Bldg
Service Water	4	200-1000	4 kv	1E	Intake Structure/Screenwell
Circulating Water	4	1500-2000	4 kv	4	Intake Structure/Screenwell

2.4.2 PWR Plants

Table 2.3 presents a similar summary of large electric motors in use at PWR plants. They all represent pumping applications, with the typical quantities of pump motors in each application, ranges of horsepower ratings, and operating voltage as indicated in the table.

Table 2.3 Typical Large Electric Motors at PWR Plants

SYSTEM/APPLICATION	TYPICAL QTY MOTORS	TYPICAL HP RANGE	VOLTAGE CLASS	SAFETY CLASS	TYPICAL PLANT LOCATION
Reactor Coolant (RCS)	2-4	6500-9000	6.6/13.8 kv	4	Primary Containment
RHR/Low Pressure Safety Injection	2-4	300-700	4/6.6 kv	1E	Auxiliary Bldg
Auxiliary (Emergency) Feedwater	1-3	600-800	4/6.6 kv	1E	Turbine or Auxiliary Bldg
Feedwater (Steam Generator Feedwater)	1-3	1500-12000	4/6.6/13.8 kv	4	Turbine Bldg
Condensate Pump	3-4	1500-4000	4/6.6/13.8 kv	4	Turbine Bldg
CVCS Charging Pump (High Head SI)	2-4	100-1000	4/6.6 kv	1E	Auxiliary Bldg
Containment Spray	2-4	250-500	4/6.6 kv	1E	Auxiliary Bldg
High Pressure Safety Injection (SI)	2-3	450-1000	4/6.6 kv	1E	Auxiliary Bldg
Heater Drain Pumps	2	1250-1750	4/6.6 kv	4	Turbine Bldg
Component Cooling Water	2-4	200-800	4/6.6 kv	1E	Auxiliary Bldg
Service Water	3-4	800-3000	4/6.6 kv	1E	Intake Structure/Screenwell
Circulating Water	4-6	1500-2000	4/6.6/13.8 kv	4	Intake Structure/Screenwell

Other large electric motor data obtained from the NPRDS large motor population survey showed information such as the manufacturer, voltage class, and horsepower rating. These data are presented in Appendix A.

2.5 Design Enhancements for Nuclear Applications

The design specifications for large electric motors in a PWR plant and a BWR plant were reviewed, along with their equipment and system descriptions, in order to identify differences in design for large motors in various nuclear applications. These data were supplemented by manufacturers' literature and other documentation. All large motors installed in nuclear power plants conform to NEMA Standard MG-1 (Ref. 13), Part 20, for large induction motors and Part 21, for large synchronous motors, as to all the fundamental features of materials, workmanship, design, and tests. Further design requirements and features for large electric motors were found to be a function of the operating environment. The environmental considerations resulted in differences primarily in the electric motor insulation systems, enclosures, and bearing systems.

2.5.1 Mild Service Environments

Generally, there is very little difference between the large motor designs for BOP applications and nuclear applications in mild environments. The type of application, such as pumping, compressor, fan, etc., associated service requirements, such as low head pump, high head pump, continuous operation, frequent or infrequent starting, etc., and the operating environment are the important factors in the determination of motor specifications.

Motor specification sheets for a BOP motor, in this case for a circulating water pump, and a Class 1E nuclear safety-related motor, a nuclear service water pump, at a PWR plant are shown in Figures 2.5 and 2.6, respectively. Although the service water pump motors are safety-related, and the circulating water pumps are not, these applications are very similar and the operating environment is basically the same as far as physical location, ambient temperature, humidity, and barometric pressure. This is considered a mild environment. Consequently, the specifications for these motors are similar: squirrel cage induction motor, fully guarded drip proof enclosure; non-hygroscopic Class B, sealed (thermalastic epoxy or polyseal, vacuum pressure impregnated (VPI)) insulation; 1.0 service factor; vertical mounting. As a Class 1E application, however, the service water pump motors have the additional requirement that they are to be manufactured in accordance with applicable QA requirements, certified as seismically qualified to withstand a Safe Shutdown Earthquake (SSE) in accordance with IEEE Std. 344-1975 (Ref. 14), and certified as environmentally qualified per IEEE Stds. 323-1974 (Ref. 3) and 334-1974 (Ref. 4).

2.5.2 Nuclear Service Outside of Containment

Most Class 1E large electric motors in nuclear pumping applications are located inside the reactor building in a BWR plant, or in the auxiliary building or engineered safety features building at a PWR. Large motors in this type of service are almost exclusively squirrel cage induction motors that are specified with fully guarded drip proof enclosures similar to those for BOP and mild environments as discussed above. Due to the higher operating temperature and humidity in these locations, higher temperature rated insulations, Class F or Class H, are specified. Low level radiation exposures are normal in these applications. Therefore, stator winding insulation, motor terminations, and connectors must be radiation tolerant over the 40 year specified operating life.

Some motors in the BWR reactor building and the PWR auxiliary building may be required to operate for some time while exposed to more severe conditions of temperature, humidity, steam or chemical spray impingement, pressure, and radiation during design basis accident (DBA) conditions such as a high energy line break, LOCA, or main steam line break. Consequently, the insulation systems, motor leads, and terminations in these Class 1E motors are specified for higher temperature, moisture/steam resistance, and radiation tolerance. Stator windings are specified to be insulated and sealed via multiple applications using a VPI process to provide a thicker, well-sealed insulation, and add rigidity to minimize coil deflection and insulation fatigue during operation.

Bearings are often sleeve type, however some of the specifications reviewed specified antifriction bearings. They must be designed to operate while exposed to accident conditions such as high pressure and humidity, and the effects of water and chemical sprays. This may be accomplished through the use

1	CLIENT	INDUCTION MOTOR DATA PROJECT J.O. No.
2	FURNISHED BY General Electric	DATE BY
3	MARK No. 3CWS-P1A, 3CWS-P1B, 3CWS-P1C, 3CWS-P1D, 3CWS-P1E, 3CWS-P1F	
4	PURCHASER'S REQUIREMENTS	DATA FURNISHED BY SELLER
5	SERVICE Circulating Water Pump	MAKE General Electric
6	TYPE Squirrel Cage	FRAME No.
7	No. OF UNITS 6	HORSEPOWER 1500
8	MOUNTING Vertical	SERVICE FACTOR 1.0
9	ELEC. CHARACTERISTICS 4000 V 3 PH 60 HZ	FULL LOAD RPM 272
10	SYNCH SPEED, RPM 277	FULL LOAD AMP 235
11	HORSEPOWER 1500	LOCKED ROTOR AMP 1400
12	SERVICE FACTOR 1.0	STARTING TORQUE, % F.L. 80
13	ENCLOSURE Dripproof	PULL-OUT TORQUE, % F.L. 200
14	INSULATION CLASS B	EFF.- FULL LOAD, % 92.8
15	INSULATION TREATMENT Sealed	EFF.- 3/4 LOAD, % 92.6
16	AMBIENT TEMP - C 40	EFF.- 1/2 LOAD, % 91.3
17	STATOR TEMP RISE - C 90 by RTD at S.F.	P.F.- FULL LOAD, % 74.0
18	BEARING TYPE Kingsbury	P.F.- 3/4 LOAD, % 67.0
19	BEARING TEMP RELAY	P.F.- 1/2 LOAD, % 55.0
20	BEARING THERMOCOUPLE RTD Req'd	P.F. AT STARTING, % 20
21	HALF COUPL. OR SHEAVE MTD BY Motor Mfg.	SHORT CIRCUIT A-C TIME CONSTANT, SEC .032
22	ROTATION * Clockwise	X / R RATIO 10
23	WK^2 OF DRIVEN EQUIP (LB-FT^2) 9670	SPACE HTRS., TOTAL WATTS 3600
24	BRKWY. TORQ. DRVN. EQUIP. See 7145.1042	GUIDE BEARING TYPE Sleeve
25	OVERSIZE COND. BOX Required	THRUST BEARING TYPE Plate
26	COND. BOX LOCATION * GE 135D5708	BEARING SERVICE - HR Continuous
27	SPACE HEATERS, VOLTAGE, PHASE 208, 1	NORMAL BRG. OPER. TEMP. - C 40 Amb. 50 Rise
28	SPLIT END BELLS —	NET WEIGHT 27,500
29	TERMINAL LUGS TYPE Compression, by Purchaser	OIL COOL. SYS. REQ'D —
30	STATOR HIGH TEMP. DEVICE RTD	BRG. OIL PRESS. RANGE, PSI —
31	ADJUSTABLE SLIDE RAILS —	BRG. OIL REQ'D EA. BRG., GPM —
32	SOLEPLATES —	NAME PLATE CODE LETTER G
33	PROJECT ELEV., FT. 24	PERMISSIBLE STARTS PER HR. WITH:
34	SHAFT (HOLLOW, SOLID) Solid	MOTOR AT AMBIENT TEMP. 2
35	COUPLING (SELF-RELEASE,	MOTOR AT RATED TOTAL TEMP. 1
36	SOLID, NONREVERSING,	TYPE SEALED INSUL. SYS. Polyseal GEZ 542
37	ADJUSTIBLE, FLEXIBLE)	DESCRIPTION OF INSUL. SYS. VPI GEZ 5402
38	DOWNTHRUST - CONTINUOUS 24,800 lbs.	MAX. STALL TIME WITH L.R. AMPS, SEC 15 typ
39	UPTHRUST - CONTINUOUS 0 lbs.	ACCEL. TIME, FULLY LOADED
40	UPTHRUST - MOMENTARY 11910 lbs.	WITH 100 % V, SEC 2
41	DOWNTHRUST - MOMENTARY 35,790 lbs.	WITH 80 % V, SEC 4
42		WITH % V, SEC
43	SIDE THRUST	
44	MAX REVERSE SPEED 220 RPM	
45	DRAIN PLUG AND VENT	Noise Level 100 dbA
46	AIR INTAKE AND DISCHARGE SCREENS Required	
47	C.T. RATIO —	WK^2 OF ROTOR, LB-FT^2 25,000
48	SURGE CAPACITORS —	
49	ANTI-FRICT. BRG. SERVICE - HR	BHP LOSS IN THRUST BRG., KW 2 (est.)
50	MINIMUM STARTING VOLTAGE % 80	
51	GUIDE BRG. MIN. LIFE 15 yrs.	
52	REMARKS:	REMARKS:
53	ALL PERFORMANCE DATA BASED ON NORMAL RATED	ALL PERFORMANCE DATA BASED ON NORMAL RATED
54	VOLTAGE AND FREQUENCY	VOLTAGE AND FREQUENCY
55	ITEMS 34-44 APPLY TO VERTICAL MOTORS ONLY	
56	PUMP SPEED TORQUE CURVE 7145.1042	
57	PUMP PERFORMANCE CURVE 7145.1041	
58	FEEDER CABLE SIZE 3 - 1/C - 350 MCM Al Shielded	
59		
60	* VIEWED FROM END OPPOSITE COUPLING END	

Figure 2.5 Specification sheet for squirrel cage induction motor for PWR BOP circulating water pump

1	INDUCTION MOTOR DATA CLIENT	PROJECT J.O. No.
2	FURNISHED BY General Electric	DATE BY
3	MARK No. 3SWP*P1A, 3SWP*P1B, 3SWP*P1C, 3SWP*P1D	
4	PURCHASER'S REQUIREMENTS	DATA FURNISHED BY SELLER
5	SERVICE Service Water Pump	MAKE General Electric
6	TYPE Squirrel Cage	FRAME No. 6338PZ42
7	No. OF UNITS 4	HORSEPOWER 600
8	MOUNTING Vertical	SERVICE FACTOR 1.0
9	ELEC. CHARACTERISTICS 4000 V 3 PH 60 HZ	FULL LOAD RPM 885
10	SYNCH SPEED, RPM 900	FULL LOAD AMP 84.1
11	HORSEPOWER 600	LOCKED ROTOR AMP 547
12	SERVICE FACTOR 1.0	STARTING TORQUE, % F.L. 100
13	ENCLOSURE Dripproof	PULL-OUT TORQUE, % F.L. 225
14	INSULATION CLASS B	EFF.- FULL LOAD, % 92.5
15	INSULATION TREATMENT Sealed	EFF.- 3/4 LOAD, % 92
16	AMBIENT TEMP - C 40	EFF.- 1/2 LOAD, % 91
17	STATOR TEMP RISE - C 80 by RTD at S.F.	P.F.- FULL LOAD, % 83
18	BEARING TYPE Ang. Contact Ball Thrust/Rad. Ball Guide	P.F.- 3/4 LOAD, % 78
19	BEARING TEMP RELAY	P.F.- 1/2 LOAD, % 65
20	BEARING THERMOCOUPLE RTD Req'd	P.F. AT STARTING, % 27
21	HALF COUPL. OR SHEAVE MTD BY Motor Mfg.	SHORT CIRCUIT A-C TIME CONSTANT, SEC
22	ROTATION * Clockwise	X / R RATIO 3.4527
23	WK^2 OF DRIVEN EQUIP ($LB\text{-}FT^2$) 375	SPACE HTRS., TOTAL WATTS 442
24	BRKWY. TORQ. DRVN. EQUIP. See 24-VSN	GUIDE BEARING TYPE Ball
25	OVERSIZE COND. BOX Required	THRUST BEARING TYPE Ang. Contact Ball
26	COND. BOX LOCATION * GE 234C788EF	BEARING SERVICE - HR Continuous 15 yr.
27	SPACE HEATERS, VOLTAGE, PHASE 120, 1	NORMAL BRG. OPER. TEMP. - C 54 - 65
28	SPLIT END BELLS —	NET WEIGHT 6500
29	TERMINAL LUGS TYPE Compression, by Purchaser	OIL COOL, SYS. REQ'D —
30	STATOR HIGH TEMP. DEVICE RTD, 10 Ohm Cu 2/PH	BRG. OIL PRESS. RANGE, PSI —
31	ADJUSTABLE SLIDE RAILS —	BRG. OIL REQ'D EA. BRG., GPM —
32	SOLEPLATES —	NAME PLATE CODE LETTER G
33	PROJECT ELEV., FT. 24	PERMISSIBLE STARTS PER HR. WITH:
34	SHAFT (HOLLOW, SOLID) Solid	MOTOR AT AMBIENT TEMP. 2
35	COUPLING (SELF-RELEASE,	MOTOR AT RATED TOTAL TEMP. 1
36	SOLID, NONREVERSING,	TYPE SEALED INSUL. SYS. B Polyseal GEZ 5128
37	ADJUSTIBLE, FLEXIBLE)	DESCRIPTION OF INSUL. SYS. VPI GEZ 5402
38	DOWNTHRUST - CONTINUOUS 3200 lbs.	MAX. STALL TIME WITH L.R. AMPS, SEC 14
39	UPTHRUST - CONTINUOUS 0 lbs.	ACCEL. TIME, FULLY LOADED
40	UPTHRUST - MOMENTARY 1000 lbs.	WITH 100 % V, SEC 1.5
41	DOWNTHRUST - MOMENTARY 0 lbs.	WITH 80 % V, SEC
42		WITH 70 % V, SEC 5
43	SIDE THRUST —	
44	MAX REVERSE SPEED —	
45	DRAIN PLUG AND VENT —	Noise Level 100 dbA
46	AIR INTAKE AND DISCHARGE SCREENS Required	
47	C.T. RATIO —	WK^2 OF ROTOR, $LB\text{-}FT^2$ 567
48	SURGE CAPACITORS —	
49	ANTI-FRICT. BRG. SERVICE - HR 15 yr. minimum	BHP LOSS IN THRUST BRG., KW 0.16
50	MINIMUM STARTING VOLTAGE % 70	CRITICAL FREQ., CPM 2900
51	GUIDE BRG. MIN. LIFE 15 yrs.	
52	REMARKS:	REMARKS:
53	ALL PERFORMANCE DATA BASED ON NORMAL RATED	ALL PERFORMANCE DATA BASED ON NORMAL RATED
54	VOLTAGE AND FREQUENCY	VOLTAGE AND FREQUENCY
55	ITEMS 34-44 APPLY TO VERTICAL MOTORS ONLY	
56	PUMP SPEED TORQUE CURVE 24-VSN	
57	PUMP PERFORMANCE CURVE 7141.1005	
58	FEEDER CABLE SIZE Triplex 4/0 Al Shielded	
59		
60	* VIEWED FROM END OPPOSITE COUPLING END	

Figure 2.6 Specification sheet for squirrel cage induction motor for PWR Class 1E service water pump

of elastomeric seals. The motor enclosure must provide adequate relief from pressure differentials that could force water, dirt, or other contaminants into the bearings, or extrude grease or oil out of the bearing, causing extreme wear (Ref. 15).

The Class 1E large electric motors in mild nuclear service environments, such as the BWR reactor building and PWR auxiliary building, are required to be manufactured in accordance with applicable QA requirements, certified as seismically qualified to withstand a Safe Shutdown Earthquake in accordance with IEEE Std. 344-1975 (Ref. 14), and certified as environmentally qualified per IEEE Stds. 323-1974 (Ref. 3) and 334-1974 (Ref. 4). Some of the specifications reviewed required that the motors be manufactured by General Electric, Westinghouse, or Allis Chalmers, acknowledging their experience in production of Class 1E motors. This is reflected in the summary of large motors grouped by manufacturer in Appendix A.

2.5.3 In-Containment Nuclear Service

Large motors inside containment are the reactor recirc pump motors in the BWR and the reactor coolant pumps in the PWR. The ambient conditions inside these structures constitute a harsh nuclear operating environment. The primary containment ambient conditions in a BWR typically consist of the following (Ref. 16):

Normal Operating Temperature - 135°F
Maximum Operating Temperature- 150°F
Maximum Pressure (Nitrogen)- 16.7 psig
Maximum Relative Humidity- 95%
Radiation Exposure- 30 Rads/hour, gamma

The reactor containment ambient conditions in a PWR typically consist of the following (Ref. 17):

Maximum Operating Temperature- 120°F
Normal Relative Humidity- 50%
Maximum Relative Humidity- 100%
Radiation Exposure- 50 Rads/hour, gamma

These are harsh nuclear environments with high ambient temperatures during operation, high humidity, ambient exposures to radiation of up to 50 Rad/hr, and cumulative exposures of up to 33 MRad total integrated dose over the service life of 40 years (Ref. 17). Furthermore, these motors are normally inaccessible during operation, so high reliability is an important consideration and design features must be incorporated that will allow these motors to operate reliably for the extended periods between scheduled maintenance.

Consequently, even though they are not considered Class 1E nuclear safety-related equipment, BWR recirc pump motors and PWR reactor coolant pump motors incorporate many of the design features that are used in the Class 1E applications as described in Section 2.5.2 above. These include non-hygroscopic, Class F or H, thermalastic epoxy sealed insulation, sealed bearings, radiation resilient materials, and corrosion resistant design and materials. Additional features found are anti-reverse rotation devices and large inertial flywheel assemblies.

Due to the relatively limited space and enclosed atmosphere inside containment, limiting ambient temperatures is a concern. Therefore, large motor enclosures for in-containment applications may be of three basic types: 1) guarded drip proof, 2) drip proof with a cooling water-to-air heat exchanger on the air discharge from the motor, or 3) totally enclosed with a cooling water-to-air heat exchanger. The latter two enclosure designs serve to actively reduce the temperature of cooling air exiting the motors.

Although the BWR recirc pump motor and PWR coolant pump motors are not required for safe shutdown, seismic design and testing considerations are still required since these motors must continue to operate during and after an Operating Basis Earthquake (OBE). In addition, they must be able to maintain their integrity throughout and following a Safe Shutdown Earthquake (SSE) or an SSE simultaneous with a LOCA so that the reactor coolant boundary remains intact, and pump seals and thermal barriers are not damaged. The reactor coolant pump must also maintain a coastdown capability following these events, as well as the capability to maintain reactor coolant flow during the coastdown.

3. STRESSORS, FAILURE MECHANISMS, AND CAUSES

This section of the report identifies the major stressors that contribute to the aging and degradation of large electric motors in nuclear generating stations. The aging mechanisms that lead to large motor failures are identified, along with the causes of those failures, based on a review of large motor designs and a review and analysis of operating history data. The aging and degradation of large electric motors are characterized as they relate to the various parts and subcomponents of large squirrel cage induction motors.

3.1 Operating Environments and Stressors

The basic stressors that affect the operating life of electric motors are well known throughout the industry. The most significant are heat, mechanical vibration, and wear. Electric motor stressors have been discussed in detail in an earlier NPAR electric motor study (Ref. 5), so they will be categorized and summarized here as they relate to large motors.

3.1.1 Stressors

The stressors that affect large electric motors are:

Heat
Pressure
Radiation
Humidity/Water Spray
Vibration/Seismic
Chemicals
Steam
Mechanical Cycling/Rubbing
Electromagnetic Cycling
Foreign Object Ingestion

The stressors act independently and/or synergistically to cause failures in the major subcomponents of large electric motors, such as the stator windings, electrical terminations, bearings, and rotor cage. All of the stressors listed above contribute to the gradual or catastrophic degradation of the insulation system. Mechanical and electromagnetic cycling, ingestion of foreign objects, and vibration-related stressors act upon the mechanical integrity of the machine. They can cause bearing and lubrication system problems, rotor breakage, mounting/enclosure failures, and failures of the shaft/couplings.

3.1.2 Sources of Large Motor Stressors

The sources or origins of the stressors may be grouped into four categories: 1) operational, component level, 2) operational, system level, 3) environmental, and 4) human factors. These are summarized in Table 3.1. By identifying the nature and origin of large motor stressors, a determination may be made as to the best approach to mitigate the effects of each stressor. The effects of some stressors can only be counteracted by incorporating features into the original specification and design of the motor. Others may be mitigated by system level design, good operating and maintenance practices, and the proper surveillance, monitoring, and testing activities.

Component level stressors, such as heat originating from electrical and mechanical losses, can never be eliminated, however their effects are predictable and can be mitigated by design, good manufacturing, and monitoring/testing. System level operational stressors originate from a variety of electrical, mechanical, and operational conditions, both transient and steady-state. Many of the effects of these

Table 3.1 Origins of Large Electric Motor Stressors

CATEGORY/ ORIGIN OF STRESSOR		STRESSORS									
		Heat	Pressure	Radiation	Humidity/Water Spray	Vibration/Seismic	Chemicals	Steam	Mechanical Cycling/Rubbing	Electromagnetic Cycling	Ingest Foreign Object
OPERATIONAL (Component Level)	I^2R heating	X									
	Friction	X				X			X		
	Windage					X			X		
	Mechanical Imbalance	X				X			X		
OPERATIONAL (System Level)	Mechanical Overload	X				X			X		
	Frequent Starting	X							X	X	
	Undervoltage	X							X	X	
	Overvoltage	X								X	
	Under Frequency	X							X	X	
	Voltage Imbalance	X				X			X	X	
	LOOP/electrical transients	X				X			X	X	
	Trips	X				X			X	X	
	Support Equipment Problems (clg air/wtr, lube oil system, I&C, circuit breakers, heaters, etc.)	X				X		X	X	X	X
	Associated Equipment (driven loads; discharge, suction, bypass valves/dampers, strainers)	X				X		X	X		
ENVIRONMENTAL	Ambient Conditions	X	X	X	X		X				
	Moisture & Water Impingement				X	X					
	Steam	X	X		X	X		X			
	Submersion/Immersion		X		X	X	X				
	Chemical Spray				X	X	X				
	Vibration					X			X		
HUMAN FACTORS	Misapplication/Undersized	X				X			X	X	
	Mis-operation (Excessive Starting)	X							X	X	
	Mis-operation (Wrong Valve/Damper Lineups)	X				X		X	X	X	
	Poor Maintenance (Testing)	X				X	X	X	X	X	X
	Poor Maintenance (Lube Oil/Grease)	X				X	X		X		X
	Poor Maintenance (Ventilation Filters/Screens)	X									X
	Poor Maintenance (Bearings)	X				X			X	X	X
	Manufacturing Defects	X				X	X		X	X	X
	Installation Error	X				X	X		X		X

kinds of stressors can be mitigated or arrested by good plant and system design, electric power system quality, protective relaying, and efficient plant operation and maintenance.

Environmental factors, including both normal ambient conditions for operation, as well as accident conditions, are significant stressors for electric motors. Most of these environmental considerations are location and application specific. They can be well defined and, consequently, accounted for in the specification and design of the electric motor that will be used in a particular application and plant location. The geographic location of the plant, the time of the year, and the operating status of the plant (full power, startup, shutdown, etc.) will also contribute to the ambient temperature and humidity of some motor applications.

Table 3.2 provides a summary of some of the typical ambient conditions that would be expected in the operating environments of large electric motors in northern United States BWR and PWR plants. These estimates are based upon large motor design specifications (Refs. 16 and 17) and information gathered during site visits to Plant A, a PWR, and Plant B, a BWR. This information would be identified in the design specification for the motor so that proper insulation class, enclosure, cooling requirements, starting and operating restrictions, environmental qualification requirements, quality controls and other parameters can be incorporated into the design and manufacture of the motor.

Finally, human factors are the last source of stressors on large motors. These problems can never be fully eliminated, but their impact can be lessened through improved procedures and training, adherence to manufacturers' recommendations, good maintenance and operating practices, and thorough design engineering. Administrative and quality controls in maintenance, modification, and operating activities can also help to reduce human factors errors affecting large electric motors.

Table 3.2 Typical Environmental Conditions in BWR and PWR Plant Locations

Location		PWR	BWR
H A R S H	REACTOR CONTAINMENT (PWR Containment Bldg) (BWR Primary Containment)	Temperature - 50 to 120°F Pressure - Atmospheric Relative Humidity - 30-100% Service Radiation Dose - 50 Rads/hour Accident Environment Max Temperature - 300°F Max Pressure - 70 psig Max Relative Humidity - 100% Radiation Dose - 150 MRads Additional Considerations - potential for steam, water/chemical spray.	Temperature Range - 50 to 150°F Max Avg - 135°F Pressure - 16.7 psig (Nitrogen) Relative Humidity - 30-100% Service Radiation Dose - 30 Rads/hour Accident Environment Max Temperature - 340°F Max Pressure - 62 psig Max Relative Humidity - 100% Radiation Dose - 26 MRads Additional Considerations - potential for steam, water spray.
M I L D	PWR AUXILIARY BLDG BWR REACTOR BLDG	Temperature Range - 50 to 120°F Max Avg - 85°F Pressure - Atmospheric Relative Humidity - 10-90% Service Radiation Dose - 4 kRads Accident Environment Max Temperature - 185°F Max Pressure - 16.7 psig Max Relative Humidity - 100% Radiation Dose - 2.6 x 10^6 Rads Additional Considerations - potential for steam, water & chemical spray,	Temperature Range - 50 to 150°F Max Avg - 135°F Pressure - Atmospheric Relative Humidity - 30-95% Service Radiation Dose - 4 kRads (est.) Accident Environment Max Temperature - 215°F Max Pressure - 16.7 psig Max Relative Humidity - 100% Radiation Dose - 2.1 x 10^6 Rads Additional Considerations - potential for steam, water spray.

Table 3.2 (Cont'd)

Location		PWR	BWR
MILD	CONTROLS BUILDING	Temperature Range - 65 to 104°F Max Avg - 85°F Pressure - Atmospheric Relative Humidity - 10-75% Service Radiation Dose - <100 Rads Accident Environment Ambient - Same as normal environment described above	Same as for PWR.
MILD	TURBINE BUILDING	Temperature Range - 50 to 120°F Max Avg - 85°F Max Excursion - 120°F Pressure - Atmospheric Relative Humidity - 10-75% Service Radiation Dose - <100 Rads Accident Environment Ambient - Same as normal environment described above	Temperature Range - 50 to 120°F Max Avg - 85°F Max Excursion - 120°F Pressure - Atmospheric Relative Humidity - 10-75% Service Radiation Dose - <100 Rads Accident Environment Ambient - Same as normal environment described above Additional Considerations - potential for submersion, water spray; radiation in main steam line and turbine areas.
	INTAKE STRUCTURE	Temperature Range - 40 to 120°F Max Avg - 75°F Pressure - Atmospheric Relative Humidity - 10-100% Service Radiation Dose - <100 Rads Accident Environment Ambient - Same as normal environment described above Additional Considerations - salt spray atmosphere, corrosive chloride systems potential for submersion, water spray.	Same as for PWR.

Identifying the nature and origins of the stressors that cause aging and degradation in large electric motors is necessary in order to analyze the causes of failures and to locate the sites within the machine that are vulnerable to each stressor. This information enables designers and reliability engineers to improve and enhance motor design, and helps operating and maintenance personnel to tailor their activates to improve motor performance in operation. The failure modes and effects analysis (FEMA), discussed in the next section, is a systematic method for using this information to analyze large motor degradation and aging, and improve reliability through focused maintenance activities.

3.2 Failure Modes and Effects Analysis

In order to understand the relationships of the various stressors to large motor operational performance, a failure modes and effects analysis (FMEA) was performed. The FMEA provides a systematic procedure for determining how each component of a device or system can fail, the mechanisms that cause it to fail, and how it can affect the overall performance of the device or system. The means for detection of the identified failure mechanisms are established along with methods for mitigating the effects of the failure mechanisms. The criticality of individual component failures can then be determined in order to prioritize inspection, surveillance, maintenance and mitigation activities and to allocate maintenance resources. FMEAs can also indicate the usefulness of design improvements or modifications.

For this study, a generic FMEA was performed for a large squirrel cage induction motor since, as indicated in Figure 2.1, this type of machine is used in the vast majority of large motor applications in nuclear plants. Each major component of the motor was individually analyzed to determine their failure modes including the failure mechanisms and causes, and indications or methods of detecting the failures. The effects of each failure on the motor were determined and then classified by severity level. Finally, techniques or activities are identified that could be used to mitigate the effects of the failure mechanisms.

The large squirrel cage induction motor was broken down into five major component groups or categories:

1. the **stator assembly** including the windings, laminated core, stator leads and coil cross-ties, and stator surge ring, blocks, spacers, and winding end supports

2. the **rotor assembly** including rotor core, squirrel cage assembly, shaft assembly, air cooling slots and spacers, and vanes

3. the **bearings** including bearings, seals, and lubricating oil system

4. the **motor frame, enclosure and mounting** including bearing supports, terminal box and connections, and ground connections

5. integral **monitoring sensors and heaters** including stator winding and bearing RTDs, vibration monitoring, lube oil system monitoring instrumentation, and the motor space heaters

The important subcomponents in each of the above five categories were then analyzed using the FMEA approach described. The results of the generic FMEA for the large squirrel cage induction motor are documented in Table 3.3.

The first two columns of Table 3.3 identify the component group number, or category, and name. This is followed in the next column by a brief functional description of the component and how it fits into the design of the machine. The fourth and fifth columns list the main failure modes of the component and the failure mechanisms that can contribute to the occurrence of that failure mode.

The sixth column in the table indicates the possible effects that can result from each failure mode. The effects of some failures, such as the failure of one (of usually six) stator winding RTD channel (failure mode 5.1.1), can be minor, very localized, and rather uneventful. Others, may exacerbate aging and degradation stressors, such as heat and vibration. The most severe events are those that result in a motor trip, i.e., the loss of function of the motor, or even worse, also result in damage to expensive motor stator and rotor assemblies. These events would require major repair and rework by outside motor repair shops, and a substitute motor must be installed to return the system to service.

Methods or activities that can potentially detect the failure mechanisms that lead to each failure mode are identified in the next column. These are followed by a list of activities that can be used to mitigate or monitor the effects of the failure mechanisms.

Finally, the severity of each failure mode is evaluated, as judged by the effects of the failure. The severity is coded, in the convention of the Nuclear Plant Reliability Data System (NPRDS) severity level classifications (Ref. 18), with respect to the effect that the failure has on the function of the motor, as follows:

J - Immediate loss of motor function
K - Degraded motor performance
L - Incipient problems that can be repaired easily, but would become more severe if left unchecked

The likelihood of the occurrence of each failure mode can be determined from an analysis of the operating experience that the nuclear industry has had with large electric motors. The next section of the report examines large motor operating performance data and analyzes the failures of these machines.

Table 3.3 Large Squirrel Cage Induction Motor Failure Modes and Effects Analysis

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISMS	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
1.1	Stator Winding	Produces a sinusoidally distributed, rotating magnetic field in the stator when 3-phase ac voltage is applied to the 3-phase stator winding.	1.1.1 Winding-to-ground fault	• Thermal degradation of insulation due to high ambient temperature, restricted ventilation, under- or over-voltages, low frequency, mechanical overload, voltage imbalance, single-phasing, too-frequent starting, high process fluid temp, dust or dirt accumulation • Mechanical degradation of insulation due to vibration and rubbing • Breakdown of insulation due to electrical transients and surges • Degradation of insulation due to moisture, lubricant, chemical reactions, or dirt • Manufacturing defect in insulation • Mechanical damage from loose part or ingested part	1.1.1a Electrical trip 1.1.1b Damage to stator windings requiring motor repair/rewind	• Comparative surge test • IR/PI • MCA • Internal visual inspection • AC hipot test • Insulation power factor test • Partial discharge test	• Good maintenance practices to keep motor clean and ventilation clear and unrestricted. • Use surge capacitors. • Good operating practices to reduce number of starts. • Monitor and trend vibration. • Monitor and trend ambient temp, winding temp, motor amps, rpm, process fluid temp, cooling water temp. • Monitor and trend insulation condition parameters • Improve quality of station electric power. • Consider upgrading to higher insulation class on next rewind.	J
			1.1.2 Winding-to-winding fault	• Same as above for failure mode 1.1.1.	1.1.2 Same as above for failure mode 1.1.1			J
			1.1.3 Turn-to-turn fault	• Same as above for failure mode 1.1.1.	1.1.3 Same as above for failure mode 1.1.1			J
			1.1.4 Open winding	• Breakdown of insulation and melting of conductor due to electrical transients and surges	1.1.4 Same as above for failure mode 1.1.1			K

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
1.1	Stator Winding (Continued)	Produces a sinusoidally dributed, rotating magnetic field when 3-phase ac voltage is applied to the 3-phase stator winding.	1.1.4 Open winding coil (Continued)	• Broken winding conductor due to vibration, electromagnetic transients, and/or cyclic fatigue.	1.1.4 Same as above for failure mode 1.1.1.	1.1.4 Same as above for failure mode 1.1.1.	1.1.4 Same as above for failure mode 1.1.1.	K
1.2	Stator Leads and Coil Cross-ties	Connect motor line terminations to individual stator winding coils	1.2.1 Phase-to-ground fault	• Same as above for failure mode 1.1.1.	1.2.1 Same as above for failure mode 1.1.1	• Comparative surge test	• Good maintenance practices to keep motor ventilation clean and unrestricted.	J
			1.2.2 Phase-to-phase fault	• Same as above for failure mode 1.1.1.	1.2.2 Same as above for failure mode 1.1.1	• IR/PI • MCA		J
			1.2.3 Open circuit	• Breakdown of insulation and melting of conductors due to electrical transients and surges • Broken conductor due to vibration, electromagnetic transients, and/or cyclic fatigue. • Mechanical damage from loose part or ingested part • Mechanical damage from contact with rotating parts	1.2.3 Same as above for failure mode 1.1.1	• Internal visual or borescope inspection •Infrared thermography •AC hipot test	• Periodic internal or borescope inspection. • Use surge capacitors. • Good operating practices to reduce number of starts. • Monitor and trend vibration.	J
			1.2.4 Loose leads or coil cross-ties	• Loosening of leads, coil cross-ties, and fasteners due to vibration, electromagnetic transients, and/or cyclic fatigue. • Mechanical damage from loose part or ingested part	1.2.4a Degradation and damage to insulation and conductors; may lead to failure modes 1.2.1, 2, or 3. 1.2.4b Same as above for failure mode 1.1.1.		• Monitor and trend ambient temp, winding temp, motor amps, rpm, process fluid temp, cooling water temp. • Improve quality of station electric power.	K

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
1.3	Stator Core	Insulated, magnetic iron alloy laminations, bound together by locking bars to form stator core; magnetic flux path for stator	1.3.1 Loose laminations and locking bars in stator core assembly	• Loosening of stator core assembly due to vibration • Loosening of stator core assembly due to electro-magnetic transients • Misalignment of core assembly during manufacture	1.3.1a Increased losses (heat) due to larger leakage flux 1.3.1b Increased motor current	• Visual or borescope inspection • Infrared thermography	• Periodic visual or borescope inspection • Periodic infrared thermography surveys and trending • Monitor and trend vibration • Monitor and trend motor amps, rpm, winding temp	L
			1.3.2 Lamination overheating	• Thermal degradation and wear of lamination insulation	1.3.2a Increased losses (heat) due to excessive current in iron core 1.3.2b Increased motor current	• Same as above for failure mode 1.3.1	• Same as above for failure mode 1.3.1	L
1.4	Stator Surge Ring, Blocks, Spacers, and Supports	Provide mechanical support and restraint for stator winding ends against continuously varying magnetic flux and electromagnetic transients	1.4.1 Loose surge ring, blocks, spacers, and supports	• Loosening of surge ring assembly due to vibration • Loosening of surge ring assembly due to electro-magnetic transients	• Breakdown of end winding insulation due to vibration and rubbing	• Same as above for failure mode 1.3.1	• Same as above for failure mode 1.3.1	L
			1.4.2 Broken surge ring and supports	• Breakage of surge ring assembly due to vibration • Breakage of surge ring assembly due to electro-magnetic transients	• Same as above for failure mode 1.4.1	• Same as above for failure mode 1.3.1	• Same as above for failure mode 1.3.1	L

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
2.1	Rotor Squirrel Cage Assembly	Rotating magnetic field produced by 3-phase voltage applied to stator winding induces currents in the squirrel cage rotor circuit that develop the same number of rotor poles as there are stator poles. Torque is produced in the direction of the rotating stator flux as the rotor poles react to it.	2.1.1 Rotor bars cracked at end ring	• Fatigue due to vibration and mechanical cycling • Fatigue due to electro-magnetic cycling and transients • Defective welds or brazed joints	2.1.1a Increased rotor cage resistance and heating 2.1.1b Increased vibration and wear of core laminations insulation 2.1.1c Crack adjacent bars due to increased flexure	• Visual or borescope inspection • Vibration monitoring • MCSA • Infrared thermography	• Periodic visual or borescope inspection • Periodic infrared thermography surveys and trending • Monitor and trend vibration • Monitor and trend motor amps, rpm, winding temp	K
			2.1.2 Rotor bars loose in core slots	• Loosening due to vibration and mechanical cycling • Loosening due to electro-magnetic cycling and transients • Loosening due to thermal cycling and excessive starting • Defective swaging during manufacture	2.1.2 Increased vibration and wear of core laminations insulation		• Same as above for failure mode 2.1.1	L
			2.1.3 Broken rotor bar	• Same as above for failure mode 2.1.1	2.1.3 Same as above for failure mode 2.1.1		• Same as above for failure mode 2.1.1	J
			2.1.4 Displaced rotor bar	• Same as above for failure mode 2.1.1	2.1.4a Contact stator damaging stator windings, stator core, rotor assembly, and bearings 2.1.4b Electrical trip		• Same as above for failure mode 2.1.1	J

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
2.2	Rotor Core	Insulated, magnetic iron alloy laminations, bound together by locking bars to form stator core; magnetic flux path for rotor	2.2.1 Loose laminations and locking bars in rotor core assembly	• Loosening of rotor core assembly due to vibration • Loosening of rotor core assembly due to electro-magnetic transients • Misalignment of core assembly during manufacture	2.2.1a Increased losses (heat) due to larger leakage flux 2.2.1b Increased vibration 2.2.1c Increased motor current	• Visual or borescope inspection • Vibration monitoring • Infrared thermography • Growler test	• Periodic visual or borescope inspection • Periodic infrared thermography surveys and trending • Monitor and trend vibration • Monitor and trend motor amps, rpm, winding temp	K
			2.2.2 Lamination overheating	• Thermal degradation and wear of lamination insulation	2.2.2a Increased losses (heat) due to excessive current in iron core 2.2.2b Increased motor current	• Same as above for failure mode 2.2.1	• Same as above for failure mode 2.2.1	L
2.3	Shaft Assembly	Carries rotating elements of motor including rotor assembly, balancing weights, and flywheels, and transmits the torque generated by the motor to the driven load via a coupling	2.3.1 Misaligned	• Installation or manufacturing error • Mechanical transient such as seized pump, bearing, displaced rotor bar • Vibration • Bowing of horizontal motor shaft	2.3.1a Increased vibration 2.3.1b Increased wear and damage to bearings	• Visual inspection and alignment check • Vibration monitoring • Bearing temperature monitoring	• Periodic visual inspection • Monitor and trend vibration • Monitor and trend bearing temperature	J
			2.3.2 Cracked shaft	• Material defect • Corrosion • Fatigue • Vibration	2.3.2a Increased vibration 2.3.2b Potential shaft failure	• Visual inspection • Vibration monitoring • NDE techniques	• Periodic visual inspection • Monitor and trend vibration	K

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
2.3	Shaft Assembly (Continued)	Carries rotating elements of motor including rotor assembly, balancing weights, and flywheels, and transmits the torque generated by the motor to the driven load via a coupling	2.3.3 Broken shaft, coupling, alignment keys	• Crack propagation due to vibration and mechanical cycling • Mechanical transient such as seized pump, bearing, displaced rotor bar • Corrosion	2.3.3a Motor trip 2.3.3b Mechanical seizure of motor 2.3.3c Damage to rotor assy, stator assy, bearings	• Same as above for failure mode 2.3.1	• Same as above for failure mode 2.3.1	J
			2.3.4 Vibrating	• Coupling failure or misalignment • Bearing failure • Unbalance resulting from failure or other change in mass of rotating assembly: flywheel, balance weights, rotor cage, driven load	2.3.4a Motor trip 2.3.3b Excessive bearing wear or failure 2.3.3c Damage to rotor assy and stator assy	• Same as above for failure mode 2.3.1	• Same as above for failure mode 2.3.1	K
3.1	Antifriction Bearings	Support and provide for movement of rotating elements of the motor	3.1.1 Wear of bearing rollers and race	• Insufficient or excessive lubrication • Dirt, moisture, or other contamination in lubricant • Wrong lubricant • Lube oil cooling insufficient; high bearing temperature • Unbalanced or misaligned rotating elements • Transverse mechanical loading	3.1.1a Excessive vibration 3.1.1b Thermal breakdown or burning of lubricant 3.1.1c Reduced bearing life	• Bearing temperature monitoring • Vibration monitoring • Bearing inspection • Lube oil level, temperature, filtration monitoring • Lube oil sampling and analysis	• Periodic inspection and cleaning of bearings • Periodic inspection and maintenance of lube oil system, including oil sample analysis • Monitor and trend vibration • Monitor and trend bearing temperature • Good maintenance practices, procedures, and training for bearings and lube oil system	L

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
3.1	Antifriction Bearings (Continued)	Support and provide for movement of rotating elements of the motor	3.1.1 Wear of bearing rollers and race (Continued)	• Material degradation due to corrosion • Material degradation due to circulating currents				
			3.1.2 Failure of rollers, roller cage, or race; bearing seizure	• Same as above for failure mode 3.1.1	3.1.2a Excessive vibration 3.1.2.b Contact and mechanical damage to rotor and stator assemblies 3.1.2c Motor trip	• Same as above for failure mode 3.1.1	• Same as above for failure mode 3.1.1	J
3.2	Sleeve and Kingsbury Type Thrust Bearings	Support and provide for movement of rotating elements of the motor	3.2.1 Degraded and worn bearing surfaces	• Same as above for failure mode 3.1.1	3.2.1 Same as above for failure mode 3.1.1	• Same as above for failure mode 3.1.1	• Same as above for failure mode 3.1.1	L
			3.2.2 Bearing wiped	• Same as above for failure mode 3.1.1	3.2.2 Same as above for failure mode 3.1.1	• Same as above for failure mode 3.1.1	• Same as above for failure mode 3.1.1	J
3.3	Bearing Seals	Maintain lube oil or grease within bearing housing and prevent entry of dirt, moisture, and other contaminants	3.3.1 Degradation and deformation of seals	• Wrong lubricant • Lube oil cooling insufficient; high bearing temperature • Unbalanced or misaligned rotating elements • Normal aging • Installation error • Materials defect • Insufficient or excessive lubrication	3.3.1a Loss of lubricant 3.3.1b Increased bearing temperature 3.3.1c Entry of dirt, dust, moisture, or other contaminants into lubricant and bearings	• Bearings and seals inspection • Bearing temperature monitoring	• Periodic inspection of bearings and seals • Periodic replacement of bearing seals	K

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
3.3	Bearing Seals (Continued)	Maintain lube oil or grease within bearing housing and prevent entry of dirt, moisture, and other contaminants	3.3.2 Seals worn	• Same as above for failure mode 3.3.1 • Excessive seals wear due to worn bearings	3.3.2a Loss of lubricant 3.3.2b Increased bearing temperature 3.3.2c Entry of dirt, dust, moisture, or other contaminants into lubricant and bearings	• Same as above for failure mode 3.3.1	• Same as above for failure mode 3.3.1	K
3.4	Bearing Lube Oil System (Forced Oil or Circulating Oil Types)	Provide pumped supply of lubricating oil to motor bearings and transfer heat from bearings via CCW cooled heat exchanger	3.4.1 Insufficient oil supply to bearings	• Low oil pressure due to main oil pump or auxiliary oil problem • Low oil pressure due to clogged or dirty oil filter • Low oil pressure due to dirty or contaminated oil • Low oil level in reservoir • Lube oil leak	3.4.1a High bearing temperature 3.4.1b Thermal degradation and burning of lube oil 3.4.1c Increased bearing wear 3.4.1d Increased wear and degradation of seals	• Bearing temperature monitoring • Periodic check of lube oil system parameters: visual inspection, level, temperature, flow, filter delta-P	• Monitor and trend bearing temperature • Monitor and trend bearing vibration • Periodic maintenance of lube oil system including visual inspection, lube oil sampling and analysis, oil change, and oil filter change	K
			3.4.2 Insufficient cooling of lube oil	• Insufficient component cooling water supply pressure • High CCW inlet temp to lube oil heat exchanger • CCW leaking • Blocked or restricted CCW lines	3.4.2 Same as above for failure mode 3.4.1	• Bearing temperature monitoring • Periodic check of CCW supply to lube oil heat exchanger	• Monitor trend bearing temperature • Monitor trend bearing vibration • Periodic maintenance of CCW supply to motor including visual inspection, flow rate and functional check, heat exchanger inspection, clean/change screens or filters	K

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
4.1	Motor Frame, Enclosure, and Mounting	House stator assembly, support bearings and rotor assembly, protect against water entry, protect against ingestion of large objects, provide pathway for cooling air to pass through motor	4.1.1 Loose motor mount	• Loosening of fasteners due to vibration • Improper torquing of fasteners during installation • Materials defect	4.1.1a Increased vibration 4.1.1b Increased bearing wear 4.1.1c Misalignment and/or damage to motor internals, shaft, coupling, driven load	• Visual inspection • Vibration monitoring	• Periodic visual inspection • Monitor and trend vibration • Good maintenance, modification, and installation practices, procedures, and training	K
			4.1.2 Broken motor mount	• Cyclic fatigue of mount or fasteners due to vibration or mechanical overloads • Improper torquing of fasteners during installation • Materials defect	4.1.2 Same as above for failure mode 4.1.1	• Same as above for failure mode 4.1.1	• Same as above for failure mode 4.1.1	J
			4.1.3 Obstructed or restricted airflow through motor	• Dirty guard screens or air filters • Poor application/location design • Bad housekeeping practices allows object(s) to block airflow or excessive dirt and dust accumulating in area	4.1.3a Increased operating temperature 4.1.3b Accelerated thermal degradation of temperature sensitive components	• Visual inspection • Monitor winding temperature • Monitor bearing temperature	• Periodic visual inspection • Monitor and trend stator winding temperature • Monitor and trend bearing temperature • Good maintenance and housekeeping practices, procedures, and training	L
			4.1.4 Foreign object, dirt, contaminants, rodent, insect ingested through ventilation opening	• Missing or broken guard screen or filter	4.1.4a Contamination of motor internals 4.1.4b Damage to motor internals 4.1.4c Electrical faults	• Visual inspection	• Periodic visual inspection • Good maintenance and housekeeping practices, procedures, and training	L

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
4.2	Terminal Box and Connections	House, enclose, and protect (from moisture, dirt, and contamination) the high voltage connections to the motor from the power feeder circuit	4.2.1 Connection loose	• Vibration	4.2.1a Electrical fault 4.2.1b Motor trip	• Visual inspection • Polarization index check • MCA	• Periodic visual inspection • Periodic preventive maintenance electrical testing	K
			4.2.2 Corroded connections	• Corrosion due to condensation, moisture or water intrusion	4.2.2 Same as above for failure mode 4.2.1	• Same as above for failure mode 4.2.1	• Same as above for failure mode 4.2.1	K
			4.2.3 Electrical fault	• Electrical transient or overload • Dirty, wet, or contaminated connections • Defective connection	4.2.2 Same as above for failure mode 4.2.1	• Same as above for failure mode 4.2.1	• Same as above for failure mode 4.2.1	J
			4.2.4 Terminations box cover loose	• Vibration • Gaskets worn or deteriorated • Installation error	4.2.2 Same as above for failure mode 4.2.1	• Visual inspection	• Periodic visual inspection	L
4.3	Ground Connections	Provide solid ground for motor for safety and protective relaying sensitivity	4.3.1 Connection loose or broken	• Vibration	4.3.1a Personnel safety hazard 4.3.1b Decreased protective relaying sensitivity	• Visual inspection	• Periodic visual inspection	L
			4.3.2 Corroded connection	• Corrosion due to condensation, moisture or water intrusion	4.3.2 Same as above for failure mode 4.3.1	• Visual inspection	• Periodic visual inspection	L

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
5.1	Stator Winding RTDs	Provide indication of stator winding temperature	5.1.1 Faulty indication or no output	• Broken or grounded wire due to vibration • Loose connections due to vibration and/or thermal cycling	5.1.1 Loss of redundant winding temperature indication	• Loss of, or faulty, temperature indication channel	• Periodic channel calibration and functional tests • Repair or replace faulty RTD circuits	L
5.2	Bearing RTDs	Provide indication of bearing temperature	5.2.1 Faulty indication or no output	• Broken or grounded wire due to vibration • Loose connections due to vibration and/or thermal cycling	5.2.1 Loss of bearing temperature indication channel	• Loss of, or faulty, temperature indication channel	• Periodic channel calibration and functional tests • Repair or replace faulty RTD circuits	L
5.3	Bearing Vibration Monitors	Provide indication of motor operating vibration	5.3.1 Faulty indication or no output	• Broken or grounded wire due to vibration • Loose connections due to vibration and/or thermal cycling	5.3.1 Loss of redundant winding temperature indication	• Loss of, or faulty, vibration monitoring channel	• Periodic channel calibration and functional tests • Repair or replace faulty vibration monitoring circuits and recorders	L
5.4	Lube Oil System Indication: sump level, temperature, flow, pressure, filter delta-P	Provide indication of lube oil system operating parameters	5.4.1 Faulty indication or no output	• Broken or grounded wire due to vibration • Loose connections due to vibration and/or thermal cycling	5.4.1 Loss of lube oil system indication or monitoring channel	• Loss of, or faulty, lube oil system indication or monitoring channel	• Periodic channel calibration and functional tests • Repair or replace faulty monitoring circuits, indicators, and recorders	L
5.5	Motor Space Heaters	Provides space heating in motor when shut down to prevent condensation, moisture, or humidity within the motor enclosure	5.5.1 No output	• Loose or broken wire; loose connection • Faulty thermostat	5.5.1 Moisture and condensation inside motor	• Space heater status indication	• Periodic heater and thermostat calibration and functional tests • Repair or replace faulty components	K
			5.5.2 Faulty operation	• Same as above for failure mode 5.5.1	5.5.2 Same as above for failure mode 5.5.1	• Space heater status indication	• Same as above for failure mode 5.5.1	L
			5.5.3 Electrical fault	• Faulty insulation	5.5.3 Same as above for failure mode 5.5.1	• Space heater status indication • Blown fuse	• Same as above for failure mode 5.5.1	K

Table 3.3 (Cont'd)

CMP No.	COMPONENT NAME	COMPONENT FUNCTION	FAILURE MODE	FAILURE MECHANISM	FAILURE EFFECTS	DETECTION METHODS	MITIGATING ACTIVITIES	SEV LVL
5.5	Motor Space Heaters (Continued)	Provides space heating in motor when shut down to prevent condensation, moisture, or humidity within the motor enclosure	5.5.4 Loose or displaced heaters	• Loosening or broken supports due to vibration • Improper installation	5.5.4a Same as above for failure mode 5.5.1 5.5.4b Contact and mechanical damage to rotor and stator assemblies	• Space heater status indication	• Periodic heater and thermostat calibration and functional tests • Repair or replace faulty components	J

Notes:
1. CMP No. - Motor component number
2. SEV LVL - Severity level of failure: J = immediate or catastrophic
K = degraded
L = incipient

4. OPERATIONAL EXPERIENCE REVIEW

The sources of data for this review are the Nuclear Plant Reliability Data System (NPRDS) and the Licensee Event Report (LER) database. Searches of the NPRDS for large motor failures yielded 690 failure events during the eight year period from 1985 to 1992.

The search of the LER database using the Sequence Code Search System (SCSS), which provides summaries for each LER, could not be so precisely bounded as the NPRDS search since there is no criterion for motor size. Consequently, the LER database had to be searched for motor failures and for specified individual systems based on the systems found to have large motors during the design review (Section 2.4). This yielded 1228 LERs during the thirteen year period 1980 to 1992 that were individually reviewed for large motor failures. The review of these LERs showed that 642 of them involved failures of large electric motors, their direct support equipment, or associated equipment, such as their driven loads.

The large motor failures in the NPRDS database search that were identified by the NPRDS as LER events were compared with the large motor failures obtained in the SCSS search of the LER database to determine the extent of overlap that existed between these two searches. For the period 1980 to 1992, 26 of the NPRDS large motor failures that involved LERs also showed up on the LER database search performed by BNL. Of these, 19 were judged to be aging-related failures of large motors, large motor support equipment, and large motor associated equipment. This indicated that there was only minor overlap in the data obtained via these two search approaches. Therefore, it was decided that the data from the NPRDS and the LER databases would be analyzed separately, in Sections 4.1 and 4.2, respectively, and comparisons would be made as part of the analysis. The differences between these sources of data, their limitations, and comparisons of the results of the analyses are discussed in these sections of the report.

In addition, the Large Motor Reliability Survey of Industrial and Commercial Installations (Refs. 9, 10, 11) performed by the Power Systems Reliability Committee of the IEEE Industry Applications Society was used for comparison of the nuclear industry's large motor operating experience with a general database of large motor operating experience.

The operating experience revie[illegible]d to characterize the failures of large electric motors. The major failure modes, causes, and mechanisms for large motors in nuclear plant service were identified and compared. In addition, the effect of the failure of a large motor on nuclear plant systems was examined, along with the overall effect on the plant.

4.1 NPRDS Review

The NPRDS data was drawn from a search for large motor failures during the period from 1985 to 1992. Since NPRDS reporting was not comprehensive prior to 1984, 1985 was chosen as the start date for the search; the 1992 end date was selected to assure that all the applicable failures would have been reported to NPRDS for the last full year of data at the time the search was performed. The 690 large motor failures reported to NPRDS during this period were based upon operating data from 24 General Electric BWR plants, 34 Westinghouse PWRs, 12 Combustion Engineering PWRs, and 8 Babcock and Wilcox PWRs. Among these are 9 plants which began service after 1985 and thus contribute early failure data to the study population.

Quantification of age-dependent failure rates, as would be required for these aging data to be used in PRAs (Ref. 48), was considered to be beyond the scope of this study. Trends and other aging insights were established based upon information reported by the licensees.

The total of 690 failures included 185 failures reported from the 24 BWR plants and 505 failures from the 54 PWR plants. The first items of interest were the systems in which the large motor failures occurred. Table 4.1 summarizes the systems of origin for large motor failures reported at BWRs during the studied period. The main contributors among the Class 1E systems are essential service water and residual heat removal/low pressure coolant injection (RHR/LPCI) pump motors. All of the pump motors in the BWR Class 1E systems, with the exception of essential service water, are located in the reactor building secondary containment, a mild nuclear environment outside containment (see Section 2.5.2). The essential service water pumps are situated in the plant intake structure, which is also considered a mild service environment (see Section 2.5.1). The reactor recirculation systems (recirc pump motors) are the second highest contributing system at BWRs. The reactor recirc pump motors are located inside primary containment, a harsh nuclear service environment (see Section 5.2.3), and are considered non-Class 1E motors. Note that the two balance of plant (BOP) systems, particularly the condensate system, contributed a large portion of the total large motor failures at BWRs reported to NPRDS. The large motors for these systems are normally found in the turbine building at a BWR.

A similar analysis of the large motor failures reported at PWRs, grouped by system, is presented in Table 4.2. Nuclear service water, auxiliary feedwater, and high pressure safety injection system reported the most large motor failures among the Class 1E systems. All of these pump motors, with the exception of nuclear service water, are located in the auxiliary building or engineered safety features building at PWR plants, which are considered mild nuclear service environments. As in the BWRs, the nuclear service water pumps and drive motors are found in the intake structure of the plant. The reactor coolant

Table 4.1 Large Motor Failures at BWR Plants - NPRDS 1985-92

SYSTEM		NPRDS Sys Code	ALL BWRs	
			Qty	Pct
1E	Essential Service Water	WAA	34	18.4%
	RHR/LPCI	CFA	31	16.7%
	Low Pressure Core Spray (LPCS)	SFA	10	5.4%
	High Pressure Core Spray (HPCS)	SFB	3	1.6%
	Rx Bldg Component Cooling Water (CCW)	WBA	2	1.1%
Non 1E	Rx Recirculation	CBA	42	22.7%
BOP	Condensate	HHD	49	26.5%
	Feedwater	CHA	14	7.6%
TOTAL			185	

Table 4.2 Large Motor Failures at PWR Plants - NPRDS 1985-92

SYSTEM		Westinghouse		CE		B & W		ALL PWRs	
		Qty	Pct	Qty	Pct	Qty	Pct	Qty	Pct
1E	Aux/Emerg Feedwater	8	2.2%	10	11.7%	0	0%	18	3.5%
	CCW	6	1.7%	1	1.2%	0	0%	7	1.4%
	CVCS	15	4.2%	0	0%	0	0%	15	3.0%
	Containment Spray	9	2.5%	0	0%	0	0%	9	1.8%
	HPSI	13	3.6%	1	1.2%	3	4.8%	17	3.3%
	LPSI/RHR	1	0.3%	1	1.2%	0	0%	2	0.4%
	Nuclear Service Water	56	15.7%	6	7.0%	3	4.8%	65	12.9%
Non 1E	RCS	80	22.4%	39	45.9%	36	57.1%	155	30.7%
BOP	Condensate	118	33.1%	22	25.9%	21	33.3%	161	31.9%
	Feedwater	51	14.3%	5	5.9%	0	0%	56	11.1%
TOTALS		357		85		63		505	
% of TOTAL PWRs		70.7%		16.8%		12.5%			

pumps (RCP) are the second highest contributor at PWRs, just as was seen for the reactor recirculation system at BWRs. The RCPs and their drive motors are inside the reactor building at a PWR, which is considered a harsh nuclear environment.

Similar to what was noted in Table 4.1 at the BWR plants, the BOP systems were major contributors of large motor failures at PWRs. The condensate systems at both PWRs and BWRs were the sources of the most large motor failure reports during the period studied.

To obtain a good representation of large motor performance in Class 1E and non-Class 1E systems that would also allow comparison of motors operating in PWRs with those in BWRs, the PWR reactor coolant pump (RCP) and residual heat removal (RHR) pump motors, and BWR reactor recirculation (Recirc) and RHR pump motors were selected for detailed analysis. Due to the importance of these systems, there was better assurance that the failures reported to NPRDS were more comprehensive, and that the population of the motors in the aforementioned plants, upon which these analyses are based, could be accurately determined. The similar locations and functions of these systems allowed a more direct and meaningful comparison of the large motor performance in PWRs and BWRs.

The NPRDS data for PWR Reactor Coolant Pump (RCP) and Residual Heat Removal (RHR) Pump motors, and BWR Reactor Recirculation (Recirc) and RHR pump motors, covering a total population of 302 large motors were analyzed. These motors, which included 126 manufactured by Westinghouse, 140 by General Electric, and 36 by Allis Chalmers, are vertically mounted, squirrel cage induction motors from 500 hp up to 1250 hp for the RHR motors, and up to 9000 hp for the RCP and Reactor Recirc Pump motors. As discussed previously in Section 2.5.3, the motors for the PWR RCP and the BWR reactor recirc pump operate continuously in harsh nuclear environments inside the reactor containment structure and primary containment, respectively, with ambient temperatures up to 135°F, high radiation, and humidity. Most BWR primary containments maintain nitrogen inerted atmospheres during operation. The RHR pump motors are Class 1E equipment that operate in the PWR auxiliary building or the BWR reactor building. As described in Section 2.5.2, these are mild nuclear environments, but in the event of an accident, this equipment is required to function for specified intervals under the potentially extreme conditions of the post-accident environment. They have been designed and environmentally qualified to continue to operate under accident conditions occurring at the end of their qualified life.

4.1.1 Aging Assessment

A total of 220 failure events for RHR pump motors, BWR recirc pump motors, and PWR RCP motors were reported to the NPRDS from 1985 through 1992. Based on the definition of aging (see Section 8) as given in NUREG-1144 (Ref. 44), 90% of these events were attributed to normal aging, and the remainder were caused by human errors made during maintenance (7.7%) and operation (2.3%).

To understand the trend in failures of motors as they age, the data were sorted according to the age of the motor at failure. According to the respective plant contributions, this data was normalized by the total motor population contributing to the failures at a specific year. Since the time line history of any motor in this population is not available, the failure frequency (rather than the failure rate) versus the age at failure is developed, as shown in Figure 4.1. Since the dominant age-related failures of motors are attributed to mechanical and material aging mechanisms such as normal wear, corrosion, and the degradation of seals and insulation, the aging trend for this group follows closely the characteristic bathtub reliability curve, which presents the relationship of the frequency of component failure to component age. The rate at which the failure frequency increases in later life is fairly constant, most likely due to the extensive maintenance and testing surveillance that these motors receive.

4.1.2 Failure Analysis

The primary failure modes were examined to determine the status of the motors at the time of failure. More than half of the reported failures (54%) occurred while the motor was out of service during maintenance, standby, or testing, 31% during operation, and 15% were failures to start. These failures were classified as degraded (60%), immediate (29%) and incipient (11%). This indicates that, despite the extensive maintenance and surveillance that these motors typically receive, nearly half of the failures still occurred during starting or operation. This proportion of unnoticed motor failures may signify that plant preventive maintenance and monitoring activities are not focusing on identifying incipient failures before they lead to the more severe operating failures.

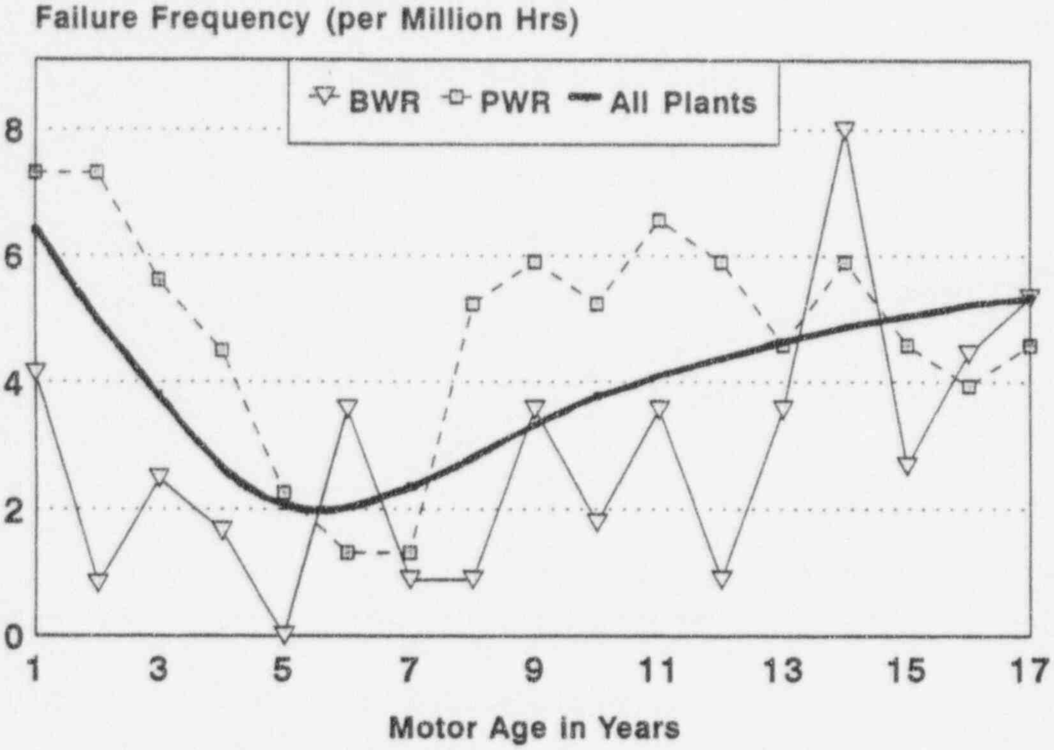


Figure 4.1 Failure frequency vs. age for RCP, reactor recirc, and RHR pump motors larger than 500 hp - NPRDS 1985-92

Each failure reported to NPRDS is classified by severity level: immediate, degraded or incipient (see Sections 3.2 and 8). Figure 4.2 is a plot of the severity level of the large motor failures reported to NPRDS from 1985 to 1992 for PWRs and BWRs. The quantities of failures for the period were normalized, by dividing by the population of large motors in PWRs or BWRs, to produce a failure fraction per motor. This then allowed a comparison of motor failures at PWRs with those at BWRs on a per-motor basis. Figure 4.2, a plot of the severity level of the reported failures, shows that a large number of failures resulted in either degraded operation or immediately ceasing the operation of the affected motors. This reinforces the trend that the existing plant activities are not focused on identifying incipient failures. To further understand this trend in relation to BWR and PWR applications, the total number of failures are normalized with respect to their motor populations and the resulting number is identified as "failure fraction" (see the abscissa). The failure fraction for PWR motors is one and half times that for BWR motors. Relatively speaking, the motor reliability programs in BWR plants appeared to be more effective than those in PWRs for the period covered by the data.

Failure fractions attributed to motor components are shown in Figure 4.3. In this class of large motors the greatest number of failures involved the bearings (including bearing lubrication), accounting for nearly half of the failures. This finding is basically consistent with the findings of the IEEE Industry Application Society (IAS) large motor survey (Refs. 9, 10, 11) for motors greater than 200 hp throughout all industries (44% bearing-related failures), and the Electric Power Research Institute (EPRI) survey (Ref. 19) of electric utility motors greater than 100 hp (41% bearing-related failures). This does,

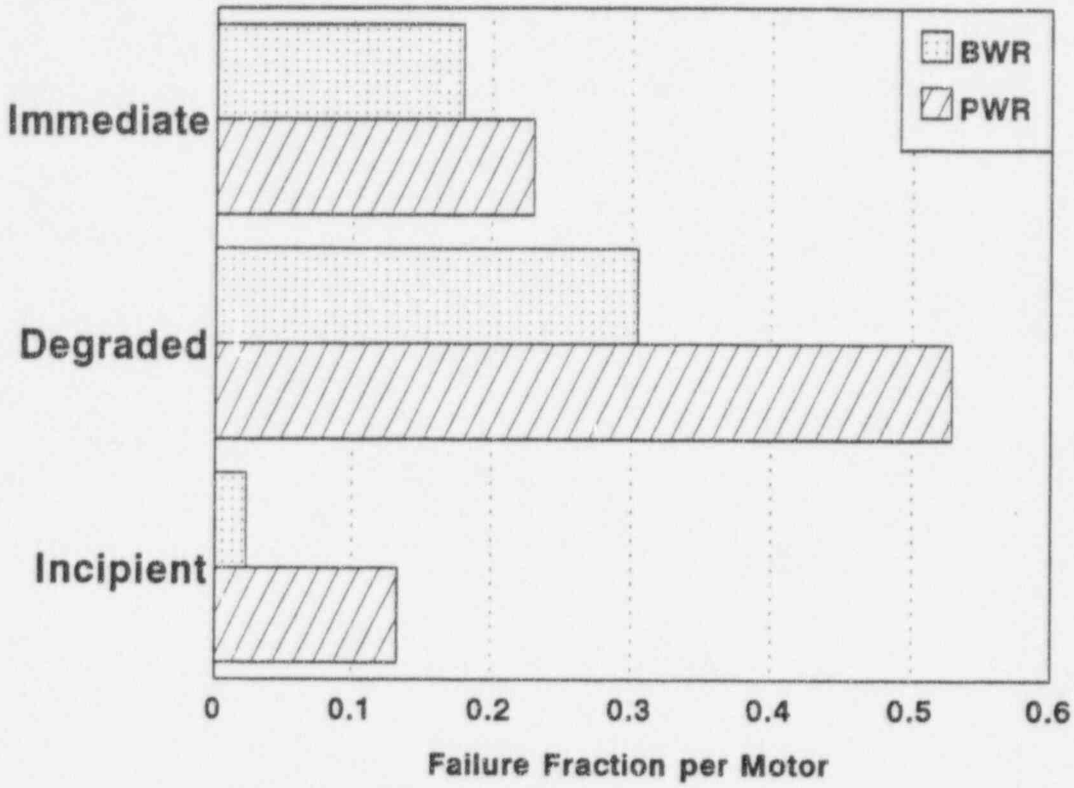


Figure 4.2 Failure severity level - NPRDS 1985-92

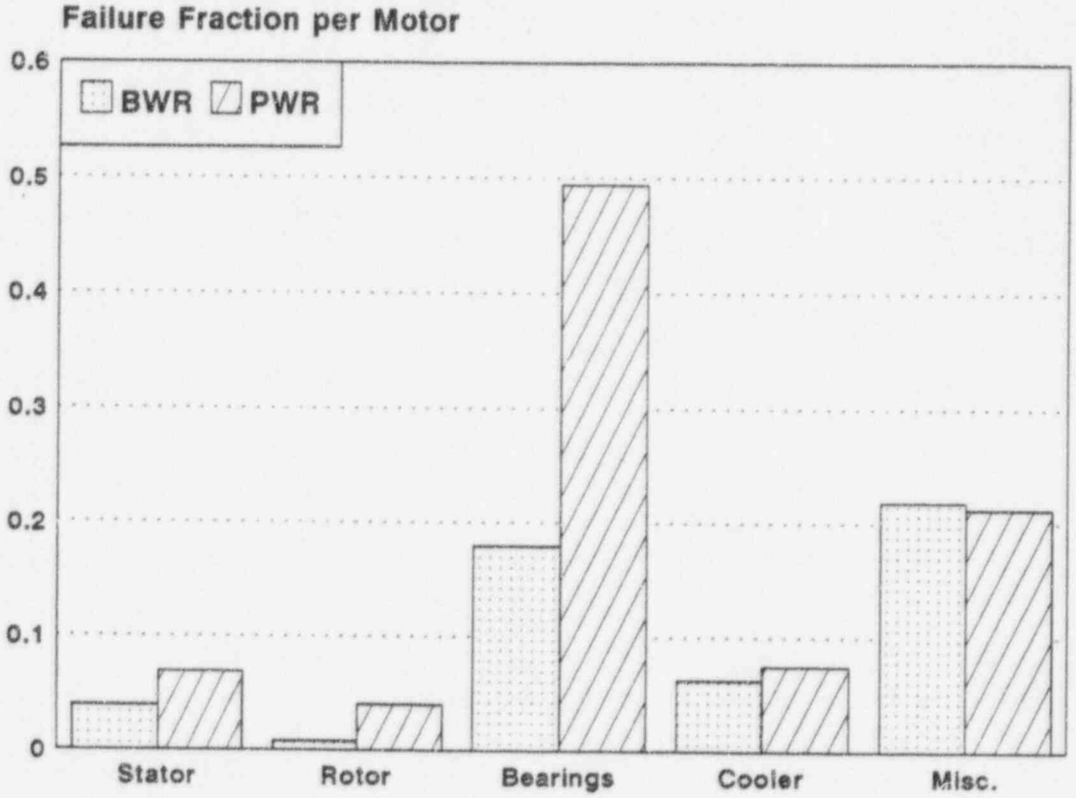


Figure 4.3 Large motor subcomponent failures - NPRDS 1985-92

however, contrast with findings in earlier aging studies for pump motors smaller than 100 hp (Ref. 5) in which stator insulation degradation was the primary subcomponent responsible for failures (37%), followed by bearing problems (25%).

Figure 4.3 shows that problems with respect to bearing failures are associated more with the large motors in PWRs than with BWR motors. The miscellaneous failures contain failures of support equipment for large motors as discussed in Section 1.2. Miscellaneous failures for BWRs and PWRs include electrical and I&C related problems. Also grouped under the miscellaneous category, a large number of motor-related failures at BWRs were caused by the failures of the reactor recirc system MG sets, which are considered support equipment for the BWR recirc pump motor (see discussion in Section 2.3).

Review of the large motor population data obtained from NPRDS showed that there are three major suppliers of large electric motors to the nuclear industry (designated as Suppliers A, B, and C, in this report). A special search of the NPRDS data base for large motors supplied by these manufacturers was made. For the eight-year period from 1/1/85 through 12/31/92, the average failure frequencies for large motors operating through this period, grouped by manufacturer, were calculated by the NPRDS algorithm (Ref. 20). The failure frequencies calculated are provided in Table 4.3. For the eight-year period indicated, the Supplier B motors enjoyed the best performance, followed closely by Supplier C motors. Supplier A motors had a higher average failure frequency than the other two major manufacturers. Since BWRs predominantly utilize Supplier B motors, this may partially explain the better performance shown by the BWR motors in Figures 4.1 through 4.3.

These three manufacturers are essentially the exclusive suppliers of PWR RCP motors, BWR recirc pump motors, and the Class 1E RHR motors. An analysis of the NPRDS data, grouped according to these three motor manufacturers, was made to examine if any inherent design problems might exist that had contributed to the larger fraction of PWR motor failures. Figure 4.4 illustrates the subcomponent failures for the three major suppliers of large motors. Motors manufactured by both Suppliers A and C have significantly higher failure fractions with respect to bearings than Supplier C motors. The causes for this trend are further examined by performing a more detailed breakout of the bearing related failures

Table 4.3 Average Failure Frequency for Large Motors Supplied by Major Large Motor Manufacturers, Eight Year Period 1/1/85 through 12/31/92 - NPRDS

Manufacturer	No. of Motors	No. of Failures	Calendar Hours (Millions of Hrs)	Failure Frequency (per Million Hrs)
Supplier A	338	154	19.4411	7.92
Supplier B	736	170	46.2519	3.68
Supplier C	696	250	41.2682	6.06
All Large Motors	1968	627	118.1836	5.31

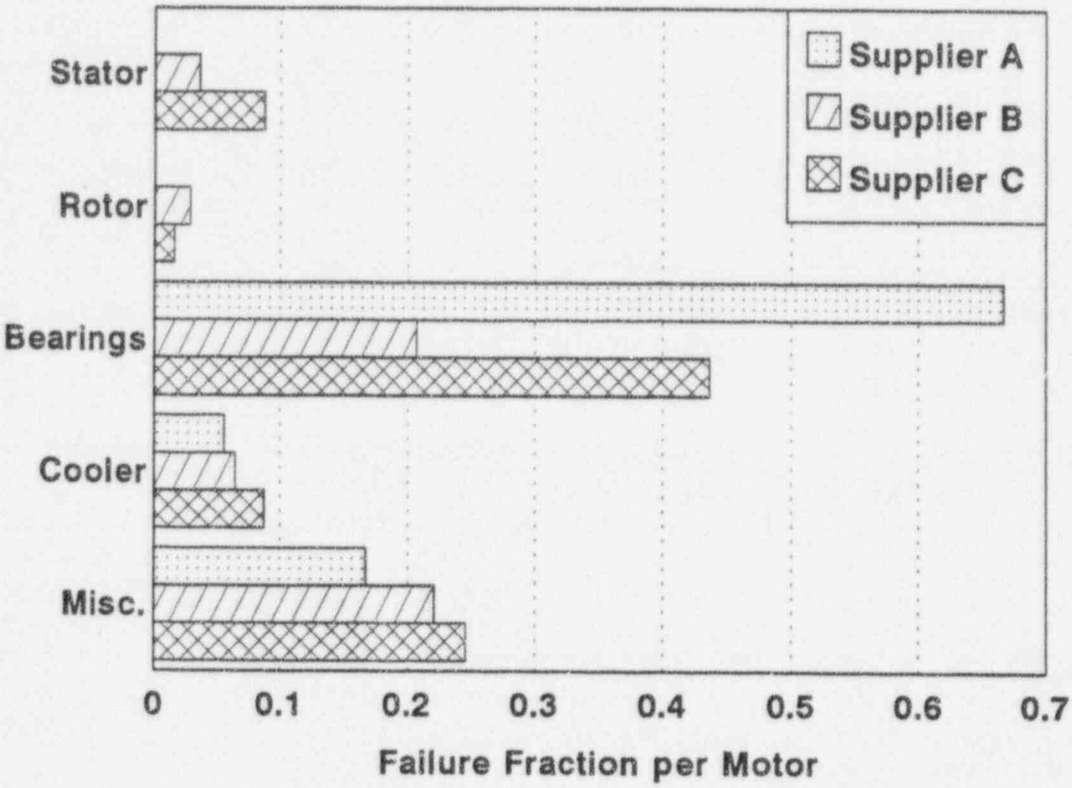


Figure 4.4 Failure fraction for large motor components grouped by manufacturer - NPRDS 1985-92

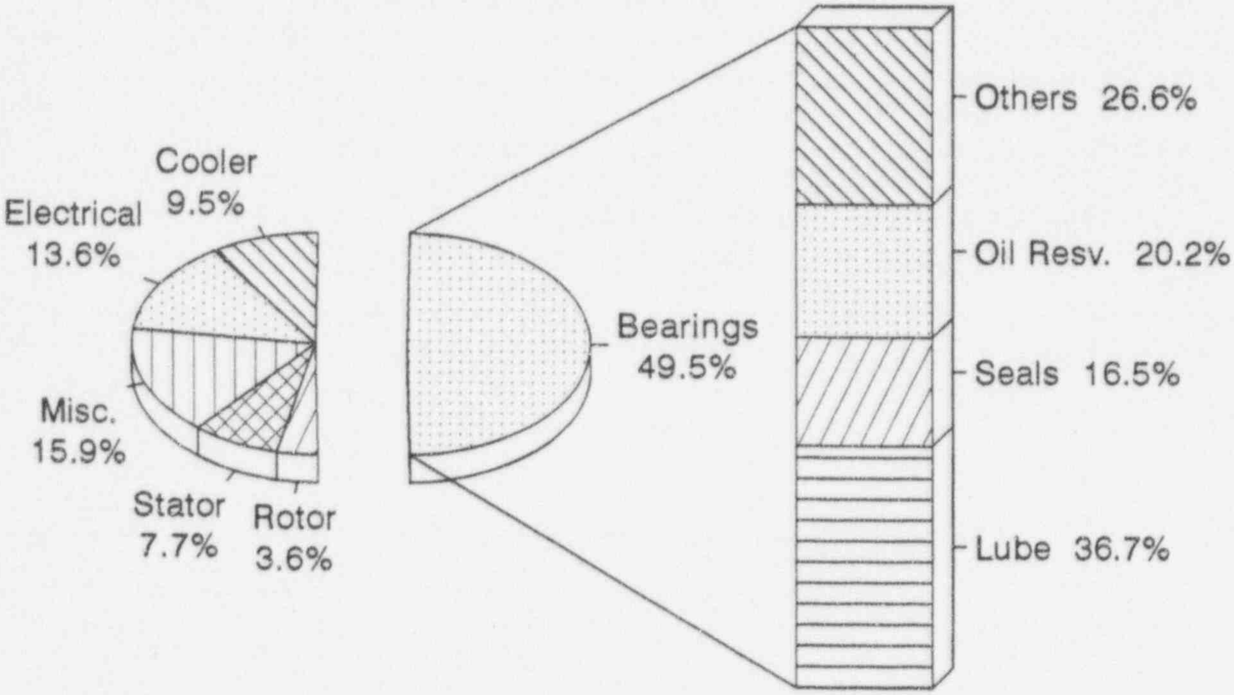


Figure 4.5 Major component failure contributions with breakout for bearing-related failures-NPRDS 1985-92

to identify the root causes of failures for these motors. Figure 4.5 shows the subparts of the bearing failures category that had contributed to this large percentage of bearing problems. Contaminated and/or inappropriate oil level in the bearing housing constituted 37% of the bearing failures. It is followed by problems associated with the oil reservoir (20%) which was dominated by leakage or oil pump malfunction. Normal aging and wear of oil seals, cracking of tubes, and blockage of oil flow made up another 16% of bearing problems.

Finally, another 27% of bearing failures were attributed to normal wear of the bearing element itself (balls, rollers, cage, raceways, etc.) and its guides/collars.

Under the miscellaneous failures category (15.9%), it is observed that almost half of these were support equipment failures, mainly associated with electrical problems. These electrical problems included failures of circuit breakers, heaters, surge capacitors, fuses, and other control equipment failures. Other failures in this category are associated with control/alarm devices which were found to be faulty after serving a long period of time.

Although the failure fractions for PWR and BWR motors are not similar for the bearing-related failures, the failure mechanism classifications, shown in Figure 4.6, for the motors operating in these plants are almost identical. This indicates that there is no significant difference in the mechanisms that cause large motors to fail in BWRs and PWRs, i.e., the aging degradation is similar. The differences in performance are then most likely attributable to maintenance, accessibility, and application factors. Focusing maintenance activities on the detection of the dominant age-related failure mechanisms, shown in Figure 4.6, and the motor components that are affected by these mechanisms, as indicated in the FMEA in Table 3.3, can help to improve the operating performance of large motors.

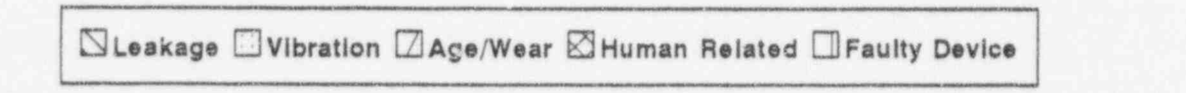


Figure 4.6 Failure mechanisms grouped by plant type - NPRDS 1985-92

Figure 4.6 shows that leakage and age/wear dominate the underlying failure processes. These failure mechanisms are reflected in the FMEA in Table 3.3 for the dominant failure component groups: Group 3, bearings/lube oil systems and Group 1, stator. As indicated in the FMEA, leakage of lubricant can cause increased bearing wear and higher operating temperatures, which can then contribute to degradation of stator and rotor insulation by contamination and higher operating temperature. Leakage in the lube oil system leads to low reservoir oil level, insufficient oil pressure, insufficient flow, or high lube oil temperature; as seen in Component Group 3.4 in the FMEA, these all are contributors to increased bearing wear and high operating temperatures. In addition, the third leading failure mechanism in Figure 4.6, vibration, has an impact on the degradation of the dominant failure component groups: bearings, stator, and rotor.

The major failure components, and their associated failure mechanisms are tabulated in the FMEA, Table 3.3, for the large squirrel cage induction motor. The various failure modes, causes, and mechanisms that were identified in the NPRDS were included in the development of the table.

4.1.3 Failure Effects

An analysis of the effects of failures of RHR, RCP, and Reactor Recirc pump motors was performed. A large portion of the failures of the subject motors occurred when the systems were in service, rather than when the machines were out of service for testing, maintenance, or other reasons (see Figure 4.7). This indicates that the types of degradation leading to these failures are difficult to detect, the maintenance and monitoring methods that are being used are not effective, the wrong monitoring methods are being emphasized (to detect the kinds of failures that the data show are occurring), or the wrong parameters are being monitored. Figure 4.7 also indicates that the motors operating in PWR applications have exhibited higher failure fractions when compared to BWR motors.

The symptoms of the failures of the subject motors, as reported to NPRDS, were analyzed next. The failure symptoms observed for these events included leakage, abnormal characteristics, physical fault, and demand fault as indicated in Figure 4.8. A small fraction of these failure events were detected when they were found out-of-specifications. Recalling from Figure 4.3 that a large portion of the failures reported to NPRDS involved motor bearings and their lube oil systems, the dominant failure symptom, leakage, in many of those cases refers to oil and grease leakage, and bearing and lube oil cooling water leakage. In Figure 4.2, it was indicated that most of the reported NPRDS failures were classified as "degraded" level. For leakage in bearing and lube oil systems, this indicates that at the time of discovery, the leakage was probably limited in most cases, having not yet deteriorated into an immediate failure. (See failure modes 3.3.1 and 2, and 3.4.1 and 2 in the FMEA, Table 3.3). It also partially explains why most of the reported failures, as shown in Figure 4.7, occurred while the system was in service: lube oil and cooling water leaks would most likely be observed when lines were pressurized and fluids were flowing as they would be during operation of the motor.

Since over 90% of the reported NPRDS failures in these machines are attributed to aging/normal wear, the above analyses of the data suggest that improvements in the current plant practices and methods for the early detection of motor degradation would do much to reduce the kinds of large electric motor failures that have been reported in the NPRDS.

System Effects - To provide a better understanding of the effects of large motor failures on the plant systems in which they are used, the data that were examined were expanded to include failures reported

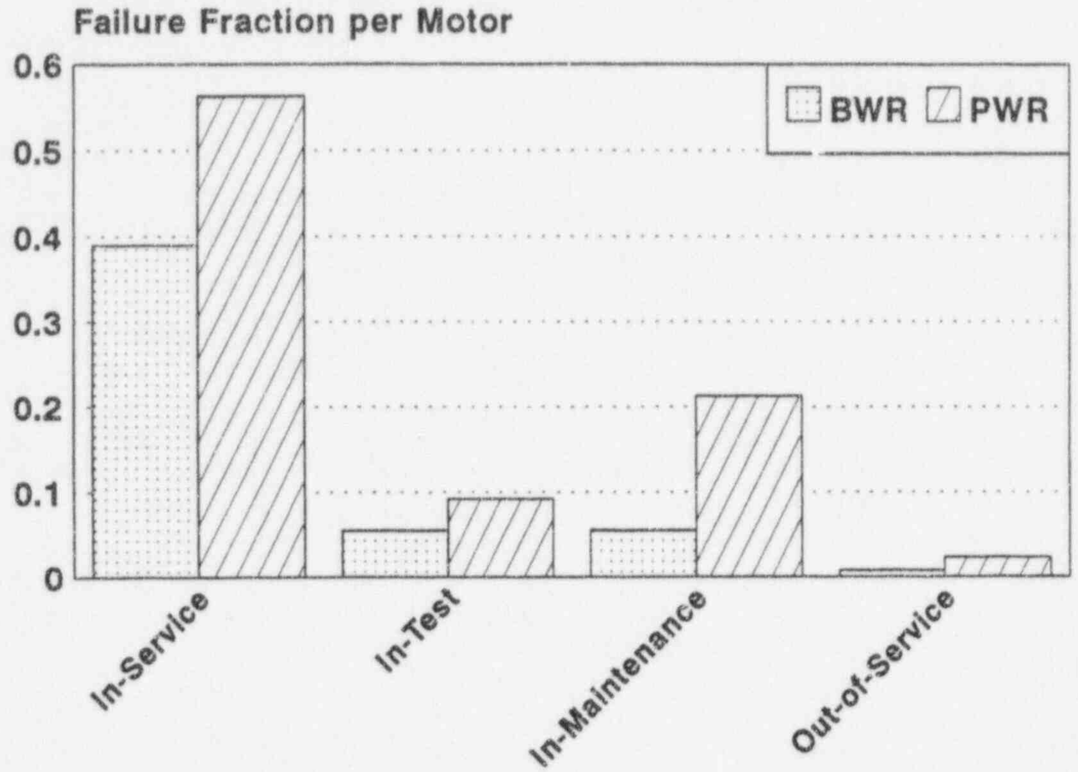


Figure 4.7 System status at time of failure, grouped by plant type - NPRDS 1985-92

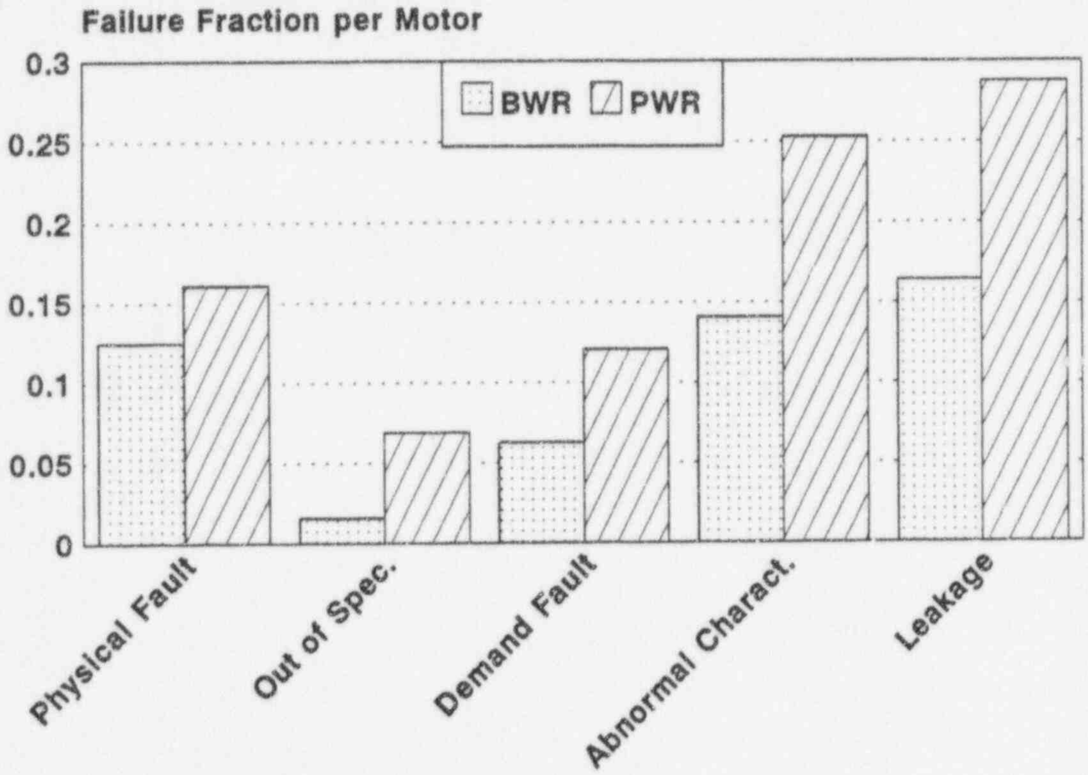


Figure 4.8 Failure symptoms grouped by plant type - NPRDS 1985-92

to NPRDS for the time period 1980 to 1994 for all major plant systems that utilize large motors. The expanded period of study provided a greater quantity of motor failures from which to determine the sensitivity of the systems to these failures.

The system effects resulting from large motor failures were grouped by system for each of the four major NSSS suppliers. These data have been tabulated in Table 4.4 for comparison. Systems located in each of the plant areas described in Table 3.2 are represented, and the number of failures reported is shown in the last line for each system.

The effect that large motor failures have on the system in which they are operating is very dependent on application. The Class 1E motors on nuclear safety systems (RHR, PWR auxiliary feedwater, charging pump motor, BWR core spray, PWR containment spray, PWR safety injection, and service water) are operating in fully redundant systems that are designed to tolerate the loss of a single motor/pump. Consequently, the data in the table show that complete loss of safety system function was never observed due to a large motor failure. The dominant system effect for failures of motors in safety systems is the loss of redundancy or subsystem. There was "no effect" reported in between one-sixth to one-third of the failures on most of the safety systems. The exception was for PWR containment spray where nearly 64% of the large motor failures had no effect. Because of the differences in their functions, direct comparison of the BWR and PWR safety systems was not practical.

Table 4.4 System Effects of Large Motor Failures
NPRDS 1980-94

System	Effect on System (percent of failures)	PWRs			All PWRs	All BWRs	All Plants
		Westnghse	CE	B&W			
PWR RCP	Loss of Function	2.7%	0.0%	0.0%	1.5%	0.0%	1.2%
	Degraded Operations	24.5%	12.2%	14.8%	19.5%	12.8%	18.3%
BWR Reactor Recirculation	Loss of Redundancy	28.2%	41.5%	14.8%	27.3%	38.3%	29.4%
	Loss of Subsystem	17.3%	34.1%	31.5%	24.4%	17.0%	23.0%
	No Effect	27.3%	12.2%	38.9%	27.3%	31.9%	28.2%
	Number of Failures	110	41	54	205	47	252
RHR	Loss of Function	0.0%	0.0%		0.0%	0.0%	0.0%
	Degraded Operations	0.0%	0.0%		0.0%	2.9%	2.8%
	Loss of Redundancy	0.0%	0.0%	None	0.0%	47.1%	44.4%
	Loss of Subsystem	0.0%	0.0%		50.0%	26.5%	27.8%
	No Effect	100.0%	100.0%		50.0%	23.5%	25.0%
	Number of Failures	1	1	0	2	34	36
Auxiliary Feedwater	Loss of Function	0.0%	0.0%		0.0%		0.0%
	Degraded Operations	22.2%	0.0%		12.5%		12.5%
	Loss of Redundancy	33.3%	14.3%	None	25.0%	N/A	25.0%
	Loss of Subsystem	22.2%	42.9%		31.3%		31.3%
	No Effect	22.2%	42.9%		31.3%		31.3%
	Number of Failures	9	7	0	16	0	16

Table 4.4 (Cont'd)

System	Effect on System (percent of failures)	PWRs			All PWRs	All BWRs	All Plants
		Westnghse	CE	B&W			
CVCS Charging Pump (HHSI)	Loss of Function	0.0%			0.0%		0.0%
	Degraded Operations	5.0%			5.0%		5.0%
	Loss of Redundancy	45.0%	None	None	45.0%	N/A	45.0%
	Loss of Subsystem	20.0%			20.0%		20.0%
	No Effect	30.0%			30.0%		30.0%
	Number of Failures	20	0	0	20		20
BWR Core Spray	Loss of Function					0.0%	25.0%
	Degraded Operations					16.7%	16.7%
	Loss of Redundancy	N/A	N/A	N/A	N/A	50.0%	25.0%
	Loss of Subsystem					16.7%	16.7%
	No Effect					16.7%	16.7%
	Number of Failures	0	0	0	0	12	12
PWR Containment Spray	Loss of Function	0.0%			0.0%		0.0%
	Degraded Operations	0.0%			0.0%		0.0%
	Loss of Redundancy	36.4%	None	None	36.4%	N/A	36.4%
	Loss of Subsystem	0.0%			0.0%		0.0%
	No Effect	63.6%			63.6%		63.6%
	Number of Failures	11	0	0	11	0	11
PWR Safety Injection	Loss of Function	0.0%	0.0%	0.0%	0.0%		0.0%
	Degraded Operations	0.0%	0.0%	0.0%	0.0%		0.0%
	Loss of Redundancy	33.3%	75.0%	40.0%	42.3%	N/A	42.3%
	Loss of Subsystem	33.3%	0.0%	30.0%	26.9%		26.9%
	No Effect	33.3%	25.0%	30.0%	30.8%		30.8%
	Number of Failures	12	4	10	26	0	26
Condensate	Loss of Function	0.8%	4.3%	0.0%	1.1%	5.5%	2.2%
	Degraded Operations	3.9%	8.7%	0.0%	4.0%	14.5%	6.5%
	Loss of Redundancy	34.4%	17.4%	42.3%	33.3%	29.1%	32.3%
	Loss of Subsystem	24.2%	43.5%	19.2%	26.0%	30.9%	27.2%
	No Effect	36.7%	26.1%	38.5%	35.6%	20.0%	31.9%
	Number of Failures	128	23	26	177	55	232
Main Feedwater	Loss of Function	0.0%	0.0%		0.0%	0.0%	0.0%
	Degraded Operations	26.0%	0.0%		23.6%	5.6%	19.25%
	Loss of Redundancy	28.0%	40.0%	None	29.1%	5.6%	23.2%
	Loss of Subsystem	24.0%	40.0%		25.5%	38.9%	28.8%
	No Effect	22.0%	20.0%		21.8%	50.0%	28.8%
	Number of Failures	50	5	0	55	18	73
Service Water	Loss of Function	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Degraded Operations	3.6%	0.0%	14.3%	4.6%	0.0%	2.9%
	Loss of Redundancy	34.5%	33.3%	57.1%	36.9%	47.5%	41.0%
	Loss of Subsystem	21.8%	33.3%	0.0%	20.0%	37.5%	26.7%
	No Effect	40.0%	33.3%	28.6%	38.5%	15.0%	29.5%
	Number of Failures	55	3	7	65	40	105

The nonsafety systems in Table 4.4 (PWR RCP, BWR reactor recirc, condensate, and main feedwater) are all multiple train, multiple pump, systems. The pumps are typically not full capacity pumps. Many plants use turbine driven feedwater pumps, or a combination of turbine driven pumps with electric motor driven pumps for backup or startup, so there are less data for feedwater pumps than for condensate pumps which are always driven by electric motors.

Due to the multiple pump/train arrangements, failures of large motors on nonsafety systems usually resulted in a loss of redundancy or the loss of one loop or subsystem, similar to what was seen for the safety related systems. Approximately 30% of the large motor failures on the nonsafety systems had no effect. Degraded operation resulted in 4% to 24% of the failures.

Comparison of the PWR RCP and BWR reactor recirc systems showed few differences in the system effects of failures. "No effect" dominated in large motor failures on PWR condensate systems and BWR feedwater systems.

Plant Effects - For the evaluation of the effects of large motor failures on the plants in which they are used, the same data were examined as for the systems effects analysis: all large electric motor failures reported to NPRDS for the time period 1980 to 1994 for major plant systems that utilize large motors.

The plant effects resulting from large motor failures were grouped by system for each of the four major NSSS suppliers. These data have been tabulated in Table 4.5 for comparison, similar to what was done previously for the systems effects analysis.

Again, plant effect is dependent on the application. The Class 1E motors on the nuclear safety systems are utilized on fully redundant systems that are designed to function despite single failures. Since safety systems serve primarily as means to safely shutdown the reactor during an accident, or to mitigate the effects of an accident, they have little direct effect on power operation of the plant. Technical Specifications requirements, however, may force plants to reduce power or shutdown if safety systems become inoperable or lose a redundant train.

Consequently, as would be expected, most (>90%) of the large electric motor failures on safety systems have no effect on plant operation. In a few cases, the failure resulted in reduced power operation, or the unit being taken off-line, probably due to Technical Specifications limiting conditions for operation (LCOs). Only one reactor trip was reported as a result of a large motor failure on a safety system; that incident involved a B&W plant high pressure injection system.

More than 58% of PWR RCP motor failures and 70% of BWR recirc pump motor failures resulted in no effect on plant operation. The PWR reactor coolant system was more susceptible to motor failures that resulted in reactor trips (11.2%) than the BWR recirc system (2.1%). Combustion Engineering plants were most susceptible with 10 (24%) failures resulting in reactor trips. PWRs were also more likely to be forced to go off-line due to a RCP motor failure (26.8%) than BWRs (14.9%) for a recirc pump motor failure. BWRs were more likely to continue operating, but at reduced power, rather than shutting down. This was due to design differences between these two reactor types.

Most condensate pump or condensate booster pump motor failures had no effect on plant operation. However, as an important part of the power production process, loss of a large pump motor in the condensate system resulted in reduced power operation in PWRs 13% of the time, and in BWRs, more

Table 4.5 Plant Effects of Large Motor Failures-NPRDS 1980-94

		PWRs			All PWRs	All BWRs	All Plants
System	Effect on System (percent of failures)	Westnghse	CE	B&W			
PWR RCP	Reduced Power Operations	2.7%	0.0%	7.4%	3.4%	12.8%	5.2%
	Unit Off-Line	26.4%	36.6%	20.4%	26.8%	14.9%	24.6%
BWR Reactor Recirculation	Reactor Trip	9.1%	24.4%	5.6%	11.2%	2.1%	9.5%
	No Effect	61.8%	39.0%	66.7%	58.5%	70.2%	60.7%
	Number of Failures	110	41	54	205	47	252
RHR	Reduced Power Operations	0.0%	0.0%		0.0%	0.0%	0.0%
	Unit Off-Line	0.0%	0.0%	None	0.0%	5.9%	5.6%
	Reactor Trip	0.0%	0.0%		0.0%	0.0%	0.0%
	No Effect	100.0%	100.0%		100.0%	94.1%	94.4%
	Number of Failures	1	1	0	2	34	36
Auxiliary Feedwater	Reduced Power Operations	0.0%	0.0%		0.0%		0.0%
	Unit Off-Line	0.0%	14.3%	None	6.3%	N/A	0.0%
	Reactor Trip	0.0%	0.0%		0.0%		0.0%
	No Effect	100.0%	85.7%		93.8%		100.0%
	Number of Failures	9	7	0	16	0	9
CVCS Charging Pump (HHSI)	Reduced Power Operations	0.0%			0.0%		0.0%
	Unit Off-Line	0.0%	None	None	0.0%	N/A	0.0%
	Reactor Trip	0.0%			0.0%		0.0%
	No Effect	100.0%			100.0%		100.0%
	Number of Failures	20	0	0	20	0	9
BWR Core Spray	Reduced Power Operations					0.0%	0.0%
	Unit Off-Line	N/A	N/A	N/A	N/A	0.0%	0.0%
	Reactor Trip					0.0%	0.0%
	No Effect					100.0%	100.0%
	Number of Failures	0	0	0	0	9	9
PWR Containment Spray	Reduced Power Operations	0.0%			0.0%		0.0%
	Unit Off-Line	0.0%	None	None	0.0%	N/A	0.0%
	Reactor Trip	0.0%			0.0%		0.0%
	No Effect	100.0%			100.0%		100.0%
	Number of Failures	11	0	0	11	0	11
PWR Safety Injection	Reduced Power Operations	8.3%	0.0%	10.0%	7.7%		7.7%
	Unit Off-Line	0.0%	0.0%	10.0%	3.8%	N/A	3.8%
	Reactor Trip	0.0%	0.0%	10.0%	3.8%		3.8%
	No Effect	91.7%	100.0%	70.0%	84.6%		84.6%
	Number of Failures	12	4	10	26	0	26
Condensate	Reduced Power Operations	14.1%	13.0%	7.7%	13.0%	16.4%	13.8%
	Unit Off-Line	0.8%	0.0%	0.0%	0.6%	0.0%	0.4%
	Reactor Trip	1.6%	8.7%	0.0%	2.3%	9.1%	3.9%
	No Effect	83.6%	78.3%	92.3%	84.2%	74.5%	81.9%
	Number of Failures	128	23	26	177	55	232

Table 4.5 (Cont'd)

System	Effect on System (percent of failures)	PWRs			All PWRs	All BWRs	All Plants
		Westnghse	CE	B&W			
Main Feedwater	Reduced Power Operations	34.0%	0.0%		30.9%	0.0%	23.3%
	Unit Off-Line	2.0%	0.0%	None	1.8%	0.0%	1.4%
	Reactor Trip	8.0%	0.0%		7.3%	0.0%	5.5%
	No Effect	56.0%	100.0%		60.0%	100.0%	69.9%
	Number of Failures	50	5	0	55	18	73
Service Water	Reduced Power Operations	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Unit Off-Line	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Reactor Trip	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	No Effect	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	Number of Failures	55	3	7	65	40	105

than 16.4% of the time, as indicated in Table 4.5. BWRs were also susceptible to reactor trips more than 9.1% of the time as a result of motor failures in the condensate system.

None of the large electric motor failures on the main feedwater system in BWRs had any effect on plant operation. In PWRs, 60% of the failures on the main feedwater system had no effect, but 30.9% resulted in reduced power operation. A reactor trip was reported in 7.3% of the large electric motor failures on the main feedwater system at PWRs, usually due to the steam generator level transients that resulted.

4.2 Licensee Event Report (LER) Review

As mentioned previously, the LER database search yielded 1228 events involving electric motors in the period from 1980 to 1992. The search of the LER database using the Sequence Code Search System (SCSS) could not be so precisely bounded as the NPRDS search since there is no criterion for motor size. Consequently, the LER database had to be searched for motor failures of any size, but was bounded by specifying individual systems that were known to have large motors based upon the design review (Section 2.4). The search of motor LERs included the following systems:

Containment Pressure Suppression Make-up (BWR)
Condensate & Feedwater
Containment Spray
Spent Fuel Pool/Refuel Pool Cooling & Cleanup
Essential Raw Cooling/Service Water
Essential Compressed Air
Circulating Water
Reactor Building HVAC
Fuel Building HVAC
Chilled Water
Control Building HVAC

Reactor Auxiliary Building HVAC
Secondary Containment HVAC-Standby Gas Treatment
Drywell/Torus HVAC & Purge (BWR)
Component Cooling Water (CCW)
Low Pressure Core Spray (LPCS) (BWR)
Suppression Pool Cleanup (BWR)
Reactor Water Cleanup (RWC) (BWR)
Raw Service Water
Raw Cooling Water
Compressed Gas
Control Rod Drive (CRD)
CRD Cooling Water
Primary Coolant (PWR)
Intermediate Pressure Injection (PWR)
High Pressure Core Spray (HPCS) (BWR)
Chemical and Volume Control System (CVCS) (PWR)
Residual Heat Removal (RHR)
Reactor Recirculation (BWR)
Auxiliary Feedwater/Emergency Feedwater (AFW/EFW) (PWR)
Control & Service Air

Some of the advantages of the LER data in the study of large motors are that they give a better understanding of how support equipment failures and associated equipment failures (such as driven loads, suction and discharge valves, and suction strainers and screens) can effect large motor availability. This is in contrast to the NPRDS data which are strictly component oriented, covering for the most part, only failures within the electric motor. The NPRDS data provide almost no direct information on the support and associated equipment that can greatly affect motor operability. For this reason, the LER data are also better able to indicate the effects of large motor failures on the systems in which they are located, interactions with other plant systems, and the potential consequences of the large transients that can arise following large motor failures in reactor-related systems, as well as in balance of plant (BOP) systems. This helps to explain why there was very little overlap between the search results from the two databases.

By their nature, LER data also include a higher proportion of human error failures (maintenance and operating personnel errors, procedure problems, etc.) than NPRDS. This is because LERs are required for all incidents leading to reportable events as specified in 10CFR50.73, not just equipment oriented problems.

Some of the limitations of the LER data are that there is no direct indication of motor manufacturer, age at failure, motor horsepower, and operating voltage. In general, the details of the failure, such as failed subcomponents, corrective action, method of detection, symptoms, etc., are not as complete as that found in the NPRDS failure reports. This prevents the use of these data for failure rate and failure frequency calculations. It was difficult in many cases to determine the horsepower rating of a motor to decide whether it should be included in this study; as a result, some of the motors used in the LER database may be slightly less than 500 hp. The LER data are also less comprehensive than the NPRDS, in that most of the less severe failures (incipient and degraded level of severity) are generally not included. LERs, by definition, involve the most severe events and all reactor trips. As a result, the large motor failures reported in LERs generally were of a more severe nature than those found in the NPRDS data. By their nature, however, LER data provide valuable information as to the effects of large motor failures on the system, interactions with other plant systems, and the consequences of the plant transients that can arise following large motor failures.

Results of the review and analysis of the LERs obtained for large electric motor failures are described in the following subsections of the report.

4.2.1 Aging Assessment

Among the 1228 LERs reviewed there were 642 events involving failures of large motors, 14 events involving BWR large motor-generator (MG) sets, and 44 generator events. Several of the LERs were incidents in which more than one large motor failure was reported. The remainder of the LERs involved small motors, environmental qualification problems, potential design or accident response problems, technical specification violations, or failures in the power system outside the scope of the study.

Among the 642 events with motor failures, 439 occurred at PWR plants and 203 were at BWR plants; in addition there were the 14 BWR large MG set failures mentioned above. Based on the definition of aging as given in NUREG-1144, 61% of the PWR failures and 60% of the BWR failures were classified as aging related. All but one of the BWR large MG set failures were found to be aging related.

The aging related events were reviewed and analyzed for details of the motor failures. As discussed above, the LER events include failures of large electric motors as bounded in Figure 1.1. In addition, there are failures of large motor support equipment, as well as failures of mechanical loads, (defined as associated equipment, in this study) that caused the large motors involved to be unavailable. These cannot be classified as large motor failures, per se, but they will be included in some of the failure analysis discussions as a potential source of motor unavailability. The contributions from these three sources are summarized in Table 4.6 for BWRs and PWRs. The LER data reveal that slightly less than 40% of the aging related motor problems were caused by failures within the electric motor itself (see boundaries defined in Figure 1.1). An equal amount of the failures originate with motor support equipment, including the motor circuit breaker, power supply cable from the circuit breaker, control logic and instrumentation, protective relaying, and the cooling water and air supplies. Less than 25% of the events originated in the driven mechanical loads (almost exclusively pumps) and their flow path elements

Table 4.6 Sources of Large Motor Unavailability at PWRs and BWRs - LER Data 1980-1992

SOURCE	PWR	BWR	All Plants
Large Electric Motor	35.6%	42.5%	37.8%
Support Equipment	40.6%	35.8%	39.1%
Associated Equipment	23.8%	21.7%	23.1%
Number of Failures	256	120	376

(suction and discharge valves, screens, and strainers, and minimum flow valves). The importance of this is that nearly two thirds of aging related large motor unavailability identified in the LER data can be attributed to sources outside of the electric motor itself.

The LER data do not include age at failure information. It was not possible, therefore, to directly calculate age-dependent failure frequency for large electric motors in the LERs, as was done for the NPRDS data in Figure 4.1.

4.2.2 Failure Analysis

The status of the large motor systems was examined at the time that age related failures were discovered. It was found that 16% of the failures at PWRs and 31% of those at BWRs, representing approximately 21.5% of the failures for all plants, were found during testing and maintenance activities. The rest occurred while the system was in service. The LER failures occurred while the system was in service twice as often as the in-service failures reported to NPRDS. This was caused by (1) the severity of the failures reported to each database, and (2) many motor failures (including immediate) which occurred during testing and maintenance, were not reportable under the LER system. NPRDS receives reports of failures covering the entire range of severity and is therefore closer to the actual distribution of motor failures expected. LER failures, on the other hand, tend to be of "immediate" (catastrophic) severity level, and are more likely to have remained undetected up until they have precipitated a reportable event.

To verify this, the severity level determined for LER failures of large electric motors was plotted for PWRs and BWRs. These results for aging related large motor failures are provided in Figure 4.9. For each level of severity, the failure fraction per motor is given for PWRs and BWRs.

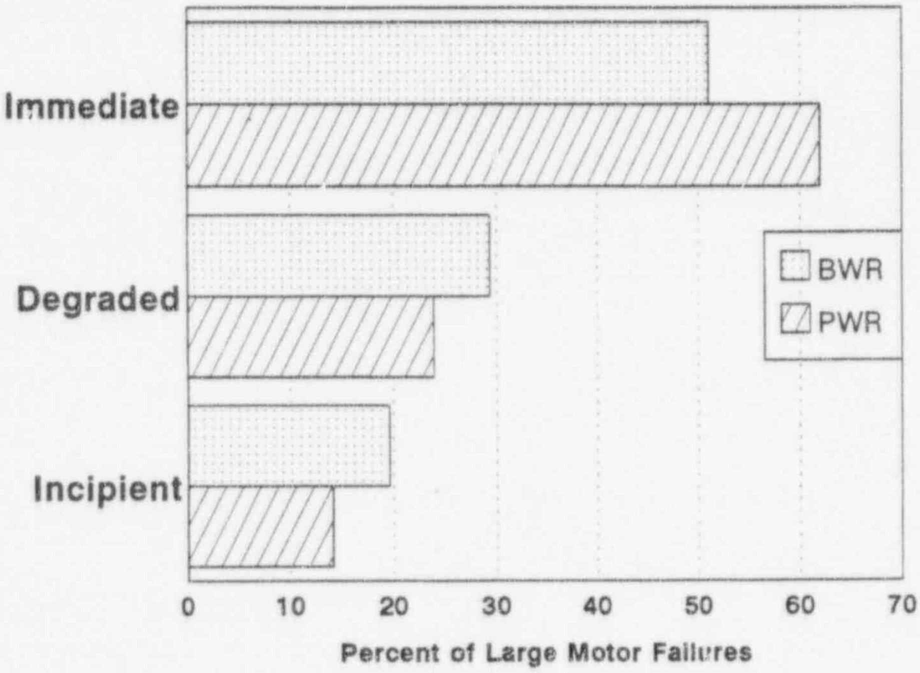


Figure 4.9 Failure severity level - LER data 1980-1992

As expected, the immediate, or catastrophic, types of failures are dominant in the LER data, followed by degraded failures with less than half the amount of the immediate failures. In Figure 4.2 for the NPRDS data, degraded failures dominated, representing more closely the actual distribution of the severity of detected failures. The LER data indicate that many degraded and incipient failures are apparently remaining undetected until they have deteriorated to a more severe level.

The disparity between the PWR and BWR in each severity category is not as pronounced in the LER data as was seen in the NPRDS data in Figure 4.2. The failure fraction per motor for PWR failures that are of immediate severity level is only slightly higher than for BWRs, and in the other two categories it is actually a bit lower than for the BWR plants.

The relative failure contributions from individual motor subcomponents were examined next. Figure 4.10 shows the results of this analysis for all aging related failures of large motors in the LER data. With a few exceptions, the LER data generally follow what was seen previously in the NPRDS data and the IEEE (Refs 9, 10, 11) and EPRI motor studies (Ref. 19). Overall, bearings and lubrication system problems were the dominant failed subcomponent in large electric motors, and stator problems were next most important. The big exception was the very large failure fraction per motor found for stators in BWR plants; this was nearly three times the amount for stators in PWR plants, and it made stator problems the dominant failure component in LERs at BWR plants. No explanation could be determined for this from the data available. The third most important group of subcomponents in the LER data included connectors, terminations, and termination boxes. These subcomponents, identified in the FMEA (Table 3.3) as Component Group 4.2, are more accessible than most other motor subcomponents and can be monitored both visually and by the basic electrical tests as indicated in Table 3.3.

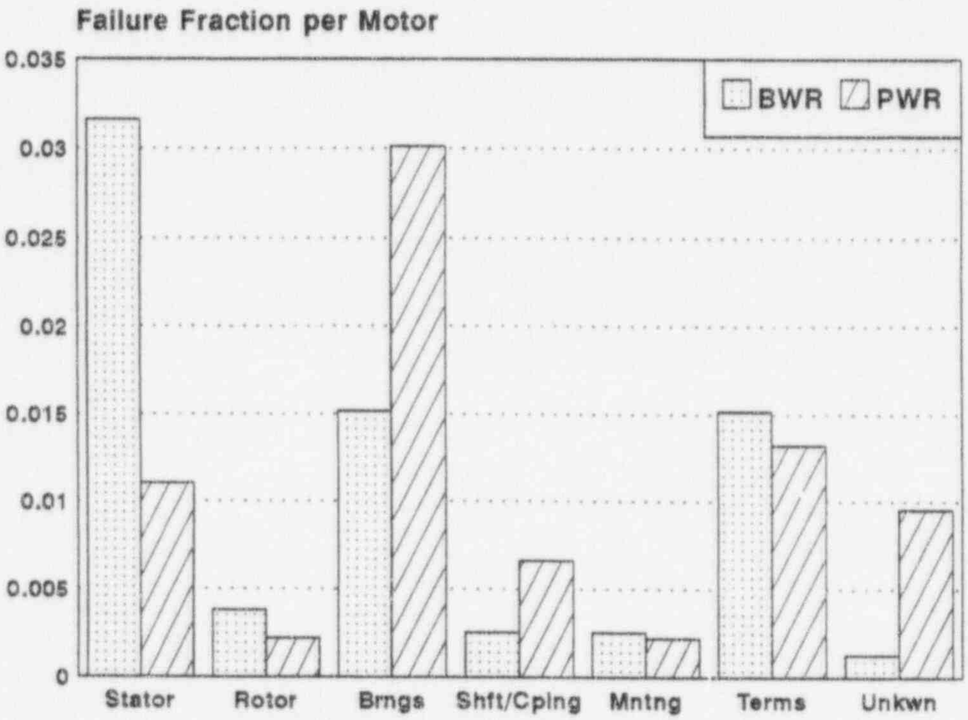


Figure 4.10 Subcomponent failure fractions - LER data 1980-1992

The overall distribution of subcomponent failures for the LER data is provided in Figure 4.11. The bearing related failures are broken out in more detail to provide a better understanding of this group's contribution. Among the bearing related failures in the LER data, more than 70% are attributed to the bearings and seals, and the remainder are due to various parts of the lube oil cooling and supply systems. Bearing failures have been described in the Table 3.3 FMEA under component groups 3.1, 3.2 and 3.3, and the lube oil system is covered as component group 3.4.

The mechanisms for failure determined from the LER data were examined. As was seen in the NPRDS data, there was little difference between the actual failure mechanisms acting upon large motors in PWRs and BWRs. Figure 4.12 summarizes this information for the LER data. Electrical aging and wear dominated, and these mechanisms are further broken out in the figure. Nearly half of the electrical aging was identified as short circuits and electrical grounds. These were attributed to stator faults, insulation degradation and wear, open conductors, and cracked or broken rotor bars. A large portion involved degradations of electrical connections, including moisture and water intrusion, loosening, dirt, and other contamination. Mechanical aging mechanisms were the next most prominent as determined from the LER data. These included wear, mechanical misalignment, mechanical damage and binding, corrosion, and effects of moisture and dirt.

4.2.3 Failure Effects

An analysis of the effects of all large motor failures obtained from the LER review was performed. Figure 4.13 illustrates that a very large portion of the large motor failures (77% overall) took place while their systems were in service. This is similar to the situation shown by the NPRDS failure data in Figure 4.7. As mentioned in the previous discussion in Section 4.1.2, the high percentage of in service failures is indicative of problems in the detection of types of degradation that are resulting in motor failures.

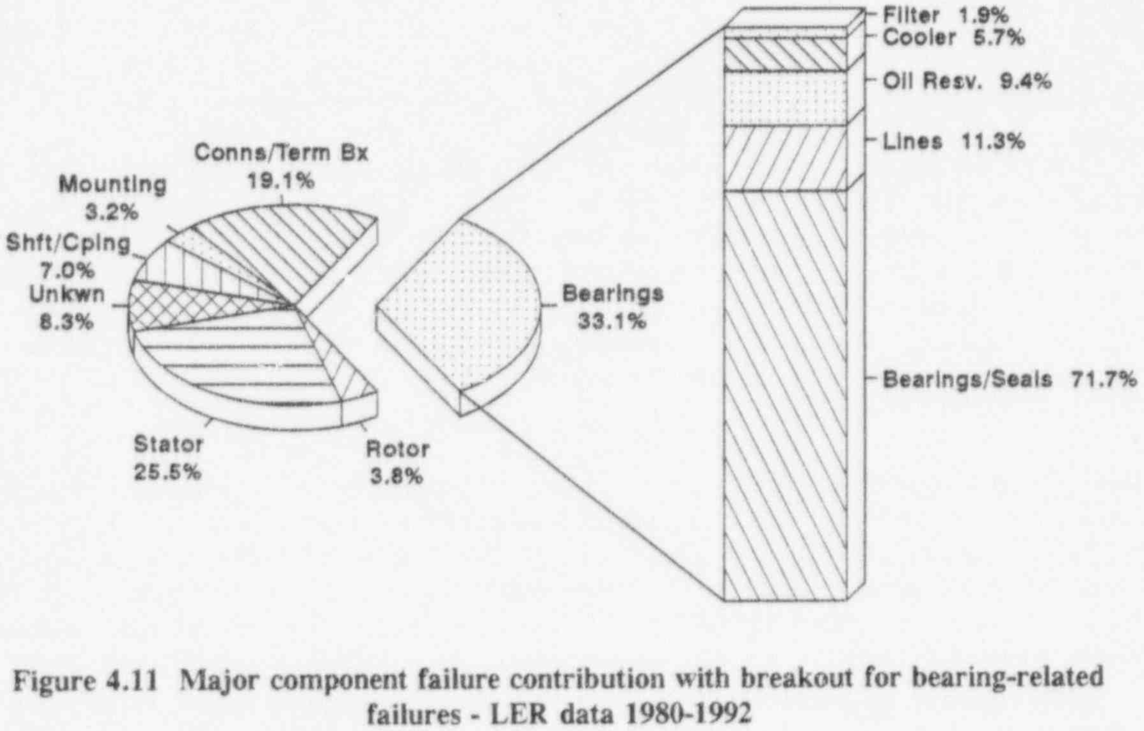


Figure 4.11 Major component failure contribution with breakout for bearing-related failures - LER data 1980-1992

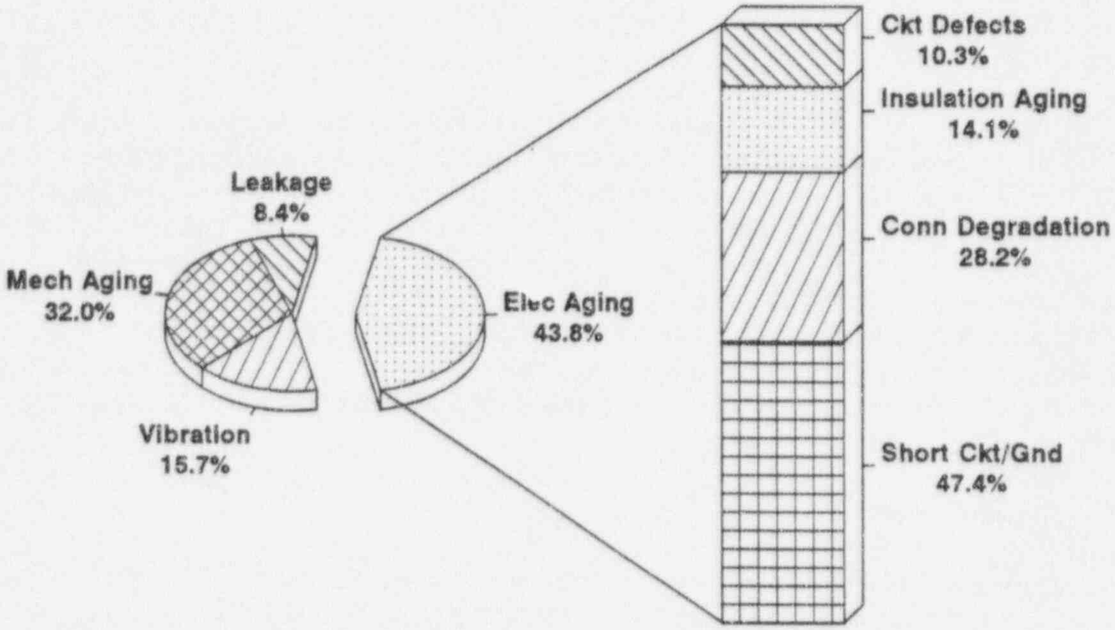


Figure 4.12 Failure mechanisms - LER data 1980-1992

BWR plants again were more effective than the PWRs in detecting problems during maintenance. BWRs also showed a slightly lower relative failure fraction per motor for the in service failures.

For additional insights in how to improve the effectiveness of preventive maintenance and testing at identifying failures, the symptoms reported for the LER motor failures were examined. This information, presented in Figure 4.14, indicates that the dominant failure symptom is physical fault. Symptoms, such as physical fault and leakage, and to some extent abnormal characteristic, are typical of in service failures. Demand fault is also mostly an in service failure, usually a failure to start when required. Symptoms such as out of specification, and possibly abnormal characteristics, are most representative of testing and maintenance activity. Figure 4.14 enforces the tendency that large motor failures in the LER data most often occurred while the machine was in service.

Since Figure 4.14 is developed from LER data, where the failures are more apt to be serious, symptoms such as physical fault, demand fault, and abnormal characteristic dominate. As expected, this differs from the symptoms developed from the NPRDS data (Figure 4.8) which more closely represent the full spectrum of failures. The data from both sources show the tendency toward failures while in service, rather than the more desirable situation, where degradation is found during testing and maintenance, so that it can be repaired or corrected before deteriorating to more serious failures and unscheduled outages.

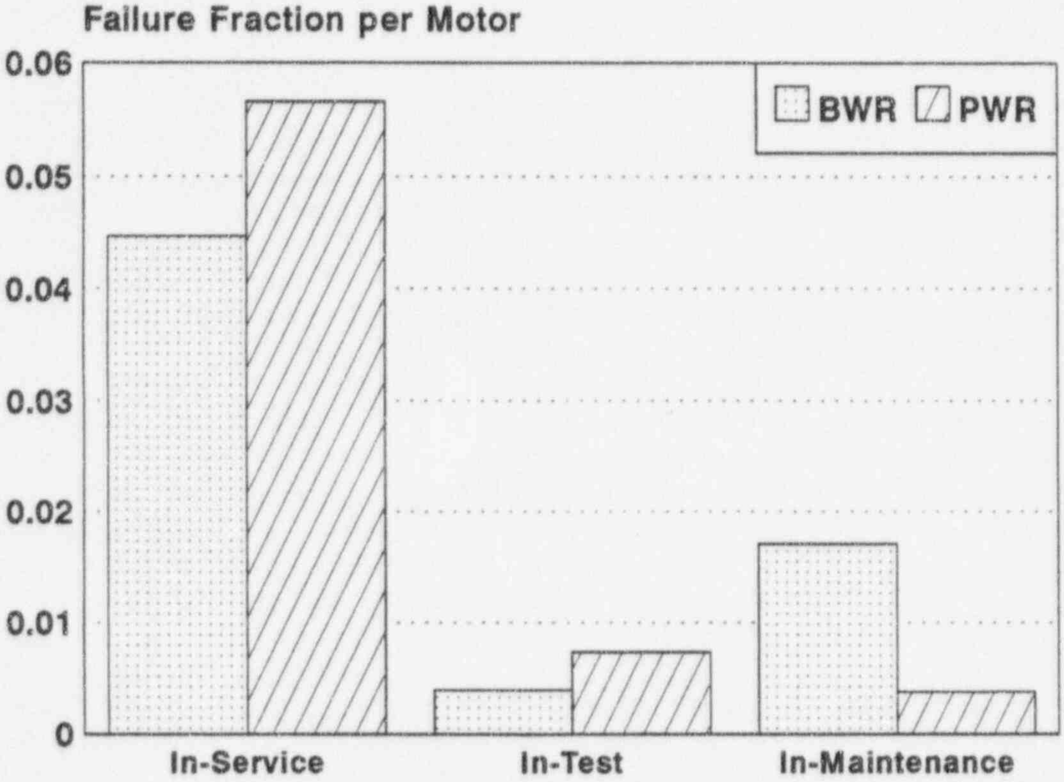


Figure 4.13 System status at time of failure, grouped by plant type - LER data 1980-92

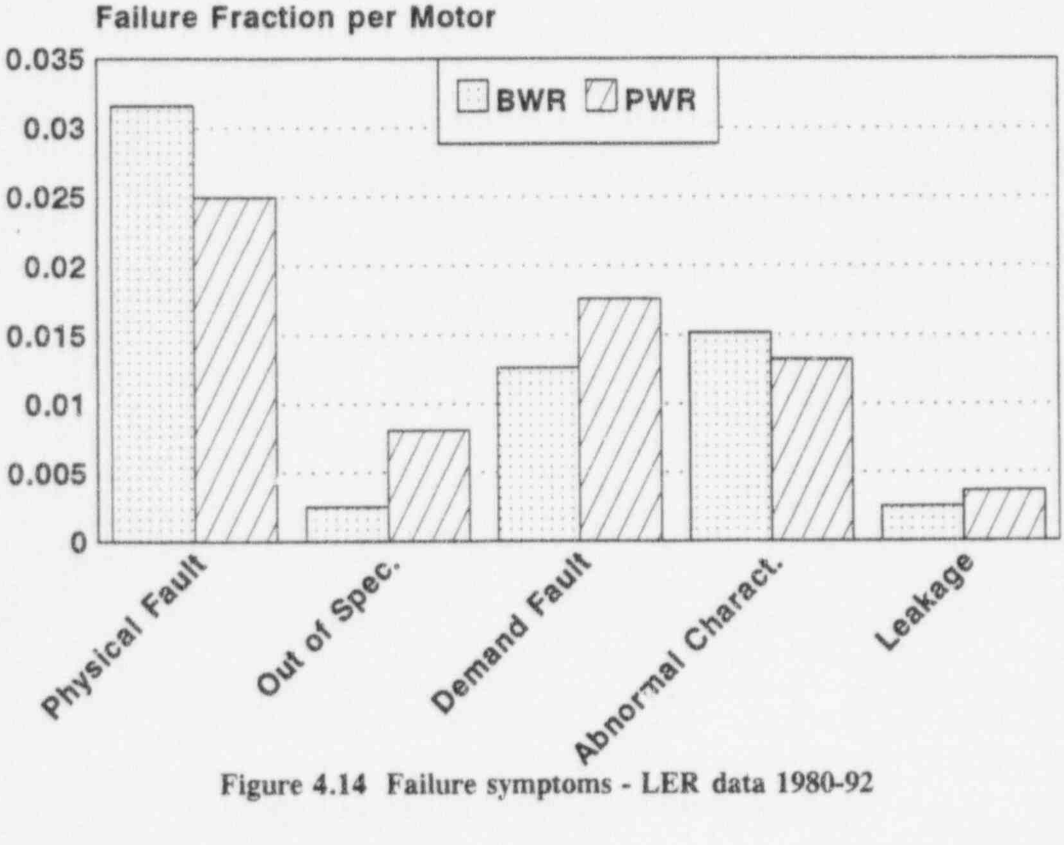


Figure 4.14 Failure symptoms - LER data 1980-92

System Effects

The LER database was examined for the effects that large electric motor failures have on the systems on which they are located. Since the purpose of examining system effects is to study the sensitivity of the system to the unavailability of a large motor, failure from any source was included. Recalling Table 4.6, significant fractions of all large motor failures resulted not only from failures within the motor (37.8%), but also from the support equipment (39.1%) and the associated equipment or mechanical loads (23.1%). The aging related loss of a large pump motor as a result of failures in the support equipment and the associated equipment will be considered along with failures within the motor proper to provide a larger body of failure data upon which to base the system sensitivity study.

To help understand the contributions of the support equipment and associated equipment failures to large electric motor unavailability, the components that were the source of the problem were noted for each LER event. The fraction of the total support equipment LERs for large motors attributed to various support components are shown in Figure 4.15. Circuit breaker and I&C problems make up the majority of the support equipment failures, and closely related to these are protective relaying failures. Together these constitute more than half of the support equipment contribution to large motor unavailability. Cooling water failures, including cooling water lines, pumps, and heat exchangers, comprised 13.3% of the support equipment problems, and room and area cooling equipment, including belts, fans, and dampers, another 11.3%. The support equipment "bearings" category (10.8%) encompasses bearings from a variety of support equipment, including cooling water pumps and drive motors, cooling fans and drive motors, circuit breakers, relays, and switches. The significance of this is that the source of motor unavailability is found in support systems as often as it is within the motor itself (as shown in Table 4.6). Maintenance and monitoring efforts directed at motor support equipment such as circuit breakers, motor I&C, and protective relaying, may be as effective in improving large motor availability as maintenance and monitoring of the electric motor itself.

Similarly, the components that caused large motor associated equipment failures in the LER data were identified and plotted on Figure 4.16. The largest contributors were pumps, as expected, since this is the most important mechanical load driven by large electric motors. Many motor failures identified in the LER search were actually pump problems, including bearing failures, impeller eye ring wear, imbalances, and breakage. Closely related were valves (25.9%), I&C (9.9%), and strainer and screen (8.6%) problems. Incorrect valve lineups or incorrect valve position indication caused many motors trips and failures since these parameters are permissive signals in pump motor starting and operating logic. Incorrect valve position and clogged or obstructed strainers, can lead to a pump motor trip due to low suction pressure, low flow, or high discharge pressure. Instrumentation errors that falsely indicate any of these conditions can also have the same result.

From the point of view of system availability, the pump/motor combination is of primary importance and should be viewed as a single unit. The large motor reliability is, in reality, just a subset of the reliability of the pump/motor combination. For purposes of this study, however, large motors are the primary focus, and therefore associated equipment failures, such as pumps, as they are found in the large motor related LER events, are examined.

The system effects noted from the LER review for several of the most important systems using large motors are summarized in Table 4.7. As was done in Section 4.1.3 for the NPRDS review, the data are grouped by system for each of the four major NSSS suppliers. Systems from each of the major plant

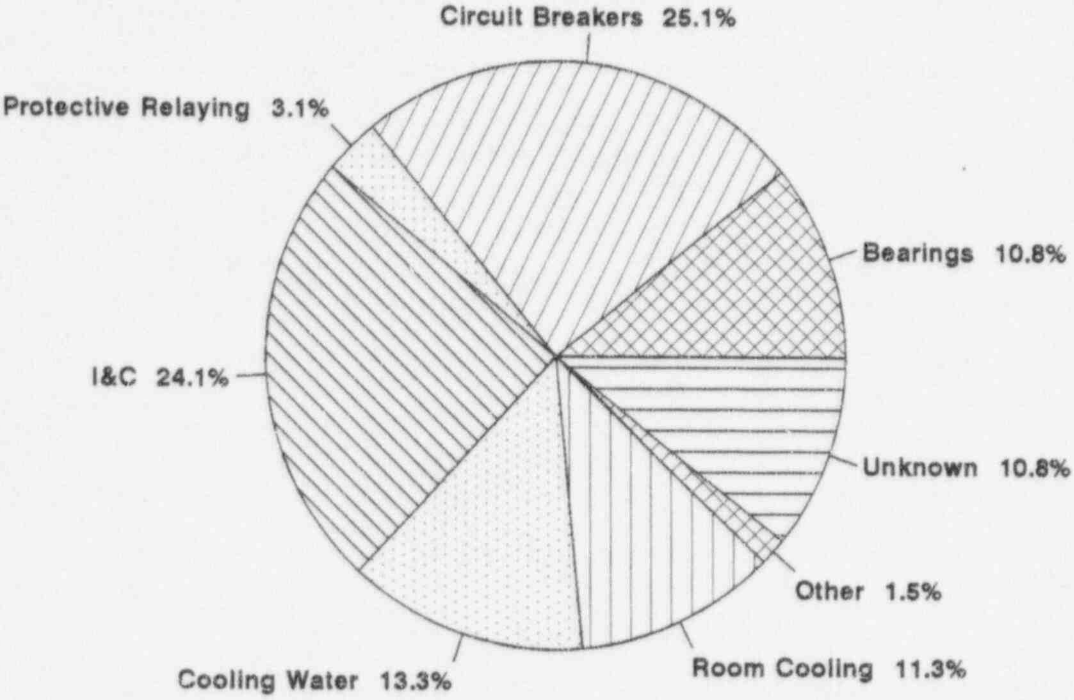


Figure 4.15 Components contributing to large motor support equipment failures - LER data 1980-92

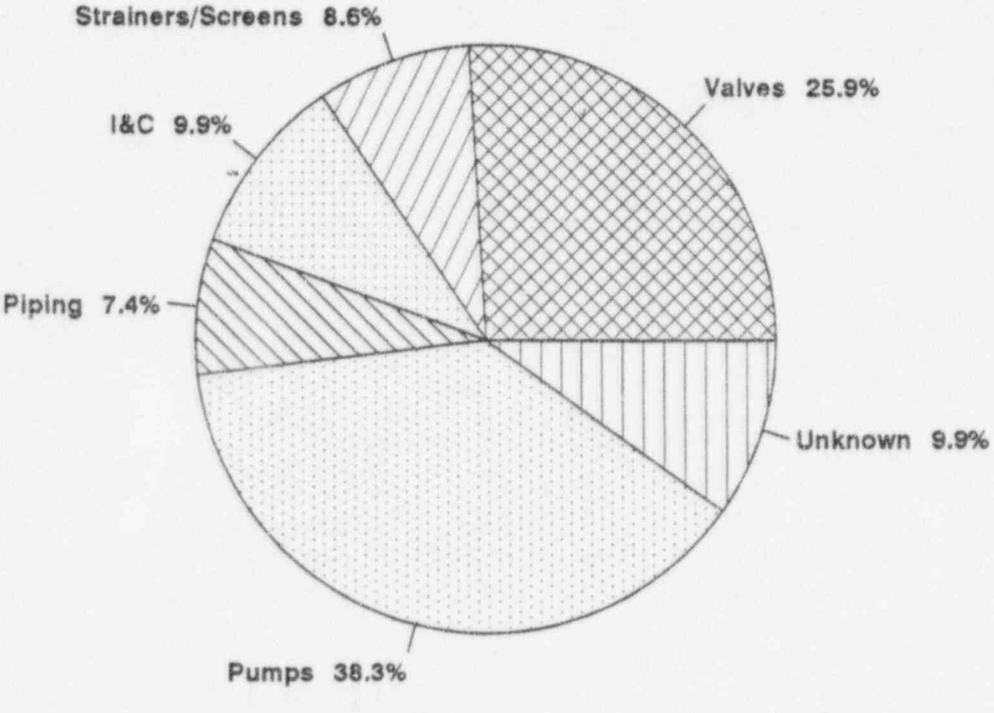


Figure 4.16 Components contributing to large motor associated equipment failures - LER data 1980-92

Table 4.7 System Effects of Large Motor Failures - LER Data 1980-92

		P W R s			All	All	All
System	Effect on System (percent of failures)	Westnghse	CE	B&W	PWRs	BWRs	Plants
PWR RCP	Loss of Function	33.3%	0.0%	0.0%	14.3%	33.3%	27.3%
	Degraded Operations	33.3%	0.0%	0.0%	14.3%	33.3%	27.3%
BWR Reactor Recirculator	Loss of Redundancy	33.3%	100.0%	100.0%	71.4%	33.3%	45.5%
	Loss of Subsystem	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	No Effect	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Number of Failures	3	1	3	7	15	22
RHR	Loss of Function	0.0%	0.0%	0.0%	0.0%	10.5%	7.4%
	Degraded Operations	0.0%	0.0%	0.0%	0.0%	2.6%	1.9%
	Loss of Redundancy	81.8%	50.0%	100.0%	81.3%	65.8%	70.4%
	Loss of Subsystem	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	No Effect	18.2%	50.0%	0.0%	18.8%	21.1%	20.4%
	Number of Failures	11	2	3	16	38	54
Auxiliary Feedwater	Loss of Function	0.0%	0.0%	0.0%	0.0%		0.0%
	Degraded Operations	0.0%	0.0%	0.0%	0.0%		0.0%
	Loss of Redundancy	100.0%	100.0%	100.0%	100.0%	N/A	100.0%
	Loss of Subsystem	0.0%	0.0%	0.0%	0.0%		0.0%
	No Effect	0.0%	0.0%	0.0%	0.0%		0.0%
	Number of Failures	11	7	4	22	0	22
CVCS Charging Pump (HHSI)	Loss of Function	8.3%	0.0%	0.0%	5.6%		5.6%
	Degraded Operations	0.0%	40.0%	0.0%	11.1%		11.1%
	Loss of Redundancy	75.0%	60.0%	100.0%	72.2%	N/A	72.2%
	Loss of Subsystem	0.0%	0.0%	0.0%	0.0%		0.0%
	No Effect	16.7%	0.0%	0.0%	11.1%		11.1%
	Number of Failures	12	5	1	18		18
BWR Core Spray	Loss of Function					16.7%	16.7%
	Degraded Operations					25.0%	25.0%
	Loss of Redundancy	N/A	N/A	N/A	N/A	25.0%	25.0%
	Loss of Subsystem					0.0%	0.0%
	No Effect					33.3%	33.3%
	Number of Failures	0	0	0	0	12	12
PWR Containment Spray	Loss of Function	7.7%	0.0%		6.3%		6.3%
	Degraded Operations	38.5%	0.0%		31.3%		31.3%
	Loss of Redundancy	38.5%	0.0%	None	31.3%	N/A	31.3%
	Loss of Subsystem	0.0%	0.0%		0.0%		0.0%
	No Effect	15.4%	100.0%		31.3%		31.3%
	Number of Failures	13	3	0	16	0	16
PWR Safety Injection	Loss of Function	0.0%	0.0%	0.0%	0.0%		0.0%
	Degraded Operations	0.0%	0.0%	0.0%	0.0%		0.0%
	Loss of Redundancy	77.8%	100.0%	100.0%	86.7%	N/A	86.7%
	Loss of Subsystem	0.0%	0.0%	0.0%	0.0%		0.0%
	No Effect	22.2%	0.0%	0.0%	13.3%		13.3%
	Number of Failures	9	2	4	15	0	15

Table 4.7 (Cont'd)

System	Effect on System (percent of failures)	PWRs			All PWRs	All BWRs	All Plants
		Westnghse	CE	B&W			
Condensate	Loss of Function	0.0%	0.0%		0.0%	0.0%	0.0%
	Degraded Operations	3.33%	0.0%		23.5%	37.5%	30.3%
	Loss of Redundancy	66.7%	100.0%	None	76.5%	62.5%	69.7%
	Loss of Subsystem	0.0%	0.0%		0.0%	0.0%	0.0%
	No Effect	0.0%	0.0%		0.0%	0.0%	0.0%
	Number of Failures	12	5	0	17	16	33
Main Feedwater	Loss of Function	20.8%	50.0%	0.0%	22.2%	0.0%	21.4%
	Degraded Operations	4.2%	50.0%	0.0%	7.4%	0.0%	7.1%
	Loss of Redundancy	75.0%	0.0%	100.0%	70.4%	100.0%	71.4%
	Loss of Subsystem	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	No Effect	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Number of Failures	24	2	1	27	1	28
Circulating Water	Loss of Function	0.0%	0.0%		0.0%	37.5%	14.3%
	Degraded Operations	58.3%	0.0%		53.8%	37.5%	47.6%
	Loss of Redundancy	41.7%	100.0%	None	46.2%	25.0%	38.1%
	Loss of Subsystem	0.0%	0.0%		0.0%	0.0%	0.0%
	No Effect	0.0%	0.0%		0.0%	0.0%	0.0%
	Number of Failures	12	1	0	13	8	21
Service Water	Loss of Function	3.8	11.1%	0.0%	4.5%	0.0%	3.6%
	Degraded Operations	19.2	11.1%	0.0%	13.6%	8.3%	12.5%
	Loss of Redundancy	73.1	77.8%	100.0%	79.5%	75.0%	78.6%
	Loss of Subsystem	0.0	0.0%	0.0%	0.0%	0.0%	0.0%
	No Effect	3.8	0.0%	0.0%	2.3%	16.7%	5.4%
	Number of Failures	26	9	9	44	12	56

locations in Table 3.2 are represented. Information on circulating water systems is not covered in the NPRDS, but is available in the LER data, so it is shown here.

As seen in the NPRDS system effects analysis, the impact that motor failures have on their systems is application dependent. The Class 1E motors operating on the fully redundant nuclear safety systems (RHR, PWR auxiliary feedwater, charging pump motors, BWR core spray, PWR containment spray, PWR safety injection, and service water) have minimal effect on the functional availability of those systems. The systems have been designed to tolerate single failure, such as the loss of one pump, and still operate satisfactorily. This is reflected by the data in the table for the safety systems.

The dominant system effect of large motor failure on the safety systems in both PWRs and BWRs is loss of redundancy. LER incidents are, by their definition, more serious than most of the failures reported to the NPRDS. Therefore, the LER data did contain a few cases where the loss of a motor produced effects more severe than just a loss of redundancy. There are more cases of these severe effects than reported in Table 4.4 for the NPRDS data. This was seen in the PWR containment spray, service water, and charging pump motors and the BWR RHR and core spray pump motors.

The PWR RCPs and the BWR reactor recirc pumps are considered nonsafety, but they are important since they are an integral component of the NSSS and operators have limited access to them during power operation. The dominant system effect is loss of redundancy, however, the GE BWRs and the Westinghouse PWRs also reported degraded operation and loss of system function. The data for Westinghouse RCPs only include three LER failures so this result is probably not significant. One other factor to consider is difference in design of the RCS between NSSS suppliers: Westinghouse plants use one RCP per RCS loop, as compared to the Combustion Engineering and Babcock and Wilcox designed plants that use two RCPs per RCS loop. The redundant RCPs may make CE and B&W plants more tolerant to the loss of one RCP. In the BWR reactor recirc system, degraded operation and loss of function were noted as frequently as loss of redundancy. This was based on fifteen LER failures. In addition, not included in the table, but also significant in this system were thirteen aging related LER failures in the reactor recirc MG sets. Seven of these resulted in loss of redundancy, four caused degraded operation, and two caused loss of system function (due to unavailability of the redundant train at the time of failure).

The balance of plant systems (condensate, feedwater, and circulation water) are all multiple train, multiple pump systems, and the large motors are used to drive pumps that are less than full capacity. Owing to this arrangement, the dominant system effect found in the large motor LER failures is the loss of redundancy. Due to the more serious nature of LER failures, the minor BOP motor failures that would have no effect on their systems, are absent from the LER database.

Plant Effects

The plant effects resulting from large motor failures were grouped by system for each of the four major NSSS suppliers. These data have been tabulated in Table 4.8 for comparison, similar to that done previously for the systems effects analysis.

The greatest number of LER events in the PWRs involved failures of large motors on the service water, main feedwater, auxiliary feedwater, CVCS (charging pumps), and condensate systems. For the BWR plants, most of the large motor LERs were on the RHR system, reactor recirc (if reactor recirc MG set drive motors are included), condensate system, and service water system.

As explained previously in Section 4.1.3, for the plant effects review based on NPRDS data, the failures of Class 1E motors on safety-related systems would not usually be expected to have much of an effect on the normal operation of the plant. This also is the case for most of the safety system motor failures summarized in Table 4.8. However, Technical Specifications LCO requirements exist for all the safety systems. As a result, if repairs cannot be made within the time permitted by the Technical Specifications, failures of large motors driving safety systems pumps will require the plants to reduce power, or even shutdown, if one or more redundant safety system trains are inoperable. This was the case for several events in the RHR systems at Westinghouse PWRs and General Electric BWRs, auxiliary feedwater at Combustion Engineering PWRs, PWR charging pump motors, and PWR service water systems.

Most of the BWR reactor recirc pump motor failures resulted in the unit being taken off line (50%), or a reactor trip (31.8%). If the fourteen failures of the MG Set drive motors are included, for a total of twenty-nine LER events, the breakout is as follows:

Reduced Power Operation	17.2%
Unit Off-Line	58.6%
Reactor Trip	10.3%
No Effect	10.3%

Most of the PWR RCP motor failures in the LER data were associated with reactor trip events. However, the number of events (7) is small.

The LERs involving the BOP systems listed in Table 4.8 indicated that failures of large pump motors on these systems can have a significant effect on plant operation. BOP systems such as condensate and circulating water consist of multiple, partial capacity pumps and multiple trains. The systems are an integral part of the power production process of the plant and disturbances, such as the tripping of a large pump motor, can initiate transients that disrupt plant operations. By definition, the most serious of these incidents are reportable, and that is why they show up in the LER database.

Table 4.8 Plant Effects of Large Motor Failures-LER data 1980-92

		PWRs			All PWRs	All BWRs	All Plants
System	Effect on System (percent of failures)	Westnghse	CE	B&W			
PWR RCP	Reduced Power Operations	0.0%	0.0%	0.0%	0.0%	6.7%	4.5%
	Unit Off-Line	0.0%	0.0%	0.0%	0.0%	73.3%	50.0%
BWR Reactor Recirculation	Reactor Trip	100.0%	100.0%	33.3%	71.4%	13.3%	31.8%
	No Effect	0.0%	0.0%	66.7%	28.6%	6.7%	13.6%
	Number of Failures	3	1	3	7	15	22
RHR	Reduced Power Operations	9.1%	0.0%	0.0%	6.3%	0.0%	1.9%
	Unit Off-Line	36.4%	0.0%	0.0%	25.0%	7.9%	13.0%
	Reactor Trip	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	No Effect	54.5%	100.0%	100.0%	68.8%	92.1%	85.2%
	Number of Failures	11	2	3	16	38	54
Auxiliary Feedwater	Reduced Power Operations	0.0%	0.0%	0.0%	0.0%		0.0%
	Unit Off-Line	0.0%	0.0%	0.0%	0.0%	N/A	0.0%
	Reactor Trip	0.0%	28.6%	0.0%	9.1%		9.1%
	No Effect	100.0%	71.4%	100.0%	90.9%		90.9%
	Number of Failures	11	7	4	22	0	22
CVCS Charging Pump (HHSI)	Reduced Power Operations	8.3%	40.0%	0.0%	16.7%		16.7%
	Unit Off-Line	0.0%	0.0%	0.0%	0.0%	N/A	0.0%
	Reactor Trip	8.3%	0.0%	0.0%	5.6%		5.6%
	No Effect	83.3%	60.0%	100.0%	77.8%		77.8%
	Number of Failures	12	5	1	18	0	18
BWR Core Spray	Reduced Power Operations					0.0%	0.0%
	Unit Off-Line	N/A	N/A	N/A	N/A	0.0%	0.0%
	Reactor Trip					0.0%	0.0%
	No Effect					100.0%	100.0%
	Number of Failures	0	0	0	0	12	12

Table 4.8 (Cont'd)

		PWRs			All PWRs	All BWRs	All Plants
System	Effect on System (percent of failures)	Westnghse	CE	B&W			
PWR Containment Spray	Reduced Power Operations	0.0%	0.0%		0.0%		0.0%
	Unit Off-Line	0.0%	0.0%	None	0.0%	N/A	0.0%
	Reactor Trip	0.0%	0.0%		0.0%		0.0%
	No Effect	100.0%	100.0%		100.0%		100.0%
	Number of Failures	13	3	0	16	0	16
PWR Safety Injection	Reduced Power Operations	0.0%	0.0%	0.0%	0.0%		0.0%
	Unit Off-Line	0.0%	0.0%	0.0%	0.0%	N/A	0.0%
	Reactor Trip	0.0%	0.0%	0.0%	0.0%		0.0%
	No Effect	100.0%	100.0%	100.0%	100.0%		100.0%
	Number of Failures	9	2	4	15	0	15
Condensate	Reduced Power Operations	8.3%	0.0%		5.9%	6.3%	6.1%
	Unit Off-Line	33.3%	0.0%	None	23.5%	43.8%	33.3%
	Reactor Trip	50.0%	100.0%		64.7%	37.5%	51.5%
	No Effect	8.3%	0.0%		5.9%	12.5%	9.1%
	Number of Failures	12	5	0	17	16	33
Main Feedwater	Reduced Power Operations	4.2%	0.0%	0.0%	3.7%	100.0%	7.1%
	Unit Off-Line	4.2%	0.0%	0.0%	3.7%	0.0%	3.6%
	Reactor Trip	45.8%	100.0%	100.0%	51.9%	0.0%	50.0%
	No Effect	45.8%	0.0%	0.0%	40.7%	0.0%	39.3%
	Number of Failures	24	2	1	27	1	28
Circulating Water	Reduced Power Operations	0.0%	0.0%		0.0%	0.0%	0.0%
	Unit Off-Line	50.0%	0.0%	None	46.2%	50.0%	47.6%
	Reactor Trip	50.0%	100.0%		53.8%	50.0%	52.4%
	No Effect	0.0%	0.0%		0.0%	0.0%	0.0%
	Number of Failures	12	1	0	13	8	21
Service Water	Reduced Power Operations	19.2%	0.0%	0.0%	11.6%	0.0%	9.1%
	Unit Off-Line	34.6%	0.0%	0.0%	20.9%	0.0%	16.4%
	Reactor Trip	46.2%	12.5%	0.0%	30.2%	0.0%	23.6%
	No Effect	0.0%	87.5%	100.0%	37.2%	100.0%	50.9%
	Number of Failures	26	8	9	43	12	55

The major plant effects observed in LERs involving condensate system motors were reactor trips and forced shutdowns of the plant. The same was observed for circulating water system motors, however, the total number of LERs was less than for the condensate system. In PWRs, about half of the large motor LERs on the feedwater system involved reactor trips. Feedwater at BWR plants was less susceptible, with only one LER identified, and this incident caused the plant to reduce power operation.

5. MAINTENANCE, MONITORING, AND SURVEILLANCE

The maintenance, monitoring, and surveillance practices available to, and used by, nuclear power generating stations for large electric motors are discussed in this section. The most common practices are outlined, along with manufacturer and industry recommendations for large motor maintenance and monitoring. The requirements of nuclear plant Technical Specifications with regards to large pump motors are described, and the elements of actual plant maintenance programs are provided. An evaluation of the focus of plant and industry activities is made in comparison to the types of failures identified in the operating history, and their importance. Based on this evaluation, techniques for the maintenance and monitoring of large electric motors are discussed.

5.1 Manufacturers' Recommendations

Large motor manufacturers have the greatest knowledge and experience with their products, and thus, the foundation of all maintenance activities must be based upon the manufacturers' recommendations. These can be grouped into two areas: continuous monitoring, consisting of automatic protective devices and alarms, and preventive maintenance, a periodic series of inspections, adjustments, and tests to keep the motor operating within specifications.

5.1.1 Continuous Monitoring

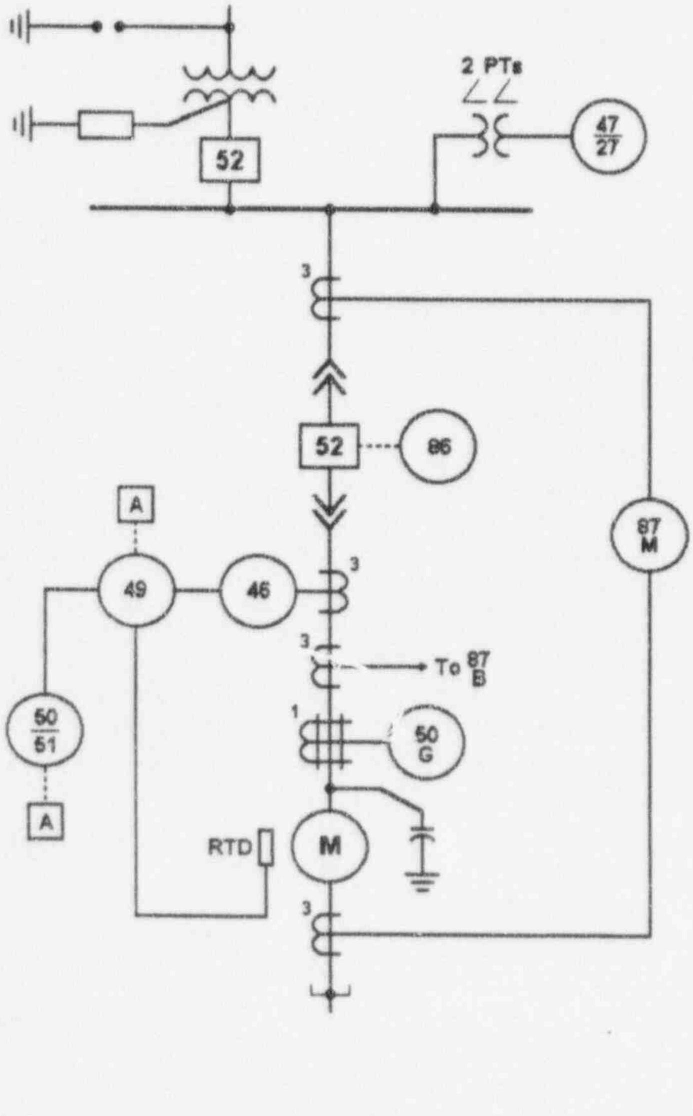
Continuous monitoring requirements are based upon the original specification for the motor in a given application. Operating a motor under conditions beyond the limits for which it has been designed, even if only occasionally, will severely shorten its life and may lead to catastrophic failures. The motor specification and the system designer should assure that the motor is initially matched to the application. Initial design considerations should cover the service conditions for the motor: environment, service factor, load characteristics, location, orientation, power supply quality, and duty cycle. The plant operating and maintenance personnel are then responsible for seeing that the motor is operated within design parameters. Continuous monitoring is performed to verify that the actual service conditions do not exceed certain specific design parameters.

The protective relaying and surge protection recommended by the manufacturer and the system designer are designed to protect the electrical integrity of the motor from damage caused by power supply problems or internal faults. These problems are summarized in the FMEA in Table 3.3 for the Group 1 stator components and Group 4.2 connectors. A one-line diagram of a typical protection scheme for a large induction motor is shown in Figure 5.1. Station lightning arresters provide protection from voltage surges originating outside the plant. Surge capacitors, located in proximity to the motor, provide additional surge protection at the motor and dampen electrical transients. The protective relays shown in the figure protect against under and over-voltage conditions, current imbalances, single phasing, internal faults, overloads, ground faults, and starting overcurrents. Large synchronous motors would require additional relaying for field excitation protection and synchronization.

Continuous monitoring to protect the mechanical integrity of the machine can include: stator winding temperature, bearing temperature, bearing vibration, lubricating oil temperature, cooling water temperature, discharge air temperature, lubrication oil flow and/or pressure, and lubricating oil level. As described in the FMEA in Table 3.3, temperature limits protect the electrical insulation from excessive thermal degradation, and prevent breakdown of the lubricant. Vibration limits alert operators to imbalances in the pump/motor or bearing wear so that they can be corrected before damage has occurred to the insulation, the rotor, the bearings, or other components. Lubricating oil system parameters assure that an adequate supply of clean oil is supplied to the bearings to keep them operating properly. These parameters may be transmitted to indicators, recorders, alarms, or computer data acquisition systems.

5.1.2 Preventive Maintenance

Preventive maintenance recommendations from manufacturers emphasize four main areas: (1) general cleanliness, (2) insulation and windings, (3) bearings and lubrication, and (4) vibration (Refs. 21-24). These are accomplished by periodic inspections, adjustments, and condition monitoring tests.



LEGEND	
DEVICE	FUNCTION
A	Alarm
M	AC Motor
PT	Potential Transformer
RTD	Resistance Temperature Detector
27	Undervoltage Relay
46	Unbalanced Current Relay
47	Phase-sequence Voltage Relay
49	Thermal Overload Relay
50	Instantaneous Overcurrent Relay
50G	Instantaneous Ground Overcurrent Relay
51	AC Time Overcurrent Relay
86	Lock-out Relay
87B	Bus Differential Relay
87M	Motor Differential Relay

Figure 5.1 Example one-line diagram of protective relaying scheme for large electric motor

General Cleanliness - Dirt, dust, oil, and grease can have a detrimental effect on the life of an electric motor. Buildup of the these substances outside the machine, can restrict cooling air flow through ventilation screens and passages causing increased operating temperature. Accumulations internally, on winding surfaces and leads, inhibit heat dissipation and result in increased operating temperature. Some dusts may be conductive as well as abrasive and can lead to insulation failure. It can also absorb oil and grease forming a gummy coating on machine internals, that can further inhibit heat dissipation, contribute to insulation breakdown, and chemically deteriorate insulation materials and bearing seals. Excessive dirt and particles, which are abrasive, can also work their way into bearings and lubricants causing damage to these critical elements.

Manufacturers recommend periodic cleaning and housekeeping, both externally, in the area of the machine, and internally as well. Operators can visually inspect the machine while it is running to note unusual noises, vibration, presence of water or moisture, sparking or smoke, leaks, high operating current, or other abnormal conditions on their daily rounds, and also to verify that ventilation passages are kept clear of dirt or any external obstructions that could impede cooling air flow.

Insulation and Windings - In addition to the normal daily operator rounds and parameter checks, the windings and internals of the motor should be cleaned at regular intervals ranging from six to eighteen months depending upon the location and accessibility of the motor. Suction or vacuum cleaning should be used to remove loose particles of dust and dirt that have built up on motor windings and internals. Clean, dry, oil-free compressed air at low pressure (30-50 psi) can be used to blow oil- and grease-free dirt and dust off of windings and away from inaccessible areas such as air ducts and coil spaces at the end turns. Care must be taken not to just blow the dirt into another, even more inaccessible, part of the motor, or into an area where it can do more harm.

If the dust has become oily or greasy, cleaning may be accomplished by low pressure steam cleaning with a neutral nonconducting detergent (Ref. 21), or gently hand-cleaned with a solvent (Refs. 22 and 25). All moisture must be removed and the winding thoroughly dried before reinstallation. Revarnishing of the windings may be necessary following more extensive cleanings, if the varnish has worn down or evidence of winding movement is noted.

Insulation resistance (IR) testing is recommended primarily as an "indication of the suitability of an insulation for operation or for further test at an overpotential" (Ref. 23). Due to the sensitivity of insulation resistance measurements to temperature, humidity, volume of insulation, and other factors, manufacturers recommend trending (monthly, if possible, Ref. 23) the temperature-corrected insulation resistance history of each machine for changes that could indicate potential insulation problems. Research has shown that generally insulation resistance should be considered a "go/no-go" test of insulation condition (Ref. 7). Polarization index (PI), the ratio of the 10 minute insulation resistance to the 1 minute insulation resistance, is recommended for determination of the dryness of windings and presence of contamination.

Another electrical test mentioned by several manufacturers (Ref. 23) is the ac overpotential test. It is used to obtain assurance in the minimum strength of the insulation. The overpotential test, more commonly known as the high potential or high-pot test, could potentially puncture insulation that might otherwise give many more years of reliable service. Therefore, it should be preceded by a visual inspection of the insulation condition and insulation resistance measurement. Limits on the test voltage must be carefully selected to avoid unnecessarily damaging the insulation during the test; often the test is used prior to overhaul to identify weak spots in the motor's insulation.

Lubrication and Bearings - Lubrication, whether it be grease or lubricating oil, should be of the type and grade specified by the manufacturer. The quantity of grease used is important because overgreasing can lead to leakage from the seals. Excessive grease can contaminate the windings and rotor surfaces and inhibit heat transfer. It can also block ventilation passages, further restricting cooling air flow. Excessive grease within the housing can also raise bearing temperature and increase wear on the bearings (Ref. 27). Insufficient oil level in oil lubricated bearings and forced-feed lubrication systems can produce high bearing temperatures, breakdown of oil lubricating properties, and excessive wear (see Table 3.3, failure modes 3.1.1 and 3.4.1).

For grease lubricated bearings, the grease will loose its lubricating ability over time. The grease must be replaced periodically to account for this. The period for changeout will vary, depending upon the type of grease, bearing size, operating temperature, duty cycle, operating speed, dirt or other contamination, and the environment in which the motor operates (Refs. 22 and 26).

Similarly, large electric motors that use oil lubricated, and forced-feed oil lubricated bearings, will require periodic oil changeout. Oil change intervals vary depending upon service conditions, as explained in the above paragraph, but a nominal interval is six months. At the time of the oil change, bearing housings can be cleaned, the oil sump cleaned and sediments removed, oil filter changed, and oil system flushed as required (Refs. 21, 23-26). Manufacturers recommend that the oil be subject to chemical analysis to assess the lubricating properties of the oil, level and type of contamination, and to examine particles (size, type, and concentration) that could be indicative of excessive bearing wear, leakage, or other problems.

Bearings have a finite life, which can be affected by the operating conditions of the motor. This will require replacement of the bearings at periodic intervals, or sooner if inspections, bearing temperature, vibration, or other indications show that damage or excessive wear has occurred (Refs. 21-26).

Periodic inspection and replacement of bearings is recommended based upon the service conditions of the particular application. Air gap measurement and insulation resistance of insulated bearings and bearing pedestals are other tests that can help to identify excessive bearing wear conditions.

Vibration - If excessive vibration or noise is noted, it should be traced to its source and corrected (Ref. 22). Vibration can be caused by several problems including: misalignment, loose coupling, uneven air gap alignment, settling of the foundation, loose or improperly torqued motor mounts, parts rubbing the rotating element, sprung or bent shaft, rotor imbalance, short circuited field coils in a synchronous motor, unbalanced stator current, or pump problems (Refs. 21 and 23).

Periodic inspection and alignment check of motor load couplings is recommended. Alignment and dynamic balancing should also be performed periodically or whenever high vibration levels are noted.

Periodic spectral analysis of machine operating vibration can provide information on the amplitude, frequency, and phase of various dominant vibration peaks (Ref. 26 and Ref. 7, Table 2-1). These can be used to determine the origin of the vibration and detect premature wear.

5.2 Industry and Research Recommendations

Much work has been done by industry in the area of electric motor maintenance. Some of the more important recent efforts are presented in this section to represent the current thinking. These are: NUREG/CR-4939 (Ref. 7), an earlier NRC-sponsored aging research study on motor reliability in nuclear power plants; IEEE Draft Guide P-1359 (Ref. 28), Section 7, on maintenance good practices for motors prepared by Working Group 3.3 of the IEEE Nuclear Power Engineering Committee; and EPRI NP-7502 (Ref. 29) on motor maintenance in the utility industry. These will be summarized in this section.

5.2.1 NRC Sponsored Research

NUREG/CR-4939, "Improving Motor Reliability in Nuclear Power Plants, Volume I: Performance Evaluation and Maintenance Practices," (Ref. 7) provided a comprehensive assessment of the inspection, surveillance, maintenance, and condition monitoring methods used for electric motors in the nuclear industry. A preventive maintenance program was suggested with test intervals based upon a reliability centered maintenance (RCM) approach within the structure of the typical 18 month refueling cycle of nuclear plants. Motor condition monitoring parameters determined during periodic testing are recorded and the data are trended. The nominal maintenance intervals for various motor components may then be adjusted according to the indications of the trended parameters and maintenance history.

As part of the study, recommendations were made on various periodic and surveillance tests that may be used on large motors. These are summarized in Table 5.1 adapted from Reference 7, along with the typical test frequency and an assessment of the trendability of the data provided from each test. Insulation resistance and polarization index tests, and overpotential (high-pot) tests were previously discussed (Section 5.1.2). Reference 7 suggested that insulation resistance/polarization index tests and surge test results are not suitable for condition monitoring, but rather are more useful as a "go/no-go" indicator for pre- and post-maintenance operation of motors.

Other electrical tests in Table 5.1 include the power factor or dissipation factor/capacitance tests, voltage impulse (surge) test, and partial discharge test. These tests are described in more detail in Appendix A, in Reference 7.

The power factor or dissipation factor tests measure the insulation power factor, i.e., the ratio of real power dielectric losses in the insulation to the applied apparent power, when a steady state ac voltage, at power frequency, is applied to the winding of a motor. When the ac test voltage is applied, most of the current that flows is charging current due to the capacitance of the winding. Capacitance is less sensitive to insulation condition than the dielectric loss, due to leakage current. As the insulation deteriorates, voids form, delamination increases, and the result is an increase in leakage current. The power factor of the insulation therefore increases as the insulation ages.

Surge testing compares the simultaneous responses of two motor windings to a rapidly rising voltage surge applied from the discharge of a capacitor in the test apparatus. Comparison of the resulting traces from the two windings on an oscilloscope, can produce characteristic responses that are indicative of various winding problems. Experts can distinguish good windings from faults such as turn-to-turn shorts, coil-to-coil shorts, phase-to-phase shorts, grounds, and open conductors.

Table 5.1 Periodic Tests on Large (>250 hp) Motors - NUREG/CR-4939 (Ref. 7)

Performance Evaluation Test	Safety	Non Safety	Frequency (Months)	Trending	Remarks
Insulation Resistance/ Polarization Index	X	X	12-18	No	IR/PI Tests are go/no-go tests. Indicates dryness of insulation. Should be used prior to energization for pre- and post-maintenance.
AC/DC Leakage (High-pot)(1)	X	X	36-60	No	Ac tests preferable for ac motors. Should be conducted in stepped voltages up to the maximum rated voltage.
Power Factor/ Dissipation Factor(2)/ Capacitance	X	X	18-36	Yes	Used for high voltage machines. Power factor tip-up plot provides void growth in insulations.
Voltage Impulse/Surge			6-18	No	Comparison of wave forms with that of a good insulation provides condition of insulation.
Partial Discharge	X	X	6-18	Yes	Used for large machines with voltage rating above 500 V.
Running Current(3,5)	X	X	12-24	Yes	No load, full load, rotor currents.
Motor Vibration(4,5)	X	X	6-18	Yes	Used to monitor structural and bearing integrities, and end turn movement.
Lubrication/Oil Analysis	X	X	18-36	Yes	Specifically for sleeve/plate bearing degradations.
Nondestructive Testing	X	X	36-60	Yes	Ultrasonic tests for detecting cracks in metal components.
Speed(3,5)	X		12-24	Yes	Surveillance test; may be monitored continuously on-line in larger motors
Bearing Temperature(3,5)	X		12-24	Yes	Surveillance test; may be monitored continuously on-line in larger motors
Bearing Vibration(3,5)	X		6-18	Yes	Surveillance test; may be monitored continuously on-line in larger motors
Winding Temperature(3,5)	X		12-24	Yes	Surveillance test; may be monitored continuously on-line in larger motors

(1) High-pot 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 preventive maintenance.
(3) Part of surveillance testing on safety-related motors.
(4) If built-in transducers are not available, portable units must be used.
(5) Can be used as on-line monitoring.

Partial discharge testing is a method developed by Ontario Hydro and the Canadian Electrical Association for measuring the level of activity of high frequency electrical discharges, or corona. Partial discharges are a symptom and a cause of gradual deterioration of high voltage stator windings, and reflect the condition of the insulation in stator windings. It can identify and locate increase in the quantity of voids, delamination, loose stator wedges, slot discharges, or contaminated end windings. Improvements in the testing probes, equipment and techniques have made partial discharge tests more user friendly, however, the experience of the operator is still an important factor in interpreting the results.

The remainder of the tests recommended in Table 5.1 were discussed in Section 5.1.2 on the manufacturers recommendations for periodic maintenance. Note that several of the periodic tests and surveillance tests shown in the table may be accommodated by on-line continuous monitoring capability.

5.2.2 IEEE Work

The IEEE Guide P-1359, "Draft Guide for Maintenance and Related Practices for Class 1E Equipment Used in Nuclear Power Generating Stations" (Ref. 28), prepared by Working Group 3.3 - Maintenance Good Practices, of Subcommittee 3 - Operations, Surveillance, and Testing, of the IEEE Nuclear Power Engineering Committee was developed to provide a reference source of maintenance good practices to the utility maintenance engineer, the equipment manufacturer, and others responsible for specifying maintenance of Class 1E equipment. Section 7, dealing with maintenance good practices for motors, provides a series of recommended preventive maintenance activities. Based upon a review of electric motor failure data from the IEEE Industry Applications Society survey (Refs. 9 and 10), the EPRI research study (Ref. 19), and NRC-sponsored NPAR program work done by Brookhaven National Laboratory (Ref. 5), the working group identified preventive measures to address the types of failures noted. Table 5.2, taken from Reference 28, summarizes the working group recommendations for continuous, periodic, and predictive maintenance. Note that these are grouped by observable conditions, or symptoms, of the degraded motor condition. This allows for easy comparison with the failure modes and effects in the FMEA in Table 3.3.

5.2.3 EPRI Research

The "Electric Motor Predictive and Preventive Maintenance Guide" (Ref. 29) prepared by Bechtel Group, Inc., for EPRI, provides information and guidance to nuclear plant licensees regarding maintenance of electric motors in nuclear and balance of plant applications. This document was also developed using the failure data from previous studies to focus maintenance activities on the kinds of failures that were being experienced in plants. In addition, information from nuclear plant maintenance personnel, motor repair shop personnel, manufacturers, diagnostic equipment vendors, and NPRDS data were incorporated into the analysis and development of predictive and preventive maintenance recommendations. The EPRI guide emphasizes a reliability centered maintenance (RCM) approach, and as such, provides detailed guidance on the types of parameters and condition monitoring that can be trended.

Tests, inspections, and their corresponding performance intervals recommended by EPRI for large squirrel cage induction motors, in direct drive applications, are presented in Table 5.3, adapted from Reference 29. For large squirrel cage induction motors, there were no differences between the tests recommended for safety-related motors and the balance of plant applications. The tests and intervals suggested for continuous duty and intermittent duty applications are nearly the same, with the exception of more frequent running current checks for the continuous duty motors. Tests that must be performed

Table 5.2 Recommended Preventive Maintenance for Motors-IEEE Draft Guide P-1359 (Ref. 28)

Observable Conditions	Recommended Preventive Measures		
	Continuous	Periodic	Predictive
Persistent Overloading	Overcurrent Protective Devices	Line Current Measurements	Not Applicable
High Ambient Temperature, Poor Ventilation or Cooling	Winding and Bearing Temperature Detectors(1)	Review of Temperature Readings(1) Visual Inspection Cleanliness Activities	Trend of Temperature Readings(2)
Abnormal Moisture	Space Heaters (areas of high moisture content)	Routine Insulation Tests(2): -Insulation Resistance -Polarization Index (IEEE Std 43-1972)	Insulation Power Factor Tests (medium-voltage motors; IEEE Std 286-1975)
High Vibration	Vibration Monitoring System (Reactor Coolant Pump Motors) Vibration Switches(1)	Vibration Level Reading(1)	Trend of Vibration Readings(3)
Poor Lubrication	Oil Pressure Monitoring (forced-feed systems)	Oil Changes Re-greasing	Oil Analysis (ASTM Stds D88-81, D974-85, and D943-81) 10 Percent Grease Life
Normal Age Deterioration	Not Applicable	Surge or Partial Discharge (Corona) Tests(4) (IEEE Std 432-1976)	Insulation System and Bearing Life Estimates (EPRI NP-3887 and IEEE Std 334-1974) Qualified Life (IEEE Std 334-1974)

(1) If detectors are not installed, take periodic readings using portable detectors.
(2) Where the adequacy of the insulation is of concern, test per IEEE Std 432-1976.
(3) Perform vibration frequency analysis when concern is warranted.
(4) Consider where age-related failures have occurred.

Table 5.3 Recommended Tests: Squirrel Cage Induction Motors Above 200 HP, Form Wound Stator, 4000 Volts and Higher, Safety-Related and Balance of Plant-EPRI NP-7502 (Ref. 29)

Recommended Tests/Inspections	Trendable	Duty Cycle (Months)		
		Continuous	Intermittent	Layup
Supply Voltage	Yes	24-48	24-48	
Running Current	Yes	6-12	12-24	
Motor Speed	Yes	24-48	24-48	
Bearing Temperature	Yes	6-9	6-9	
Winding Temperature	Yes	6-12	6-12	
Insulation Resistance[5]	Yes	12-18	12-18	12-18
Polarization Index[5]	Yes	12-18	12-18	12-18
Current Analysis	Yes	36-60	36-60	
DC Hipot (Step)[5]	Yes	36-60	36-60	
Motor Vibration	Yes	6-9	6-9	
(Oil Analysis)[5]	Yes	Note 1	Note 1	
Winding Resistance[5]	Yes	12-18	12-18	
External Inspection	No	12-18	12-18	12-18
Borescope Inspection[2, 5]	No	60-72	60-72	
Disassemble/Inspect[5]	No	120-180	120-180	
(Regrease)	No	Note 3	Note 3	Note 4
Surge Comparison[5]	No	60-72	60-72	
Rotate by Hand[5]	No			3-19

1. 3-18 months: Water content, viscosity, oxidation, spectroscopy, ferrography (direct reading or particle count).
   12-24 months (or as required): ferrography (analytical).
2. Borescope Inspection for 1000 hp and larger.
3. 1200-1800 rpm motors: 24-36 months (once per 2 operating cycles, not to exceed 40 months)
   3600 rpm motors: 12-18 months (once per 2 operating cycles, not to exceed 22 months).
4. Greasing intervals for motors in standby or layup should be 1.5 times that of continuously operating motors. Note: Performance of off-line tests on large critical motors should be scheduled to coincide with plant refueling cycles.
5. Off-line tests.

while the motor is off-line are indicated to distinguish them from typical on-line tests, many of which are continuously monitored automatically in the larger motors. The EPRI report also provides recommendations for layup of motors, that are very similar to typical manufacturer layup instructions.

An important part of the EPRI work is the recommendation for trending of data for predictive maintenance. Table 5.3 shows the data parameters that EPRI suggests be recorded and trended as part of a reliability centered maintenance program for motors. Acknowledging that bearings and bearing-related (lubrication) failures are significant in large electric motors, EPRI recommends shorter intervals on tests and inspections of the bearings, lubrications system, and oil (or grease) analysis than in the recommendation from the manufacturer or from Reference 7. More frequent surveillance of bearings and trending analysis of motor operating parameters would be very useful in improving the reliability of large electric motors.

Another strength of the RCM approach, is that it provides the flexibility to adapt maintenance activities to changes in the operating cycle. For example, if the plant changes from an 18 month operating cycle to a 24 month cycle, the condition monitoring, trending of data, and predictive maintenance aspects of an RCM program would allow effective adjustment of preventive maintenance intervals to accommodate the new operating cycle.

Similar recommendations for testing and inspection of large synchronous motors (> 1000 hp) and wound rotor induction motors can be found in Reference 29.

5.3 Plant Practices

The maintenance practices and activities at a Westinghouse PWR and a General Electric BWR were reviewed to examine how nuclear plants typically address the maintenance, surveillance, and monitoring of large electric motors.

5.3.1 Technical Specifications Requirements

There are no plant Technical Specifications and surveillance testing requirements that deal specifically with large electric motors. Rather, the pumps that are driven by the large motors are the subjects of Technical Specifications requirements. The pumps, associated valves, and the I&C equipment associated with the pumps for safety-related systems will be included in several Technical Specifications and surveillance requirements. In addition, the Technical Specifications requirements for pump and valve inservice testing (IST) based upon Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code will also indirectly serve as a performance test for many large electric motors (Ref. 30). IST pump and valve testing for pumps and valves will provide a functional test of the pump motor starting and operating logic, as well as a verification of the motor's output capacity.

At this point, a brief description of the Technical Specifications is provided for two representative plants, one a Westinghouse PWR (Ref. 31) and the other a General Electric BWR (BWR/4) (Ref. 32), as they relate to several large pump motors. A review of the standard Technical Specifications surveillance requirements and their frequencies, as derived and related to pumps and reactor coolant flow, is made. The position adopted in this analysis is that these selected surveillance requirements provide typical information on the operability of systems with pumps driven by large motors, at specified surveillance intervals. Most plants will include some steps in the related plant surveillance procedures to record and verify selected operating parameters for the drive motors. The bulk of the motor performance checks and preventive maintenance and monitoring will be included in other, dedicated motor maintenance procedures as described in Section 5.1.2.

The systems with large pump motors covered in the Plant Technical Specifications will include nuclear safety-related systems (service water and the emergency core cooling systems, such as RHR/LPCI, core spray, or high pressure core spray in BWRs, and RHR, auxiliary feedwater, safety injection, and containment spray in the PWR), nonsafety-related nuclear systems (such as, RCS in the PWR and reactor recirculation in the BWR), and some balance of plant systems. The relevant Standard Technical Specifications surveillance requirements related to large pump motors for PWRs and BWRs are summarized in Tables 5.4 and 5.5, respectively.

The tables indicate the system, the reference standard surveillance number, a description of the surveillance requirement, and finally the typical surveillance performance frequency. As mentioned previously, most of these surveillances are concerned with verifying the operability of these systems through valve lineup verification, operability checks, and pump performance verifications. The surveillances relate to the large motors indirectly as the prime movers for the pumps. Surveillance frequencies for these systems range from once every 12 hours, to once per 18 month refueling cycle.

Also included in Tables 5.4 and 5.5 are IST surveillances. All pumps and valves in PWRs and BWRs are mandated by 10CFR50.55a (Ref. 33) to comply with the inservice testing (IST) requirements set forth by Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Ref. 30). Some of the requirements for the inservice testing of pumps are outlined below.

According to the inservice testing procedures for pumps (Ref. 30), the following inservice test quantities are to be measured and reported in the plant logbook:

1) Speed (N) (if a variable speed pump)
2) Discharge Pressure (P) (for positive displacement type pumps)
3) Differential Pressure (ΔP) (for centrifugal type pumps only)
4) Flow Rate
5) Vibration Amplitude (displacement or velocity)

Early editions of the B&PV Code also specified that inlet pressure, lubricant level, and bearing temperature be monitored. However, these parameters were deleted from the latest revisions. Inlet pressure is a parameter needed to ensure proper test procedure, assuring proper lubricant level should be included as regular maintenance, and increases in bearing temperature are seen just before failure, and would not be detected in yearly tests. Reference test values are established in these tests. Subsequently, measured values shall be compared with the allowable ranges of test quantities as specified in the Code. The acceptable, the alert low and alert high values, and the required-action ranges for pump operation are specified in terms of the reference values. For example, remedial action is required if the differential pressure or the flow rate showed a deviation by more than 10% on the low or 3% the high end of the reference values.

The frequency of inservice testing of each pump shall be nominally every 3 months during normal plant operation. During shutdown periods, it is recommended that this test frequency be followed if possible; otherwise, the pump shall be tested one week after the plant resumed normal operations. The

Table 5.4 Standard Technical Specifications, Westinghouse Plants (Ref. 31)

System Pump	SR No.	Surveillance	Frequency
Reactor Coolant System (RCS)	3.4.1.3	Verify RCS total flow rate	12 hr.
	3.4.4.1 (Modes 1 & 2) 3.4.5.1 (Mode 3) 3.4.6.1 (Mode 4) 3.4.7.1 (Mode 5) 3.4.8.1 (Mode 5-Loops not filled)	Verify operating performance of each RCS loop (flow rate, temperature, pump status).	12 hr.
	3.4.5.3 (Mode 3)	Verify RCPs are OPERABLE by verifying proper breaker alignment and power availability.	12 hr.
	3.4.6.3 (Mode 4)	Verify RCS and RHR pumps are operable.	W
	3.4.7.3 (Mode 5)	Verify that second RHR pump is operable.	W
	3.4.8.2 (Mode 5-Loops not filled)	Verify that required number of RHR and RCS pumps are OPERABLE.	W
Emergency Core Cooling Systems (ECCS)	3.5.2.4	Periodic ECCS pump testing to detect gross degradation.	ITP
	3.5.2.6	Verify that ECCS pump starts upon receipt of simulated SI signal	ITP
Containment Systems (CS)	3.6.6A.3 3.6.6B.3	Verify each containment cooling train ESW cooling flow rate.	M
	3.6.6A.4 3.6.6B.4 3.6.6C.2 3.6.6D.2 3.6.6E.5 (Recirc. Spray)	Demonstrate each CS, or Quench Spray, pump's developed head at the flow test point exceeds the required developed head.	IST

Table 5.4 (Cont'd)

System Pump	SR No.	Surveillance	Frequency
Containment Systems (CS) (Cont'd)	3.6.6A.6 3.6.6B.6 3.6.6C.3 3.6.6D.3 3.6.6E.6 (Recirc. Spray)	Verify that each CI, or Quench Spray, valve actuates, and each pump starts upon receipt of a containment high pressure signal.	R
Auxiliary Feedwater System (AFW)	3.7.5.2	Verify that the AFW pumps develop suff. discharge pressure to deliver required flow at full open pressure of the MSSVs.	M
	3.7.5.4	Verify that each AFW pump starts upon receipt of actuating signal	R
Component Cooling Water System (CCW)	3.7.7.3	Verify automatic operation of CCW pumps upon receipt of actuation signal.	R
Service Water System (SW)	3.7.8.3	Verify automatic operation of SW pumps upon receipt of actuation signal.	R

Notes:

1. Key to test frequencies: 12 hr. = every 12 hours; W = 7 days; M = Monthly (31 days); Q = Quarterly (92 days); R = once per 18 month refueling cycle; ITP = Inservice Testing Program.

allowed time for analysis of test data shall be 96 hours after completion of tests. In certain instances, tests may be deferred to cold shutdowns or refueling outages.

5.3.2 Review of Plant Maintenance Activities

Site visits were made to a Westinghouse PWR plant and a General Electric BWR plant to review their maintenance programs with respect to large electric motors. The PWR plant, Plant A, has been in operation since the mid 1980s and the BWR, Plant B, has been operating since the early 1970s. The site visits included collection and review of technical information such as drawings, system descriptions, plant maintenance procedures, plant surveillance procedures, and design specifications for selected large electric motors. Plant maintenance scheduling information and maintenance history records were gathered and reviewed. Interviews were conducted with plant personnel to gain additional insights on the maintenance of large electric motors and to ensure that all significant motor failures and programs were identified. Plant personnel were also queried on their experiences with some of the new techniques for motor condition monitoring and any plans they had for adopting them into their motor maintenance programs.

Table 5.5 Standard Technical Specifications, General Electric Plants, BWR/4 (Ref. 32)

System Pump	SR No.	Surveillance	Frequency
Residual Heat Removal System (RHR)	3.4.8.1 3.4.9.1	Verify that one RHR shutdown cooling subsystem or recirculation pump is in operation	12 hrs.
	3.6.2.3.2	Verify that each RHR pump develops adequate flow for suppression pool cooling.	ITP
	3.6.2.4.2	Verify that each RHR pump develops adequate flow for suppression pool spray.	Q
	3.9.8.1 3.9.9.1	Verify adequate RHR flow rate with plant in Mode 5 (remove decay and sensible heat).	12 hr.
Emergency Core Coolant System (ECCS)	3.5.1.7	Verify adequate flow rates for the ECCS pumps.	ITP
	3.5.1.10	Verify automatic start of ECCS pumps upon initiation signal.	R
Plant Service Water System (PSW)	3.7.2.2	Verify that the water level in each pump well is sufficient for proper operation of the PSW pumps (NPSH and pump vortexing).	D
	3.7.2.6	Verify the automatic start capability of PSW pumps upon receipt of initiation signal.	R
Standby Service Water System (SSW)	3.7.3.2	Verify that the diesel generator SSW pump automatically starts upon diesel generator start and bus energization.	R

Notes:

1. Key to test frequencies: 12 hr. = every 12 hours; D = daily (every 24 hours); W = 7 days; M = Monthly (31 days); Q = Quarterly (92 days); R = once per 18 month refueling cycle; ITP = Inservice Testing Program.

The 23 large motors examined at the PWR plant included drive motors for the following applications:

Reactor Coolant Pumps (RCPs)	7000 hp	6.9 kv
Containment Structure Air Recirc Fans	250 hp	480 v
CRD Mechanism Cooling Fans	200 hp	480 v
CVCS Charging Pumps	600 hp	4.16 kv
RHR Pumps	450 hp	4.16 kv
Containment Recirculation Pumps	500 hp	4.16 kv
Steam Generator Feedwater Pump	12000 hp	6.9 kv
Condensate Pumps	4000 hp	6.9 kv

The RCPs are located inside containment, as are the containment structure air recirculation fans and the CRD cooling mechanism fans, which were included due to their location even though they are smaller than the target size of 500 hp for this study. The CVCS charging pumps, RHR pumps, and containment recirculation pumps are driven by Class 1E motors. The feedwater pump and the condensate pumps are BOP equipment and are located in the turbine building.

The 17 large motors examined at the BWR plant included drive motors for the following applications:

Reactor Recirculation Pumps	4500 hp	4.16 kv
Reactor Recirculation Pump MG Sets	4500 hp	4.16 kv
LPCI (RHR) Pumps	600 hp	4.16 kv
Feedwater Pumps	7000 hp	4.16 kv
Condensate Pumps	900 hp	4.16 kv
Condensate Booster Pumps	2000 hp	4.16 kv

The reactor recirculation pumps are located inside primary containment and are powered by the variable frequency reactor recirc pump MG sets that are located in the secondary containment part of the reactor building. The LPCI pumps are safety-related equipment and the motors are Class 1E. Feedwater, condensate, and condensate booster pumps/motors are BOP equipment located in the turbine building of the plant.

Review of one-line diagrams at both of the plants indicated that the protective relaying for the large motors was the same as that depicted in Figure 5.1. The motor winding temperature was monitored with an alarm at high temperature. Motor operating current had individual phase indication locally at the switchgear, and in the control room, with annunciator and computer alarms for overcurrent trips. Voltage was monitored at the bus level as in Figure 5.1, and differential relaying was provided for the individual motors and their supply buses. Neither the PWR nor the BWR used the unbalanced current protection (Device 46) at the level of the individual motor feeder as shown in Figure 5.1. Surge capacitors were used at the terminals of some of the motors depending upon the individual situation.

Maintenance and Monitoring at a PWR - The maintenance, monitoring, and testing of large motors at Plant A involved periodic surveillance testing for electrical insulation condition, vibration testing, and oil analysis. Surveillance testing is performed on the safety-related pump/motors as part of the Technical Specification operability verification procedures, a plant program for large motor monitoring, and ASME XI inservice inspection and testing (ISI/IST).

Technical Specification operability verification procedures and ISI/IST for the safety-related motors include suction and discharge pressure checks, pump flow, pump vibration, room/area cooler performance, and lube oil level. In addition, valve stroke times, and valve lineups are verified. Although these do not directly test the motor, they affect motor availability and can provide some indications of degraded motor performance.

An electrical insulation testing program is performed regularly for all 4160 volt and 6900 volt motors on a refueling cycle frequency (once per 18 months). The electrical insulation checks include insulation resistance, polarization index, stepped dc high potential test, surge capacitor capacitance measurement, and surge comparison tests. Data are collected and stored for later trending comparison and/or analysis. Temperature and humidity are recorded at the time of testing but the procedure does not include any provisions for temperature correction by the technicians performing the procedure.

The vibration testing for safety-related pumps/motors is included as part of the station's in-service inspection and testing (ISI/IST) program procedures, that are performed on a quarterly basis. Balance of plant pump/motors, such as the condensate and feedwater, and the RCP motors are included in a program for vibration monitoring of balance of plant pump/motors and fan/motors on a cycle of from 4 to 6 weeks.

Plant A has a plant lubrication program that covers lube oil sampling (including radioactive samples), lubrication procedures, types of lubricants, and analysis of samples. Specific lubrication maintenance techniques for large motors and other important plant motors are provided in the procedures.

Table 5.6 summarizes the surveillance monitoring and preventive maintenance for several of the large motors at Plant A. The main difference between the maintenance for Class 1E motors and the non-Class 1E motors at this plant is in the vibration monitoring area and the Technical Specifications operability tests. The BOP motors are part of a separate plant vibration monitoring program that is similar in substance to the ASME Section XI testing that the Class 1E motors undergo, but there are no Technical Specifications operability requirements. The reactor coolant pumps (RCPs) are driven by non-Class 1E motors; however, they receive the same surveillance and maintenance as the safety-related pump motors because of their importance in the RCS and limited access during power operation. Periodic preventive maintenance is virtually the same for safety and nonsafety-related large motors.

All large pump and fan motors have indication, monitoring, and/or alarms for selected parameters such as stator winding temperature, running amperes, vibration, bearing temperature. They are included on daily operations log sheets and operators' rounds, if accessible.

Other than some pump/motor balancing problems on the condensate pumps, and some problems with excessive loading on the thrust bearings of the RHR pump motors, no significant failures

Table 5.6 Surveillance and Maintenance for Large Motors at a PWR Plant - Plant A

Safety Class	Location	Pump Motor (Qty)	Surveillance Tests	Frequency	Preventive Maintenance	Frequency
Class 1E	Aux Bldg	CVCS charging pumps (3)	• ISI/IST per ASME Sect. XI • electrical insulation tests • operability tests per Tech Specs	Q R 12hr/M/Q	• IR/PI and electrical inspection • oil sample & analysis/oil change	SA SA
	ESF Bldg	RHR pumps (2)	• ISI/IST per ASME Sect. XI • electrical insulation tests • operability tests per Tech Specs	Q R 12hr/M/Q	• IR/PI and electrical inspection • oil sample & analysis/oil change • remove/inspect/ overhaul	SA SA 3Yr
Non-1E	Inside Containment	RCPs (4)	• BOP vibration monitoring • electrical insulation tests • operability tests per Tech Specs	4-6 Wks Q 12hr/M/Q	• IR/PI and electrical inspection • oil sample & analysis/oil change • remove/inspect/ overhaul and alignment	SA SA 3Yr
		Containment structure air recirc fans (3)	None	—	• IR/PI and electrical inspection • oil sample & analysis/oil change • alignment of fan/blades	SA SA R
		CRD mechanisms cooling fans (3)	None	—	• IR/PI and electrical inspection • oil sample & analysis/oil change • alignment of fan/blades	SA SA R
Non-1E BOP	Turbine Bldg	Condensate pumps (3)	• BOP vibration monitoring • electrical insulation tests	4-6 Wks R	• IR/PI and electrical inspection • oil sample & analysis/oil change • remove/inspect/ overhaul	SA SA 3Yr
		Steam generator feedwater pump (1)	• BOP vibration monitoring • electrical insulation tests	4-6 Wks R	• IR/PI and electrical inspection • oil sample & analysis/oil change • remove/inspect/ overhaul	SA SA 3Yr

Notes: (1) All motors included on operator daily log/rounds.

(2) Key to test frequencies: 12hr = every 12 hours; 4-6 Wks = every 4 to 6 weeks; M = monthly; Q = quarterly; SA = semiannually; R = once per 18-month refueling cycle; 3Yr = every other refueling cycle (36 months).

were experienced with any of the motors in Table 5.6. Most of the large motor corrective maintenance at Plant A were minor repairs involving leakage-type problems.

Maintenance and Monitoring at a BWR - The maintenance, monitoring, and testing of large motors at Plant B was very similar to the PWR plant above. It involved periodic surveillance testing for electrical insulation condition, vibration testing, and oil analysis.

The Technical Specification operability verification procedures and ISI/IST for the safety-related motors include suction and discharge pressure checks, pump flow, pump vibration, room/area cooler performance, and lube oil level. In addition, valve stroke times, pump flow rate, keep-fill pump pressure, and valve lineups are verified on a quarterly basis. Although the valve tests do not directly test the motor, they affect motor availability (as part of the motor's operating and control logic) and can provide some indications of degraded motor performance.

The electrical insulation surveillance testing program includes insulation resistance, polarization index, absorption ratio, stepped dc high potential test, surge capacitor capacitance measurement, and surge comparison tests. Data are collected and stored for later trending comparison and or/analysis. Temperature and humidity are recorded at the time of testing but the procedure does not include any provisions for temperature correction by the technicians performing the procedure.

The ISI/IST monitoring surveillances per ASME Section XI at Plant B are the same as was found at Plant A and the rest of the nuclear industry. Plant B includes the reactor recirc pumps in the program by monitoring jet pump performance parameters. All large motors, including BOP pump motors, have continuous monitoring for vibration with alarm.

Lubrication of large pump motors is included as part of the periodic preventive maintenance procedure for each motor. Oil level is checked quarterly by maintenance (in addition to operations daily rounds, where accessible), and full lube oil system inspection, cleaning, oil sample and analysis, and oil change are conducted every six months.

The electrical preventive maintenance program for large motors at Plant B consists of quarterly external cleaning and inspection, semi-annual electrical inspection and tests, and an overhaul inspection every three years. The quarterly external cleaning and visual inspection checks for dirt, oil, grease, moisture, corrosion, or other contaminants and calls for manual cleaning and vacuuming of the motor, windings, and ventilation screens if necessary. The visual inspection looks for signs of damage, chemical action, abrasive action, high temperature, condition of motor mounts, that the ventilation pathways are clear and clean, and oil level is correct. The semiannual electrical inspection directs the checking of motor ground connections, motor power and instrumentation connections, and condition of heaters. Relays, meters, indicators, and timers are given a calibration check. Every three years the motor is disassembled, cleaned, inspected and repaired as necessary. Plant B has an electrical insulation testing program that calls for testing all 4 kV motors approximately every 18 months.

Table 5.7 summarizes the surveillance monitoring and preventive maintenance for several of the large motors at Plant B. There is very little difference between the maintenance for Class 1E motors and the non-Class 1E motors at this plant. Technical Specifications operability requirements account for the differences in the surveillance testing of the different pump motors.

Basically, the types of tests are similar. The periodic preventive maintenance is nearly the same for all of the large motors at Plant B. Accessibility considerations have accounted for some differences in the vibration monitoring of the reactor recirc pump motors. For the reactor recirc pump MG set motors, the plant has elected to use a RCM approach by more frequent vibration monitoring and spectral analysis, with corrective maintenance actions as required.

Table 5.7 Surveillance and Maintenance for Large Motors at a BWR Plant - Plant B

Safety Class	Location	Pump Motor (Qty)	Surveillance Tests	Frequency	Preventive Maintenance	Frequency
Class 1E	Reactor Bldg (secondary containment)	RHR (LPCI) pumps (4)	• ISI/IST per ASME Sect. XI • electrical insulation tests • operability tests per Tech Specs	Q R M/Q/R	• external cleaning & visual inspection • IR/PI and electrical inspection • oil sample & analysis/oil change • remove/inspect/ overhaul and alignment	Q SA SA 3Yr
Non-1E	Reactor Bldg (primary containment)	Reactor recirc pumps (2)	• ISI/IST per ASME Sect. XI • jet pump operability test per Tech Specs • operability tests per Tech Specs	Q Q S/U & M/Q	• external cleaning & visual inspection • IR/PI and electrical inspection • oil sample & analysis/oil change • remove/inspect/ overhaul and alignment	Q SA SA 3Yr
	Reactor Bldg (secondary containment)	Reactor recirc pump M-G set motors (2)	• electrical insulation tests	R	• IR/PI and electrical inspection • oil sample & analysis/oil change • vibration analysis	SA SA M
Non-1E BOP	Turbine Bldg	Condensate booster pumps (3) Condensate pumps (3) Feedwater pumps (3)	• BOP vibration monitoring • electrical insulation tests • operability tests per Tech Specs	M R Q	• external cleaning & visual inspection • IR/PI and electrical inspection • oil sample & analysis/oil change • remove/inspect/ overhaul and alignment	Q SA SA 3Yr

Notes: (1) All motors included on operator daily log/rounds.

(2) Key to test frequencies: S/U = at reactor startup; 4-6 Wks = every 4 to 6 weeks; M = monthly; Q = quarterly; SA = semiannually; R = once per 18-month refueling cycle; 3Yr = every other refueling cycle (36 months).

Large motor problems at Plant B were rare, but due to its longer operating history, some were noted among the example motors in Table 5.7. Condensate and condensate booster pump motors experienced only minor problems; some oil leakage failures were recorded for the condensate booster pump motors. One of the feedwater pump motors was generating a strong burning smell during a routine surveillance; the stator insulation was found to be brittle due to operation at high temperatures. High area temperatures were thought to be the cause. The motor was sent out for rewinding.

The original 500 hp RHR LPCI pump motors were all replaced in the early 1990's with larger 600 hp motors. Undersized/overloaded motors were judged to be the cause of problems with high vibration, excessive bearing wear, and eccentric bearing loading and wear.

One of the reactor recirc pump motors experienced a ground fault in the stator winding. The motor was sent out for rewinding and repairs. The reactor recirc pump MG set motors reported no major problems of significance.

In summary, both the PWR plant and BWR plant take a similar approach to the maintenance of large electric motors. They generally treated the Class 1E motors and the non-Class 1E motors the same with the exception of the Technical Specifications operability requirements. Both of these plants placed a great emphasis on monitoring for bearing and bearing related problems, as evidenced by their attention to vibration monitoring, bearing inspection, frequent oil changing, and oil sampling and analysis programs. This is a correct approach to motor maintenance as indicated by the findings of the operating experience review in Section 4, and the FMEA in Table 3.3. This is also in keeping with the recommendations of the NUREG/CR-4939 (Ref. 7), IEEE Working Group 3.3, and the EPRI "Electric Motor Predictive and Preventive Maintenance Guide," NP-7502 (Ref 29). The bearing and lube oil maintenance intervals used at these plants are in line with the recommendations of the EPRI guide.

5.4 Advanced Monitoring Techniques

Some of the most promising of the advanced monitoring techniques for large electric motors are described briefly in this section. These techniques take advantage of developments in remote image sensing technology, analysis of data from electrical insulation testing, and digital processing of condition monitoring data. Some of the methods, have been adopted by nuclear plants already, others have used them on a trial basis or to provide additional information on problems detected by other conventional methods.

5.4.1 Infrared Thermography

Heat is detectable from the infrared radiation (IR radiation) that is emitted in the narrow frequency band in the electromagnetic spectrum just below visible light. Infrared radiation is not visible to the naked eye. Based upon this principle, infrared thermography detectors can be used to identify hot spots in operating electrical equipment. Some of the more sophisticated units can provide high resolution video images of the equipment that is being surveyed with brightness or color accurately referenced to actual temperature. Images from periodic surveys of equipment can be digitized and electronically stored for future trending comparison and analysis.

Infrared thermography surveys of operating motors can be used to monitor the condition of motor connections, cables, external surfaces, heat exchangers, bearings, ventilation inlet and outlets, and couplings. It can detect high resistance connections due to corrosion, looseness, or dirt, clogged or dirty air filters, hot couplings, high bearing temperatures, or abnormally high current flows.

Some plants are already using infrared thermography for monitoring of plant electrical equipment as part of their preventive maintenance programs or for predictive monitoring. Others, such as Plants A and B, use this tool on a case-by-case basis for additional troubleshooting and diagnostic testing of large motors, to supplement other condition monitoring tests.

5.4.2 Motor Current Signature Analysis

When a motor is driving a mechanical load, time dependent load variations, vibrations, and other periodic motor resonances are translated back to the line current as electrical noise. The motor current signature analysis (MCSA) technique uses FFT analysis of the line current in the frequency domain to generate characteristic stator current signatures of the running motor. Using the line current and slip frequency spectra of a motor running at 25% of load or more, MCSA can detect broken rotor bars, cracked rotor bars, cracked end ring, static and dynamic rotor eccentricity, bearing problems, and other cyclical loading problems (Ref. 34).

The MCSA testing is relatively simple to perform using portable equipment and a clamp-on ammeter. The test can be performed remotely from the motor, at the motor switchgear breaker or other points where the motor feeder cables can be accessed. The current data are collected and the motor's current signatures can be analyzed and trended. Software is used to help in the analysis of the motor current signature spectra, however, a skilled analyst is required to achieve the full potential of the information obtained from this testing.

MCSA has been successfully used at several plants to monitor motors driving containment cooling fans and containment air recirculation fans that are located inside containment, in high radiation areas, that are not accessible during operation (Refs. 35 and 36). Plant A and Plant B both use MCSA on a limited basis to supplement troubleshooting activities on motors experiencing vibration-type problems. Plant A is developing a program for predictive motor maintenance using motor current spectrum analysis, but it is not yet in place.

The MCSA technique has been incorporated, along with other computer based techniques, into a number of motor analysis and diagnostic packages that are commercially available.

5.4.3 Motor Circuit Analysis

Motor circuit analysis (MCA) uses precision measurements of motor phase resistance, phase to ground resistance, motor coil inductance, and capacitance of each phase to establish baseline values for these motor parameters. Trending of the changes in these parameter over time can provide a tool for monitoring the condition of the motor and predicting when maintenance is required (Ref. 37).

Tests can be performed at low voltage and minimal current so that there is no of damage to the motor and feeder cables. Phase to phase resistance and inductance are also checked to determine any phase imbalances. Statistical algorithms are used to analyze the data to determine deviations from the mean and changes over time. Imbalances in any of the motor parameters over time can be used to monitor motor degradation.

In their paper presented at the 1992 EPRI Utility Motor and Generator Predictive Maintenance Workshop (Ref. 37), Isaacson and Nicholas emphasized the key elements to effective predictive maintenance utilizing motor circuit analysis:

> "The ability to measure these parameters quickly and accurately, and then database the results is the key to effective predictive condition monitoring. This can be accomplished through the use of computer chips which only recently have been released. The use of these chips in computer controlled testers allow reduction of the time necessary to test motor circuits. Further, the accuracy of the measurements taken is enhanced when the controlling computer is also used to record these measurements automatically.
>
> "The use of a computer controlled test unit which test the parameters of the complete motor circuit while recording the results of the test is recommended. No motor leads need be disconnected. The tester is simply connected to the 'T' leads of the motor circuit. The tester should be operated by the computer and the test results stored by the computer program. The total time for each individual motor test can be as little as two minutes and should be less than ten minutes. The total time that each motor circuit must be deenergized for testing purposes is less than ten minutes." (Ref. 37)

5.4.4 Commercial Motor Diagnostic Packages

A number of commercially available diagnostic packages for motors, circuits, and electrical equipment are available. These combine traditional power measurement methods with several of the advanced condition monitoring techniques, such as the ones described above, to provide powerful diagnostic tools. Computers are used to automate the data collection process, digital processing of the results, analysis, comparison, and digital storage of the information. Automated data measurement enables the tester to collect more accurate and repeatable test results. The trending of motor data is greatly enhanced through the use of computers and the analytical software available in these diagnostic packages, and can serve as a useful tool for predictive maintenance in nuclear plants.

Some of the commercially available systems include:

Baker® Advanced Winding Analyzer, Baker Instrument Company, Fort Collins, Colorado

ECAD® Automated Test System, ECAD® Division of Pentek, Inc., Coraopolis, Pennsylvania

Electrom Digital Winding Analyzer with analysis software, Electrom Instruments, Loveland, Colorado

Liberty® Motor Power Monitor, Liberty Technologies, Inc., Conshohocken, Pennsylvania

5.5 Evaluation of Maintenance Effectiveness

As discussed in the failure analysis in Section 4, nearly half of the large motor failures occurred either during starting or while the machine was operating. This indicates that current maintenance practices could be improved so that they are more effective in identifying and mitigating aging-related degradation in large motors. Although the rate of increase in failure frequency as motors age, shown in

Figure 4.1, is gradual, a trend exists that implies a lack of understanding of the aging problems in these motors. There exist no standards or guidelines which provide specific requirements that can effectively monitor aging and can alleviate the problems shown in the operating data.

5.5.1 Maintenance Data From NPRDS

The methods for detection of aging related motor problems as reported in the NPRDS for RCP motors, RHR pump motors, and reactor recirculation pump motors for 1985 to 1992 are shown in Figure 5.2. All the elements for a good monitoring program are evident in this figure, however, most of the failures seem to have been detected during operational conditions. These include detection methods such as alarms, operational abnormalities, and non-routine observations. Ideally, it is more desirable to find failed or degraded components during preventive maintenance, ISI/IST, and periodic surveillance, so that the more extensive damage that accompanies operating failures can be avoided. The impact that forced outages of large motors can have on plant operation can also be avoided or minimized.

Comparing PWRs with BWRs in the figure, the PWR plants seem to be more effective in detecting failures by preventive maintenance and ISI/IST. A very large portion of the motor failures at PWRs, however, have been detected by alarms, indicating that the motor was probably operating at the time.

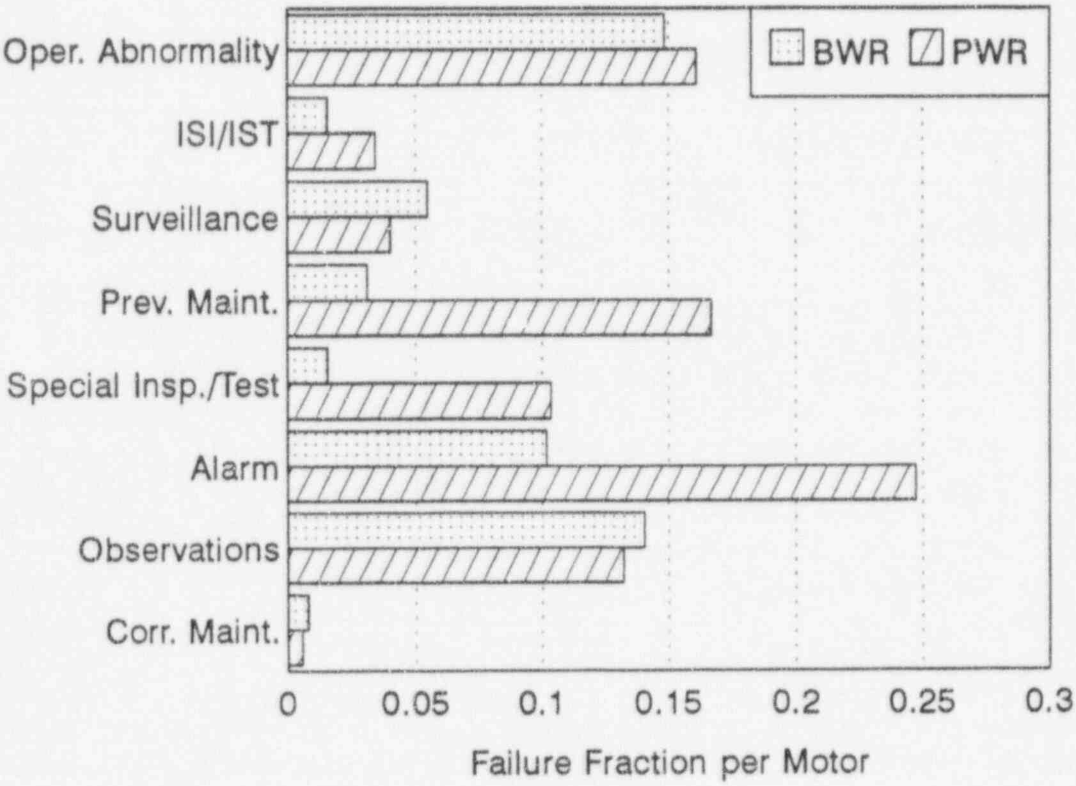


Figure 5.2 Methods of large motor failure detection - NPRDS 1985-92

To examine whether the location of the large motor (and its accessibility during operation), or its safety classification (and the increased maintenance and surveillance that Class 1E safety-related motors would receive) had an effect motor reliability, the failure frequencies (per million calendar hours) calculated from the NPRDS data (Ref. 20) were compared. Data for the ten year period from 9/1/84 to 8/31/94 are tabulated in Table 5.8, grouped by NSSS supplier, and plant type, for Class 1E and non-Class 1E motors used in various plant locations.

Table 5.8 Average Failure Frequency (per Million Calendar Hrs.) Grouped by System and Plant Type (Ten Year Period 9/1/84 through 8/31/94 - NPRDS)

SYSTEM	LOCATION	PWR Plants			All PWRs	All BWRs	All Plants
		Westnghs	CE	B&W			
RCP/Rx Recirc	Primary Containment	6.51	7.97	16.3	8.07	3.68	6.56
RHR	Aux Bldg/Rx Bldg	2.00	1.19	*	1.50	2.60	2.48
Service Water	Intake Structure	6.04	1.38	3.42	5.01	3.28	4.18
Condensate	Turbine Bldg	8.35	4.95	8.51	7.69	3.79	6.19
Feedwater	Turbine Bldg	7.71	6.11	*	7.51	4.84	6.61
All Large Electric Motors		5.72	4.30	8.04	5.67	3.22	4.72

* Insufficient data

The Class 1E motors in the table are the service water pump motors, located at the plant intake structure, and the RHR pump motors, typically located in the auxiliary building in PWRs and the reactor building in BWRs. The data show that the RHR pump motors have the lowest failure frequencies at PWRs from each of the three NSSS suppliers, and for the BWRs. The failure frequencies for service water pump motors are the second lowest of those compared at plants from each NSSS supplier, although they are slightly higher than for the RHR. This is probably because the service water operating environment is more severe with regards to humidity and corrosiveness. Generally, Class 1E motors are subject to the greatest scrutiny for preventive maintenance, monitoring, and surveillance. The data from Table 5.8 show that the effect of this is positive, and that these motors exhibit the lowest failure frequencies.

RCP motors at B&W and CE plants are of some concern, in that they have shown the highest failure frequencies of the large motors compared at those plants, and are well above those at Westinghouse PWRs. Due to their limited accessibility and their important function in the NSSS, they receive almost as much maintenance and surveillance attention as a Class 1E motor. The data for these types of PWRs, however, show that their RCP motor performance is not as good as would be expected, considering the maintenance that they receive.

The BOP systems, condensate and feedwater, generally showed the highest failure frequencies among the motors compared at each type of plant. The only exceptions were for the RCP motors at B&W and CE PWRs mentioned in the preceding paragraph. As non-Class 1E, BOP pump motors, they receive less maintenance attention and it would be expected that this would be reflected in higher failure frequencies. There should still be some concern with this result, since feedwater motor failures at PWRs, and condensate motor failures at both PWRs and BWRs were shown, in Tables 4.3 and 4.6 and the associated discussion, to result in a significant number of reactor trips or reduced power operation conditions.

In general, motors in these systems at BWRs had lower failure frequencies than the motors in equivalent PWR systems. This reenforces the previous findings in Table 4.3 and Figure 4.4 which indicated that General Electric motors enjoyed the best performance over the period studied, and that large motors at BWRs performed more reliably than in the PWRs.

Finally, based on the database, the dominant corrective actions taken to bring the motor to normal operation were reported as replacement of motor parts or repair. This can be seen in Figure 5.3, which gives a breakout of the corrective actions taken. This corrective action distribution indicates that the plants should be able to identify motor parts which have a finite life and take appropriate preventive measures prior to their failures.

Complete motor replacement was reported in about 8% of the failures. It should be pointed out that for many of these motor failures, particularly for motors with Technical Specifications LCO requirements, replacement of the entire motor may be the preferred corrective action to minimize plant

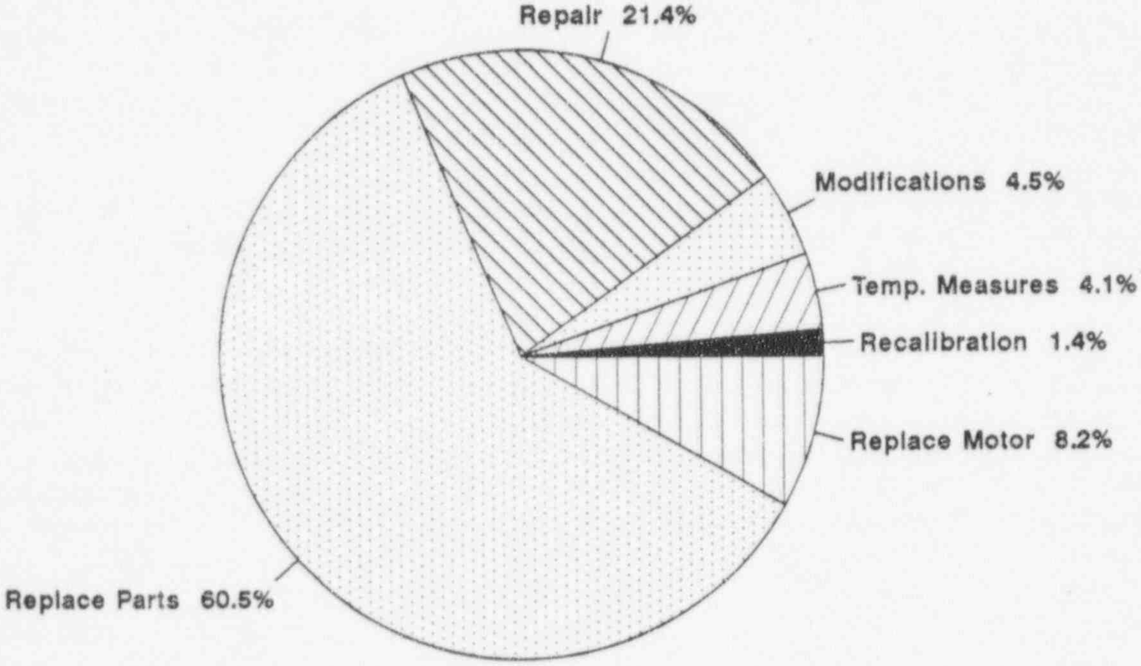


Figure 5.3 Corrective actions taken following large motor failures-NPRDS 1985-92

down time. Even though repair or parts replacement may be the only corrective maintenance required once troubleshooting has found the problem, replacement of the motor and preoperational testing often can be completed more quickly.

5.5.2 Maintenance Data From LERs

Analysis of the major failure modes of large electric motors identified in the review of LERs from 1980 to 1992 showed that nearly 83% were operating failures involving automatic trips (38.5%), manual trips (7.7%), or abnormal characteristics while the motor was running (36.4%). Another 4.9% of the LERs described a failure to start. Only 12.5% of the large motor failures in the LER database were found with the motor in a shutdown condition.

The distribution of failure modes for the LER incidents is skewed to operational failures even more so than the NPRDS data. LERs are by definition more likely to be severe failures, so this finding is an extrapolation of the trend seen in the NPRDS: maintenance and monitoring are not effective in identifying the degradations that lead to more severe failures.

The methods for detection of the failures included in the LER data were analyzed for both BWRs and PWRs (Figure 5.4). Overall, the breakout of failure detection methods for the LERs is very similar to that seen in Figure 5.2 based upon NPRDS data. Alarms were the primary means for detecting failures, followed by abnormal operating conditions, and routine or non-routine observations. Only a very small portion of the failures were identified by the preferred means of failure detection, i.e., preventive maintenance, surveillance testing, and IST/ISI. The differences in failure detection between the PWR plants and the BWR plants were not significant.

Another measure of maintenance effectiveness that was extracted from the LER data is the corrective action taken following failures. The dominant corrective actions, reported in more than half of the events, were repair or replacement of motor parts. This can be seen in Figure 5.5 which gives the breakout of the various corrective actions taken. This finding is very similar to that seen in the NPRDS data analysis, and indicates that many of the failures in the LER data involve readily replaceable motor parts. Plants should be able to identify those parts with a finite service life and incorporate appropriate preventive maintenance measures, such as condition monitoring or periodic replacement. This would help to reduce the number of more severe immediate failures and unscheduled outages that are being experienced.

Complete motor replacement was reported in more than a quarter of all the LER failure events. Since the LERs are more serious failures that the NPRDS failures, and they usually involve pumps governed by Technical Specification LCOs, it is expected to see this large number of complete motor replacements. As mentioned previously, motor changeout and preoperational testing is less time consuming than troubleshooting and repair. Hence, plants very often will elect this corrective action in order to exit a Technical Specification LCO, and get the plant back into power operation as quickly as possible. Troubleshooting and repair on the damaged motor can then be accomplished in a more thorough manner in the utility's motor shop or at an offsite vendor's repair facility. This high percentage of motor replacements also indicates that there is room for improvement in the area of monitoring for degraded conditions before they escalate into more catastrophic failures involving costly unscheduled outages.

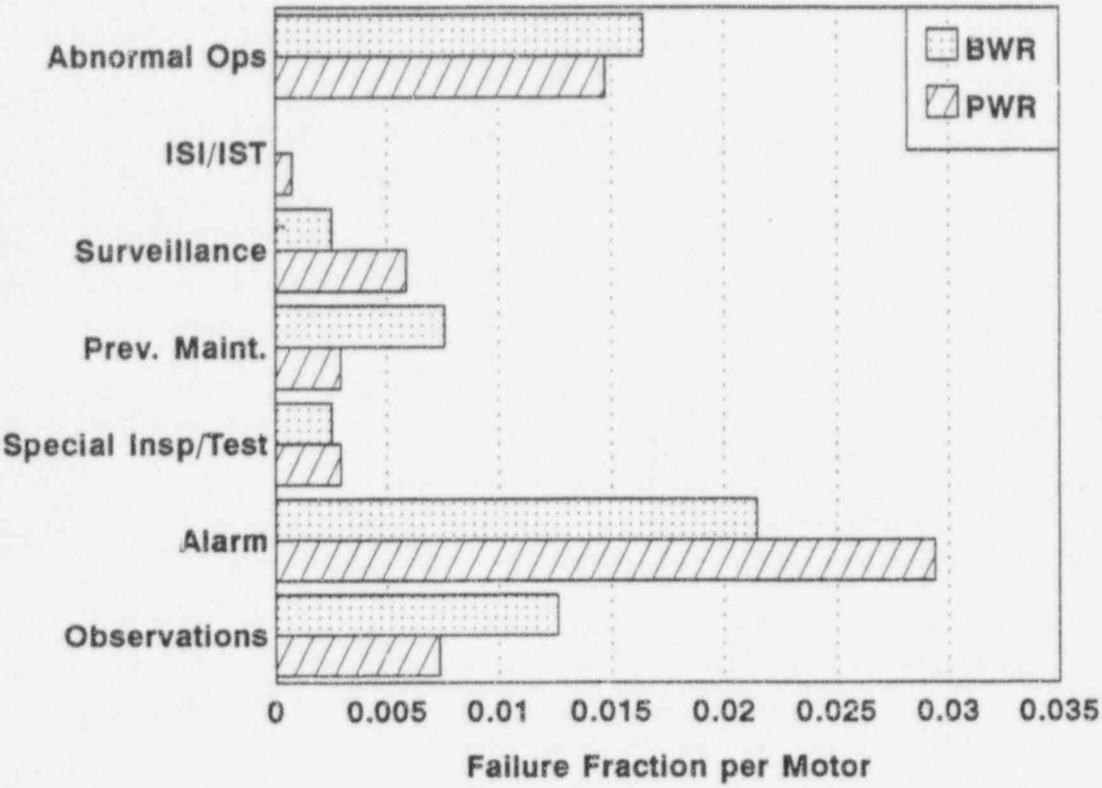


Figure 5.4 Failure detection methods - LER data 1980-92

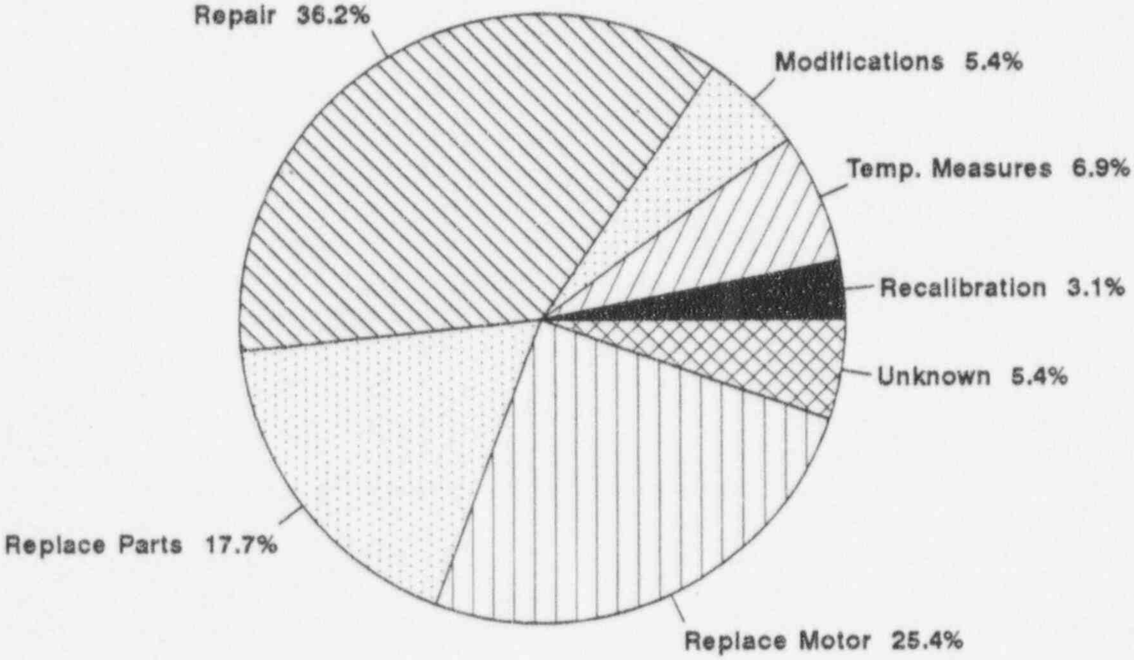


Figure 5.5 Corrective actions taken following large electric motor failures - LER data 1980-92

5.6 Trending Analysis

The previous discussions show that there are many different testing methods and techniques available for the condition monitoring of large motors. The usefulness of the information provided by these tests, however, varies widely. Many of the testing methods are affected by the temperature, humidity, contamination, or other factors at the time of the test. Even when these variables are compensated for, many tests provide only "go/no-go" information as to the condition of the insulation in the motor being tested. Guidelines have been suggested in the standards, but even these have been shown to be only rough indicators of motor condition.

The results of many tests can only be used to their full potential when performed and interpreted by experts in motor diagnostic testing. The value of expert knowledge and experience is very important in using test data to make predictions as to motor insulation condition and the need for maintenance or repair. Often, the best approach is to weigh the results from different types of condition monitoring tests in order to verify a suspicious indication on a particular test. Unfortunately, many plants do not have the benefit of such expert knowledge.

To be most effective, a surveillance and monitoring program for large motors must identify the significant parameters, and then conduct a formal program of periodic testing, data collection, trending, and analysis. Once machine specific baseline data have been established by consistent, periodic testing, collection, and plotting of condition monitoring parameters, the range of normal variations can be determined for each machine, or group of machines. Experience has shown that it is the changes from the machine specific baseline range of normal values, observed over time, that can help the maintenance engineer monitor the degradation of a motor. Deviations from the normal range in trended data from two or more condition monitoring tests over the same period of time, can provide reinforcing information to the maintenance engineer. For example, if readings of insulation resistance decrease on several successive test periods, while power factor tip-up and partial discharge activity measurements were shown to be increasing over the same period, the maintenance engineer may decide to undertake additional diagnostic testing of the winding condition (Refs. 38 and 39).

An effective trending program would contain the following basic elements: (1) identification of the significant parameters to be monitored to track motor degradation, (2) periodic testing, consistently performed tests using detailed procedures, (3) centralized data collection and plotting (to help the users visualize trends) of the motor specific trended parameters, and (4) periodic review and analysis of the data in order to identify trends, order additional diagnostic testing, anticipate the onset of problems, project preventive maintenance requirements, and optimize surveillance intervals (Ref. 40). Analysis of the data should be performed by experienced personnel who can use their knowledge to best interpret the information.

Since the trending of data is based upon machine specific condition monitoring, it is very important to track the location of each motor and its components over its service life. Motors are often removed from a location for repair and testing, sent off site for rewinding or other maintenance, and reinstalled in different positions at different times. The trending program should include provisions for tracking the individual motors and major components by serial number rather than by application position. Data can then be tied to a specific motor or motor component, rather than to a plant application, such as circulating water pump motor "A" or condensate booster pump motor "B" (Ref. 41). Control and specification of work done offsite at vendor repair shops, or even at the utility's own facilities, can often be poorly handled. EPRI's "Guidelines for the Repair of Nuclear Power Plant Safety-Related Motors

(NCIG-12)" (Ref. 42) provides information for specification, control, quality assurance, and tracking of repairs to Class 1E motors. It can also serve as a guide to utilities for repair work of other large motors at off site repair facilities.

Recognizing many of these problems and shortcomings in the data analysis process, the Electric Power Research Institute (EPRI) has sponsored the development of an advanced computer diagnostic program called MICAA^{TM} (Machine Insulation Condition Assessment Advisor) to provide accurate winding assessment assistance to utility maintenance personnel (Ref. 43). The expert program, which runs on IBM-type personal computer, helps guides utility personnel through the process of collecting motor specifications and design information, and selecting the appropriate diagnostic tests and inspections for each specific machine. Test results are analyzed by MICAA^{TM} to provide an assessment of winding insulation condition, identification of probable degradation mechanisms, and guidance in selection of appropriate maintenance and repair measures.

Establishing an effective trending analysis program for large motors can provide the ability to monitor and detect motor degradation before an immediate failure has occurred. This approach can reduce costs by allowing plants to plan scheduled maintenance and overhaul for large motors on the basis of condition, rather than time, and avoiding unscheduled plant outages resulting from catastrophic motor failures.

6. SUMMARY AND CONCLUSIONS

This study has examined the degradation and aging of large electric motors used in nuclear power plants. These motors, rated at approximately 500 hp and larger, are used in nuclear power plants to drive large pumps and fan coolers located both inside and outside the reactor building. With the exception of the Emergency Core Cooling System (ECCS) pumps and fan coolers, most of these motors are classified as nonsafety-related equipment. Recirculation (Recirc) pumps in Boiling Water Reactors (BWRs) and the reactor coolant pumps in Pressurized Water Reactors (PWRs) use very large motors (greater than 5000 hp) and are installed inside the primary containment. Class 1E large pump motors include core spray, residual heat removal (RHR), and high pressure core spray (HPCS) in BWRs (located in the reactor building secondary containment), and reactor containment fan coolers, high pressure safety injection (HPSI), low pressure safety injection (LPSI), and containment spray pumps in PWRs (usually located in the auxiliary building). Some of the large balance of plant (BOP) motors are used to drive condensate pumps, feedwater pumps, condensate booster pumps, and circulating water pumps.

6.1 Summary

This study examined the operating experience the nuclear industry has had with large electric motors, identified the stressors and aging mechanisms affecting large electric motors, assessed the effects of aging degradation on large electric motor performance and reliability, and evaluated the methods currently available to monitor, repair, and mitigate aging degradation. Some of the highlights of the study are summarized in the following sections.

6.1.1 Motor Populations and Design Review

The review of large ac motor populations in nuclear plants found that the squirrel cage induction motor was the most widely used prime mover in the nuclear industry. Squirrel cage induction motors accounted for nearly 97% of the large motor applications in PWR plants, and almost 94% of those in BWRs. A design review of large induction motors and synchronous motors identified the major components and provided details on construction of these machines. The systems and applications for large motors at PWRs and BWRs were also identified from a review of plant FSARs, system descriptions, and motor specifications.

Information from the design review was used to compare design differences in motors used inside containment in harsh nuclear environments with those in mild environments, in Class 1E nuclear safety system service, and in balance of plant applications. The review found that the design differences primarily were determined by the application and the location. Harsh environment motors had to be certified as environmentally and seismically qualified. Stator winding insulation on these machines was of a higher temperature rating (Class F or H), more radiation resilient, and sealed by a vacuum pressure impregnated process to provide a thicker, rigid, well-sealed unit compared to mild environment machines. Bearings also incorporated design enhancements to improve their longevity in the harsh environments, and the motor enclosures usually had heat exchangers for lowering the temperature of discharged cooling air. Class 1E motors and non-Class 1E motors in mild environments had very few design differences in the examples looked at for this study. Documentation and certification for the Class 1E machines was more extensive.

Even though they are not considered Class 1E nuclear safety-related equipment, BWR recirc pump motors and PWR reactor coolant pump motors incorporate many of the design features that are used in the Class 1E motors described in Section 2.5.2. These include non-hygroscopic, Class F or H, thermalastic epoxy sealed insulation, sealed bearings, radiation resilient materials, and corrosion resistant design and materials. Additional features found are anti-reverse rotation devices and large inertial flywheel assemblies. Due to the relatively limited space and enclosed atmosphere inside containment, limiting ambient temperatures is a concern. Therefore, large motor enclosures for these applications may be of three basic types: 1) guarded drip proof, 2) drip proof with a cooling water-to-air heat exchanger on the air discharge from the motor, or 3) totally enclosed with a cooling water-to-air heat exchanger.

Although the BWR recirc pump motor and PWR coolant pump motors are not required for safe shutdown, seismic design and testing considerations are still required since these motors must continue to operate during and after an Operating Basis Earthquake (OBE). In addition, they must be able to maintain their integrity throughout, and following, a Safe Shutdown Earthquake (SSE), or an SSE simultaneous with a LOCA. This is to ensure that the reactor coolant boundary remains intact, and that pump seals and thermal barriers are not damaged (thus preventing a LOCA). The reactor coolant pump must also maintain a coastdown capability following these events, as well as the capability to maintain reactor coolant flow during the coastdown period.

6.1.2 Motor Stressors and Environments

The review of motor designs, applications, and operating environments was used, together with operating history data, to identify the primary stressors acting upon motors to cause degradation and aging. The major stressors that affect large electric motors are:

Heat
Pressure
Radiation
Humidity/Water Spray
Vibration/Seismic
Chemicals
Steam
Mechanical Cycling/Rubbing
Electromagnetic Cycling
Foreign Object Ingestion

The origins of the stressors may be grouped into four categories: (1) operational, component level, (2) operational, system level, (3) environmental, and (4) human factors. These were summarized in Table 3.1. Some of the component level stressors, like heat from electrical and mechanical losses, can never be eliminated but can be addressed by good design, good manufacturing, and condition monitoring. Others, particularly those involving application, operation, and human factors, can be greatly affected by operating procedures and practices, good preventive maintenance, and effective condition monitoring.

6.1.3 FMEA

Design review information, review of stressors and environments, and operating history data were used to prepare a failure modes and effects analysis (FMEA) for the large squirrel cage induction motor. The FMEA provides a systematic procedure for determining how each component of a large motor can fail, the mechanisms that cause it to fail, and how it can affect the overall performance of the motor. The means for detection of the identified failure mechanisms are established along with methods for mitigating the effects of the failure mechanisms. The criticality of individual component failures can then be determined in order to prioritize inspection, surveillance, maintenance and mitigation activities, and to allocate maintenance resources. FMEAs can also indicate the usefulness of design improvements or modifications.

The large squirrel cage induction motor was broken down into five major component categories:

1. The **stator assembly** including the windings, laminated core, stator leads and coil cross-ties, and stator surge ring, blocks, spacers, and winding end supports.
2. The **rotor assembly** including rotor core, squirrel cage assembly, shaft assembly, and air cooling slots, spacers, and vanes.
3. The **bearings** including bearings, seals, and lubricating oil system.
4. The **motor frame, enclosure and mounting** including bearing supports, terminal box and connections, and ground connections.
5. Integral **monitoring sensors and heaters** including stator winding and bearing RTDs, vibration monitoring, lube oil system monitoring instrumentation, and the motor space heaters.

The important subcomponents in each of the above five categories were then analyzed using the FMEA approach described in Section 3.2. The results of the generic FMEA for the large squirrel cage induction motor were documented in Table 3.3.

6.1.4 Operating Experience Review

The industry's operating experience with large electric motors was reviewed using failure reports obtained from searches of the NPRDS database and the LER database. Taking into account the different characteristics of the data reported to each of these databases, failure reports were reviewed and analyzed to study the aging mechanisms and degradation affecting large motors. Some of the important findings from this analysis are described here.

NPRDS data were used to produce a plot of failure frequency as a function of motor age. This graph, Figure 4.1, displayed the characteristic "bathtub" shape indicative of normal aging and service wear, corrosion, and degradation of insulation, seals, and other materials. The dominant failure mechanisms (leakage, age/wear, and vibration) reported to NPRDS and in LERs further reinforced this (Figure 4.6).

The failure data indicated that bearings and bearing related components, such as seals, lube oil system, and cooling water were the dominant failed components in both NPRDS and LER failure reports. Next most dominant were: stator windings and insulation, motor leads and terminations, shaft and coupling, rotor, and mountings. These results are consistent with findings of other studies on large motors by IEEE (Refs. 9, 10, 11) and EPRI (Ref. 19). Earlier aging research on electric motors smaller than 100 hp (Ref. 5) found that stator problems were the cause of most failures in the small motor sizes. This implies that the aging mechanisms in large motors differ from those affecting small motors.

An important finding of the operating experience data was that most of the motor failures occurred while their systems were in service, or during motor starting, rather than during testing and maintenance (Figures 4.7 and 4.13). Also, most of the failures reported to the NPRDS were degraded or immediate level failures, rather than the less severe incipient type of failure (Figure 4.2). This proportion of unnoticed motor failures indicates that plant maintenance and monitoring activities are not focusing on the detection and prevention of incipient failures before they degenerate into the more severe types of failures seen in the operating history. Improvements in this area will increase pump/motor availability by detecting degraded conditions and yield savings through less expensive repairs and a reduction in unscheduled outages. Such improvements will also positively impact safety due to fewer transients challenging safety systems and fewer components being unavailable when required to operate.

The NPRDS data showed that motors operating in PWRs had a higher failure fraction per motor when compared to BWR motors (Figures 4.3 and 4.7). Part of this may be due to the lower failure frequency enjoyed by Supplier B motors compared to the other two major large motor manufacturers (Table 4.1 and Figure 4.4). These motors are used more extensively in the BWRs and this may be one cause of the better motor performance in BWRs. Other reasons for the difference may be due to plant design, accessibility of the motors, and operating requirements.

Despite the differences in performance between the BWR motors and PWR motors, the NPRDS data showed that the distribution of the failure mechanisms that degrade large motors is the same in both types of nuclear plants. Leakage was the dominant mechanism, followed by aging/wear, and then vibration (Figure 4.6).

The effect of a large motor failure on the system in which it is operating was most often reported as a loss of redundancy (Tables 4.4 and 4.7). Safety systems are designed with redundant pump motors and redundant loops, so that they can tolerate the failure of a single pump motor. Large motors on the nonsafety systems and BOP systems also use multiple pump motors and multiple trains, so motor failures typically caused a loss of redundancy, or the loss of one loop, in most cases. Loss of redundancy may affect reliability and potentially increase plant risk. Some of the LERs, because they involve more serious events, described events in which the loss of a pump caused degraded system operation or loss of system function, often because one or more other pumps were already out of service.

The plant effects of the failure of a large motor were dependent on the application of the motor. Again, due to the redundancy on safety-related systems, Class 1E motor failures had no effect on plant operation in more than 90% of the failures reported to NPRDS (Table 4.3). Also, since safety systems serve to safely shut down the reactor in an emergency or help to mitigate the effects of an accident, their function in the power production aspects of the plant is chiefly auxiliary. Nevertheless, the LER data contained a few incidents where large Class 1E motor failures on service water, CVCS, and RHR systems were involved in power reductions, forced shutdowns, or reactor trips. Also noted were Technical Specification actions due to safety-related motor failures.

Significant plant effects due to trips of RCP motors at PWRs and reactor recirc pumps at BWRs were more likely than in Class 1E systems. According to the NPRDS data (Table 4.3), problems with RCPs at PWRs had no effect 58.5% of the time, compared to reactor recirc pumps failures, which had no effect on the plant in more than 70% of the cases reported. The next most frequent plant effects of RCP failures at PWRs were forced shutdown (unit off-line), and then reactor trips. At BWRs, forced shutdown or reduced power operation were the next most frequent plant effects reported. PWRs were more susceptible to reactor trip in RCP failure incidents, compared to BWRs following reactor recirc pump problems.

An interesting finding of the plant effects analysis was the importance of failures of large pump motors in BOP systems. Most condensate pump or condensate booster pump motor failures were reported as having no effect on plant operation, even though these are an important means to mitigate accident effects. However, as an essential part of the power production process, loss of a large pump motor in condensate system applications resulted in reduced power operation in PWRs 13% of the time, and in BWRs more than 16% of the time, as indicated in Table 4.3. BWRs were also susceptible to reactor trips, reported more than 9% of the time as a result of motor failures in the condensate system. Review of LER data (Table 4.6) showed that PWRs and BWRs experienced reactor trips and forced outages in more than 80% of the LERs involving the condensate system.

PWRs were susceptible to incidents involving large feedwater pump motors, where nearly 31% resulted in reduced power operation according to the NPRDS reports, and a reactor trip resulted in 7.3% of the large motor failures on the feedwater system (Table 4.3). In the LER data (Table 4.6), more than half of the reports involving motor driven feedwater pumps at PWRs resulted in a reactor trip. None of the large motor failures on main feedwater systems in BWRs reported to NPRDS had any effect on plant operation, and only one reduced power LER was reported.

There were also a number of LERs involving circulating water pump problems that resulted in reactor trips, in about half of the incidents, and taking the unit off line, in the other half of the cases (Table 4.6). The distribution of these two plant effects was about the same for both PWRs and BWRs. The total number of circulating water LERs, however, is less than for the condensate or feedwater systems.

Due to the wider search criteria required for the search of the LER database for large motor failures, the LERs included failures of support equipment that caused large motor failures, and driven load equipment problems that lead to large motor unavailability. The LER data (Table 4.4) revealed that slightly less than 40% of the aging related motor problems were caused by failures within the electric motor itself (see boundaries defined in Figure 1.1). An equal amount of the failures originate with motor support equipment, including motor circuit breakers, the power supply from the circuit breaker, control logic and instrumentation, protective relaying, and the cooling water and air supplies. A bit less than a quarter of the events were caused by the driven mechanical loads (associated equipment) and their flow path elements. The importance of this is that nearly two thirds of aging related large motor unavailability reported in the LERs can be attributed to sources outside of the electric motor itself.

Further examination (Figure 4.15) of the failures of large motor support equipment found that circuit breaker and I&C problems make up the majority of the support equipment failures. Closely related to these are protective relaying failures. Together these constitute more than half of the support equipment contribution to large motor unavailability. Cooling water failures, including cooling water lines, pumps, and heat exchangers, comprised 13.3% of the support equipment problems. Room and area cooling equipment, including belts, fans, and dampers comprise another 11.3%. The significance of this data is that the source of large motor unavailability is found in support systems as often as it is within the motor itself. Maintenance and monitoring efforts directed at motor support equipment such as circuit breakers, motor I&C, and protective relaying, may be as effective in improving large motor availability as maintenance and monitoring of the electric motor itself.

Similarly, the components that caused large motor associated equipment failures in the LER data were identified and plotted on Figure 4.16. The largest contributors were pumps, as expected, since this is the most important mechanical load driven by large electric motors. Many motor failures identified in the LER search were actually pump problems, including bearing failures, impeller eye ring wear, imbalances, and breakage. Also identified were valve (25.9%), I&C (9.9%), and strainer/screen (8.6%) problems. Incorrect valve lineups or incorrect valve position indication caused many motors trips or failures since these parameters are permissive signals in pump motor starting and operating logic.

Incorrect valve position, and clogged or obstructed strainers, can lead to a pump motor trip due to low suction pressure, low flow, or high discharge pressure. Instrumentation errors that falsely indicate any of these conditions can also have the same result.

6.1.5 Maintenance, Monitoring, and Surveillance

Manufacturers' recommendations on the preventive maintenance, condition monitoring, and surveillance for large electric motors were reviewed. The basic recommendations for continuous monitoring are described, along with preventive maintenance activities and tests. The continuous monitoring consisted primarily of protective relaying, supplemented by station surge arresters and surge capacitors at the motors (Figure 5.1). These devices function automatically to assure that motors are operated within the fundamental engineering limits to which they were designed, built, and applied in the plant.

Preventive maintenance consists of periodic activities and adjustments that correct or mitigate the effects of aging degradation (see the FMEA in Table 3.3), and tests that monitor the condition of the motor to determine whether corrective maintenance and repairs, refurbishment, or overhaul are required. Preventive maintenance recommendations from the manufacturers emphasize four main areas: 1) general cleanliness, 2) insulation and windings, 3) bearings and lubrication, and 4) vibration. These activities and tests are detailed in Section 5.1.2.

To supplement the manufacturers' recommendations, recommendations from other sources in the industry were reviewed to assess how well they addressed the types of failures and the degradation that was observed in the operating history data for large motors. The review identified three good sources for this information: (1) previous motor aging work sponsored by the US NRC, (2) guidelines being developed by Working Group 3.3 - Maintenance Good Practices, of Subcommittee 3 - Operations, Surveillance, and Testing, of the IEEE Nuclear Power Engineering Committee, and (3) research by EPRI. These recommendations were weighed against the findings and trends found in the operating history data to develop the FMEA in Table 3.3 and to identify the best approach to effective large motor maintenance.

The maintenance practices and activities at a Westinghouse PWR and a General Electric BWR were reviewed to determine how nuclear plants typically address the maintenance, surveillance, and monitoring of large electric motors. This process included a review of Technical Specifications as they apply to large motors or their driven loads, and site visits to review large motor maintenance programs, activities, and procedures. The actual plant activity was found to be in keeping with manufacturers' recommendations and closely followed many of the industry recommendations. The positive effects of this policy were realized at these plants, where very few serious large motor problems have occurred.

Several advanced monitoring techniques and analysis packages, that have been developed for testing and assessing the condition of electrical equipment, were examined during this study. Some of them that have been used for large motor monitoring and testing were described in Section 5.4. These techniques take advantage of developments in remote image sensing technology, computerized testing, analysis of data from electrical insulation testing, and digital processing of condition monitoring data. Some of the methods, have been adopted by several nuclear plants already. Other plants have used them on a trial basis or to provide additional information on problems detected by conventional methods. Some of the advantages of these methods and monitoring packages are: ease of use, improved consistency and repeatability of testing, efficient use of computers to test, collect, and analyze data, simplified trending analysis, and access to expert system analysis software.

Finally, the importance of trending analysis in condition monitoring and preventive maintenance of large electric motors is discussed. The essential elements of trending analysis and its role in a reliability centered maintenance approach are described. The importance of considering multiple parameters, observing trends and changes over time, and using experienced personnel is emphasized.

6.2 Conclusions

A number of important observations were made during the course of this study of the degradation and aging of large electric motors. The following observations and conclusions were made based upon review and analysis of the operating history data, review of plant procedures, specifications, and system descriptions, discussions with manufacturers, vendors, researchers, and plant personnel, and review of research literature:

- Both the NPRDS and LER data indicated that a significant portion of the reported failures were due to normal aging degradation of the motors, subcomponents, support equipment, and materials.

- The most important contributors to large motor failures, in order of importance were found to be: bearings and bearing related components (lubrication, lubrication systems, cooling water), stator windings and insulation, terminations and motor leads, shaft and coupling, and motor mounts. This is consistent with the IEEE IAS large motor reliability survey (Refs. 9, 10, 11) and the EPRI industry survey of large motors (Ref. 19). This contrasts with findings in earlier aging studies for motors smaller than 100 hp (Ref. 7) in which stator insulation degradation was the primary subcomponent responsible for failures, followed by bearing problems. This implies that there are differences in the aging processes affecting large motors and small motors.

- The plant systems most often experiencing large motor problems in PWR plants (based on NPRDS and LER data) are: reactor coolant, condensate, service water, main feedwater, and safety injection.

- The plant systems most often experiencing large motor problems in BWR plants (based on NPRDS and LER data) are: reactor recirculation, RHR/LPCI, condensate, service water, and core spray.

- A complete loss of safety system function has not resulted due to large motor failures (PWRs and BWRs).

- The more severe operating conditions experienced by large motors inside containment, specifically, higher temperatures, humidity, and radiation, contribute to accelerated degradation and aging processes in these machines. These are partially compensated for by enhanced design features. Limited accessibility during operating, however, is the major factor that prevents timely detection of degradation and incipient failures before they progress to a more severe level.

- Maintenance programs in the nuclear plants generally follow the manufacturers' recommendations, but based on the types of failures observed, and their severity, there is room for improvement in detecting incipient failures before they have degraded into more severe failures that trip large pump motors or require immediate shutdown.

- The most difficult part of preventive maintenance monitoring for large electric motors is quantitatively assessing electrical insulation condition. The most effective approach is to establish a machine specific program combining consistent, periodic monitoring and testing of operating parameters, and visual inspection, together with trending and analysis of the changes in the monitored operating and test parameters over time. Periodic review and evaluation of data from all these sources by experienced personnel will then provide the best indication of machine condition and the need for repairs.

- The additional maintenance, monitoring and surveillance received by Class 1E pump motors on safety-related systems have had a positive effect on the operating performance of this equipment.

- Problems with the large pump motors in the RCS in PWRs, and the pump motors and MG set motors in the reactor recirculation system in BWRs, can have a greater effect on normal plant operation than do failures of the large Class 1E pump motors on safety-related systems.

- Failures in the large pump motor support equipment, such as circuit breakers, instrumentation, controls, and protective relaying, cooling water, and room/area cooling, account for as much of the large pump motor unavailability as failures within the large motor itself.

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8. GLOSSARY

Aging - Cumulative changes with the passage of time, which if unchecked, could result in the loss of function and impairment of safety. (Ref. 44)

Aging Degradation - "Aging effects that could impair the ability of a system, structure, or component to function within acceptance criteria." It is "produced by operating conditions, including both environmental conditions such as temperature and radiation as well as functional conditions such as relative motion between parts. Operating conditions produce normal stressors or error-induced stressors." (Ref. 45)

Associated Equipment - The mechanical loads driven by a large electric motor and the system components functionally linked to them that can affect the availability of the motor. Included are pumps, fans, compressors, strainers, and pump suction, discharge, and bypass valves and dampers.

Class 1E - "The safety classification of the electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or are otherwise essential in preventing significant release of radioactive material to the environment." (Ref. 46)

Degradation - "Immediate or gradual deterioration of characteristics of a system, structure, or component that could impair its ability to function within acceptance criteria." (Ref. 45)

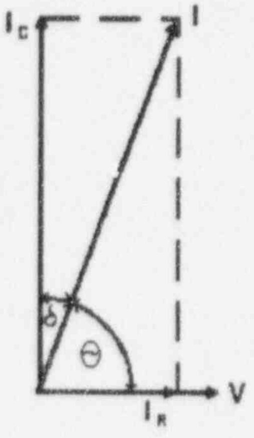
Degraded Failure - A failure severity level classification that refers to a gradual, partial, or deteriorated condition that has occurred that prevents the motor from continuing operation. For large electric motors, this could included conditions that result in a high bearing temperature, high vibration, high stator winding temperatures, excessive noise, or visible smoking or sparking, such that the machine must be shut down.

Dielectric Dissipation Factor (tan δ) - The tangent of the dielectric loss angle (δ) of a dielectric material (see Figure 8.1). It is an indicator of the amount of dielectric loss current, or leakage current, and hence is good measure of the condition of the insulation. For small values of the dielectric loss angle, the dielectric power factor and the dielectric dissipation factor are nearly the same value since:

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

Dielectric Power Factor (cos θ) - The cosine of the phase angle (θ) between the ac test voltage applied to an insulation and the resulting current (see Figure 8.1). It is the ratio of the real dielectric loss current to the total measured charging current, thereby indicating the condition of the insulation.

Dripproof Guarded Machine - A dripproof open motor "in which all the openings giving direct access to live metal or rotating parts (except smooth rotating surfaces) are limited in size by the structural parts or by screens, baffles, grilles, expanded metal or other means to prevent accidental contact with hazardous parts." (Ref. 13)



V - Applied ac voltage
I - Total measured current
I_C - Capacitive component of I
I_R - Loss component of I
θ - Dielectric phase angle
δ - Dielectric loss angle
$\cos\theta$ - Dielectric [insulation] power factor
$\tan\delta$ - Dielectric [insulation] dissipation factor
$\Delta\tan\delta$ - Power factor tip-up

Figure 8.1 Insulation power factor relationships

Dripproof Machine - An open motor "in which the ventilation openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle from 0 to 15 degrees downward from the vertical." (Ref. 13)

Failure Fraction per Motor - Quantity of failures for a given period of time divided by the population of motors being studied. The resulting failure fraction per motor allows normalized comparison of large motor failure data from PWRs with BWRs.

Failure Frequency - The number of large motor failures occurring during a given period of time.

Harsh Environment - "An environment expected as the result of the postulated service conditions appropriate for the design basis and post-design basis accidents of the station. Harsh environments are the result of a loss of cooling accident (LOCA)/high energy line break (HELB) inside containment, and post-LOCA or HELB outside containment." (Ref. 47)

Immediate Failure - A failure severity level classification that for large electric motor failures refers to sudden or complete failures that trip the motor or prevent it from starting.

Incipient Failure - A failure severity level classification that for large electric motors refers to gradually degrading conditions that, if left unchecked, would lead to degraded or immediate failures.

Insulation Class - "Insulation systems are divided into insulation classes according to the thermal endurance of the system for temperature rating purposes. Four classes of insulation systems are used in motors and generators, namely, Classes A, B, F, and H." (Ref. 13). Nuclear plant applications will typically use Classes B, F, or H insulation systems.

Insulation Resistance - The quotient of a specified applied direct potential divided by the resulting current at some given time from the start of voltage application for a given set of conditions of temperature, humidity, and previous charge. Insulation resistance is sensitive to surface condition, moisture, temperature, applied test voltage, duration of the application of test potential, and residual charge on the motor winding. (Ref. IEEE Std 43-1974)

Large Motor - For this report, large motors are ac electric motors with horsepower ratings greater than 500.

Limiting Condition for Operation (LCO) - The minimum Technical Specifications requirements for the configuration and operating parameters of a plant system in order for that system to be considered operable, for a given plant operating mode, to satisfy the design safety limits for the plant.

Mild Environment - "An environment expected as a result of normal service conditions and extremes (abnormal) in service conditions where seismic is the only design basis event (DBE) of consequence" (Ref. 47).

Motor Circuit Analysis - Precision measurement, trending, and analysis of motor circuit parameters such as individual phase resistance from the circuit breaker disconnects through the motor winding, individual phase resistance to ground, motor coil inductance, and capacitance of each phase to ground to assess the condition of an electric motor, and monitor degradation via the trends shown by these parameters over time compared to baseline values (Ref. 37).

Motor Current Signature Analysis - Also referred to as **current analysis** or **current sideband analysis**. Analysis of stator current using special Fast Fourier Transform techniques to obtain the frequency spectrum of the harmonic components in the stator current. The magnitudes of the sidebands around the dominant 60 Hz supply frequency can indicate the presence of cracked or broken rotor bars, or high resistance joints.

Polarization Index - The ratio of the insulation resistance test value at ten minutes to the insulation resistance value at one minute. If a motor winding insulation is dry and in good condition, the polarization index will be higher (typically greater than 2.0) than if the insulation is wet and/or dirty.

Power Factor Tip-Up - The difference between the power factors for an insulation measured at two different applied voltages, typically at 25% and 100% of the line-to-ground operating voltage for the motor. The power factor tip-up indicates the condition of the motor insulation (voids in the dielectric materials) and its surface. Increases in tip-up over time, when measured under identical conditions, can indicate increased service degradation and void formation due to load cycling, high temperatures, ionization, and partial discharge (corona).

Recirc - Recirculation. Reactor recirculation system in a BWR.

Scoop Tube Positioner - The Reactor Recirc Pump in a BWR is a variable speed induction motor in which the speed of the motor is controlled by varying the frequency of the ac power driving the motor. The source of the varying frequency ac power is the reactor recirc MG set. The MG set drive motor is a constant speed motor that is connected to the MG set generator by a fluid coupling whose stiffness, and hence the output speed and frequency of the MG set generator, is adjusted by the scoop tube positioner.

Severity Level - A reporting category on NPRDS (Ref. 18) that indicates how extreme the effects of a failure are. Three severity levels are designated (from worst to least severe): 1) immediate, 2) degraded, and 3) incipient.

Stressor - "Agent or stimulus that stems from pre-service and service conditions and can produce immediate or aging degradation of a system, structure, or component. Examples: heat, radiation, humidity, steam, chemicals, pressure, vibration, seismic motion, electrical cycling, and mechanical cycling." (Ref. 45)

Support Equipment - Defined in this report as the equipment required to start and support the continued operation of a large electric motor. The support equipment include the motor circuit breaker or starter, feeder cables, instrumentation and controls, cooling water supply to bearings, lube oil or ventilation heat exchangers, protective relaying, and room or area cooling and ventilation systems.

Totally-Enclosed Machine - A motor "so enclosed as to prevent the free exchange of air between the inside and the outside of the case but not sufficiently enclosed to be termed air-tight." (Ref. 13)

APPENDIX A

Large Electric Motor Population Surveys on the NPRDS

Table A.1 MOTOR TYPES grouped by NSSS Supplier - NPRDS (3/15/95)

Motor Type	NPRDS Code	Westinghouse		CE		B&W		All PWR Plants		All GE BWR Plants		TOTAL All Plants	
		Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent
Synchronous	A	17	1.9	9	3.9	0	0	26	2.1	57	7.3	83	4.1
Squirrel Cage Induction	C	877	96.2	221	96.1	116	100	1214	96.6	699	89.4	1913	93.8
Induction, Slip Ring	D	17	1.9	0	0	0	0	17	1.4	26	3.3	43	2.1
TOTALS		911		230		116		1257		782		2039	

Table A.2 MOTOR CAPACITY (Line Voltage) grouped by NSSS Supplier - NPRDS (3/15/95)

Motor Capacity (Line Voltage)	NPRDS Code	Westinghouse		CE		B&W		All PWR Plants		All GE BWR Plants		TOTAL - All Plants	
		Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent
300-499 Vac	F	13	1.4	15	6.5	2	1.7	30	2.4	17	2.2	47	2.3
500-699 Vac	G	13	1.4	0	0	0	0	13	1.0	0	0	13	0.6
2000-2599 Vac	H	0	0	0	0	0	0	0	0	9	1.2	9	0.5
3500-4999 Vac	J	588	64.5	151	65.7	80	69.0	819	65.2	686	87.7	1505	73.8
6000-6999 Vac	K	235	25.8	41	17.8	28	24.1	304	24.2	21	2.7	325	15.9
7000-12999 Vac	N	8	0.9	0	0	0	0	8	0.6	0	0	8	0.4
13000-13999 Vac	L	48	5.3	20	8.7	4	3.5	72	5.7	40	5.1	112	5.5
Unknown		6	0.7	3	1.3	2	1.7	11	0.9	9	1.2	20	1.0
TOTALS		911		230		116		1257		782		2039	

Table A.3 MOTOR HORSEPOWER RATINGS grouped by NSSS Supplier - NPRDS (3/15/95)

Motor Horsepower Rating	NPRDS Code	Westinghouse		CE		B&W		All PWR Plants		All GE BWR Plants		TOTAL All Plants	
		Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent
500-999 hp	F	355	39.0	85	37.0	45	38.8	485	38.6	247	31.6	732	35.9
1000-1999 hp	G	152	16.7	25	10.9	19	16.4	196	15.6	236	30.2	432	21.2
2000-2999 hp	H	32	3.5	12	5.1	14	12.0	58	4.6	76	9.7	134	6.6
3000 hp & up	I	372	40.8	108	47.0	38	32.8	518	41.2	223	28.5	741	36.3
TOTALS		911		230		116		1257		782		2039	

Table A.4 LARGE MOTOR MANUFACTURERS grouped by NSSS Supplier - NPRDS (3/15/95)

Motor Manufacturer	NPRDS Code	Westinghouse		CE		B&W		All PWR Plants		All GE BWR Plants		TOTAL All Plants	
		Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent	Qty	Percent
General Electric Company	G080	82	9.0	48	20.9	7	6.0	137	10.9	613	78.4	750	36.8
Westinghouse Electric Corp	W120	532	58.4	69	30.0	80	69.0	681	54.2	40	5.1	721	35.4
Allis Chalmers Corp	A180	132	14.5	81	35.2	12	10.3	225	17.9	64	8.2	289	14.2
Electric Machinery Mfg Co	E120	28	3.1	0	0.0	7	6.0	35	2.8	22	2.8	57	2.8
Siemens - Allis Inc	S188	20	2.2	21	9.1	0	0.0	41	3.3	11	1.4	52	2.6
Reliance Electric Co	R165	34	3.7	0	0.0	1	0.9	35	2.8	3	0.4	38	1.9
NEI Peebles Elect Products Inc	P076	9	1.0	0	0.0	0	0.0	9	0.7	10	1.3	19	0.9
Hitachi Ltd	H200	12	1.3	0	0.0	5	4.3	17	1.4	0	0.0	17	0.8
Louis Allis Co	L280	14	1.5	0	0.0	0	0.0	14	1.1	3	0.4	17	0.8
Portec Inc	P292	6	0.7	4	1.7	0	0.0	10	0.8	5	0.6	15	0.7
English Electric	E275	11	1.2	0	0.0	0	0.0	11	0.9	0	0.0	11	0.5
Electric Prod Div/Midland-Ross	E130	8	0.9	0	0.0	0	0.0	8	0.6	0	0.0	8	0.4
McQuay Grp McQuay-Perfex Inc	M187	8	0.9	0	0.0	0	0.0	8	0.6	0	0.0	8	0.4
General Dynamics	G075	0	0.0	0	0.0	3	2.6	3	0.2	3	0.4	6	0.3
United States Motors Corp	U013	0	0.0	6	2.6	0	0.0	6	0.5	0	0.0	6	0.3
US Electrical Motors	U150	1	0.1	0	0.0	1	0.9	2	0.2	2	0.3	4	0.2
Ideal Electric Co	I011	0	0.0	0	0.0	0	0.0	0	0.0	4	0.5	4	0.2
Ionics Inc	I175	3	0.3	0	0.0	0	0.0	3	0.2	0	0.0	3	0.1
Layne & Bowler Inc	L095	3	0.3	0	0.0	0	0.0	3	0.2	0	0.0	3	0.1
Delco Co	D092	0	0.0	0	0.0	0	0.0	0	0.0	2	0.3	2	0.1
Worthington Pump Inc	W318	2	0.2	0	0.0	0	0.0	2	0.2	0	0.0	2	0.1
Circle A W Prod Co/Siemens	C767	2	0.2	0	0.0	0	0.0	2	0.2	0	0.0	2	0.1
ABB Brown Boveri	B455	1	0.1	0	0.0	0	0.0	1	0.1	0	0.0	1	0.0
Crane Deming Pumps	C666	1	0.1	0	0.0	0	0.0	1	0.1	0	0.0	1	0.0
Pacific Pumps Div/Dresser Ind	P025	1	0.1	0	0.0	0	0.0	1	0.1	0	0.0	1	0.0
Perfex Div/McQuay-Perfex Inc	P160	1	0.1	0	0.0	0	0.0	1	0.1	0	0.0	1	0.0
Gamah Div/Stanley Aviation Corp	G020	0	0.0	1	0.4	0	0.0	1	0.1	0	0.0	1	0.0
TOTALS		911		230		116		1257		782		2039	

APPENDIX B

Standards Applicable to Large Electric Motors in Nuclear Power Plant Service

American National Standards Institute (ANSI)

ANSI/IEEE C37.96	IEEE Guide for AC Motor Protection-1988
ANSI C50.10-1990	American National Standard Requirements for Rotating Electric Machinery - Synchronous Machines
ANSI C50.41-1982	American National Standard for Polyphase Induction Motors for Power Generating Stations

Anti-Friction Bearing Manufacturers Association (AFBMA)

ANSI/AFBMA 9-1978	Load Ratings and Fatigue Life for Ball Bearings
ANSI/AFBMA 11-1978	Load Ratings and Fatigue Life for Roller Bearings
ANSI/AFBMA 13-1970	Roller Bearing Vibration and Noise (Methods of Measuring)

Institute of Electrical and Electronics Engineers (IEEE)

IEEE 1-1986	IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation
IEEE 43-1974	IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery
IEEE 56-1977	IEEE Guide for Insulation Maintenance of Large AC Rotating Machinery
IEEE 85-1973	IEEE Standard Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery
IEEE 95-1977	IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage
IEEE 98-1984	IEEE Standard for the Preparation of Test Procedures for the Thermal Evaluation of Solid Electrical Insulating Materials
IEEE 99-1980	IEEE Recommended Practice for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electric Equipment
IEEE 112-1991	IEEE Standard Test Procedure for Polyphase Induction Motors and Generators
IEEE 115-1983	IEEE Test Procedures for Synchronous Machines
IEEE 115A-1987	IEEE Standard Procedures for Obtaining Synchronous Machine Parameters by Standstill Frequency Response Testing

IEEE 116-1975	IEEE Standard Test Procedure for Carbon Brushes
IEEE 117-1974	IEEE Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery
IEEE 118-1978	IEEE Standard Test Code for Resistance Measurements
IEEE 120-1989	IEEE Master Test Guide for Electrical Measurements in Power Circuits
IEEE 252-1977	IEEE Standard Test Procedure for Polyphase Induction Motors Having Liquid in the Magnetic Gap
IEEE 275-1992	IEEE Recommended Practice for Thermal Evaluation of Insulation Systems for Alternating-Current Electric Machinery Employing Form-Wound Preinsulated Stator Coils for Machines Rated 6900 V and Below
IEEE 290-1980	IEEE Standard for Electric Couplings: Part 1-General, Rating, Performance Characteristics; Part II-Test Procedures
IEEE 323-1974	IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations
IEEE 334-1994	IEEE Standard for Qualifying Continuous Duty Class 1E Motors for Nuclear Power Generating Stations
IEEE 344-1987	IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations
IEEE 421.2-1990	IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems
IEEE 421.4-1990	IEEE Guide for the Preparation of Excitation System Specifications
IEEE 429-1994	IEEE Recommended Practice for Thermal Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Preinsulated Stator Coils for Machines Rated 6900V and Below
IEEE 432-1992	IEEE Guide for Insulation Maintenance for Rotating Electrical Machinery (5 hp to less than 10000 hp)
IEEE 433-1974	IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency
IEEE 434-1973	IEEE Guide for Functional Evaluation of Insulation Systems for Large High-Voltage Machines
IEEE 522-1992	IEEE Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electric Machines

IEEE 792-1987	IEEE Trial-Use Recommended Practice for the Evaluation of the Impulse Voltage Capability of Insulation Systems for AC Electric Machinery Employing Form-Wound Stator Coils

National Electrical Manufacturers Association (NEMA)

MG 1-1993	Motors and Generators
MG 2-1989	Safety Standard for Construction, and Guide for Selection, Installation, and Use of Electric Motors and Generators
MG 3-1974	Sound Level Prediction for Installed Rotating Electrical Machines
MG 10-1994	Energy Management Guide for the Selection and Use of Polyphase Motors

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Large electric motors serve as the prime movers to drive high capacity pumps, fans, compressors, and generators in a variety of nuclear plant systems. This study examined the stressors that cause degradation and aging in large electric motors operating in various plant locations and environments. The operating history of these machines in nuclear plant service was studied by review and analysis of failure reports in the NPRDS and LER databases. This was supplemented by a review of motor designs, and their nuclear and balance of plant applications, in order to characterize the failure mechanisms that cause degradation, aging, and failure in large electric motors. A generic failure modes and effects analysis for large squirrel cage induction motors was performed to identify the degradation and aging mechanisms affecting various components of these large motors, the failure modes that result, and their effects upon the function of the motor. The effects of large motor failures upon the systems in which they are operating, and on the plant as a whole, were analyzed from failure reports in the databases. The effectiveness of the industry's large motor maintenance programs was assessed based upon the failure reports in the databases and reviews of plant maintenance procedures and programs.

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