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OPERATING EXPERIENCE AND AGING-SEISMIC ASSESSMENT OF ELECTRIC MOTORS

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June 1985

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

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ABSTRACT

This report provides an aging assessment of electric motors and was conducted under the auspices of the NRC Nuclear Plant Aging Research Program (NPAR). The objectives of this program are to identify concerns related to the aging and service wear of equipment operating in nuclear power plants, to assess their possible impact on plant safety, to identify effective inspection surveillance and monitoring methods and to recommend suitable maintenance practices for mitigating aging related concerns and diminish the rate of degradation due to aging and service wear.

Motor design and materials of construction are reviewed to identify age-sensitive components. Operational and accidental stressors are determined, and their effect on promoting aging degradation is assessed. Failure modes, mechanisms, and causes have been reviewed from operating experiences and existing data banks. The study has also included consideration for the seismic correlation of age-degraded motor components.

The aforementioned reviews and assessments were assimilated to characterize the dielectric, rotational, and mechanical hazards on motor performance and operational readiness. The functional indicators which can be monitored to assess motor component deterioration due to aging or other accidental stressors are identified. Conforming with the NPAR strategy as outlined in the program plan, the study also includes a preliminary discussion of current standards and guides, maintenance programs, and research activities pertaining to nuclear power plant safety-related electric motors.

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FIGURES (Cont'd.)

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S.0 SUMMARY

S.1 INTRODUCTION

An aging assessment of electric motors was conducted under the auspices of the NRC Nuclear Plant Aging Research (NPAR) Program. The intentions of this program are to resolve issues related to the aging and service wear of equipment and systems at operating reactor facilities and to assess their possible impact on plant safety.

In accordance with the NPAR program, the following are the three major goals of the program:

A. To identify and characterize aging and service wear effects associated with electrical and mechanical components, interfaces, and systems likely to impair plant safety.

B. To identify and recommend methods of inspection, surveillance and condition monitoring of electrical and mechanical components and systems which will be effective in detecting significant aging effects prior to loss of safety function so that timely maintenance and repair or replacement can be implemented.

C. To identify and recommend acceptable maintenance practices which can be undertaken to mitigate the effects of aging and to diminish the rate and extent of degradation caused by aging and service wear.

Goal A and initial results from goal B have been achieved; aging and service wear effects have been characterized and preliminary inspection, surveillance and monitoring (ISM) techniques have been identified. Advanced ISM techniques will be evaluated in the next program phase as will recommendations for maintenance (Goal C).

To accomplish the identification of aging and service wear effects and appropriate ISM techniques, it was necessary to examine potential failure modes, mechanisms, and causes. This was achieved by reviewing motor design and materials of construction (Section 2), by establishing the motor stressors that are both operational and accident related (Section 3), and by reviewing existing failure related data (Chapter 4). Aging-seismic correlation was addressed during this phase of the program. An interim review of current standards, manufacturer recommendations, and condition monitoring techniques was performed in order to aid in the determination of future work (Section 5).

S.2 MOTOR DESIGN/MATERIALS OF CONSTRUCTION

Only a few categories of electric motors are of direct safety significance in nuclear power plants: 1) three phase induction motors, 2) direct current (dc) motors, and 3) three-phase synchronous motors. The squirrel cage induction motor is the "work-horse" of the nuclear industry, comprising nearly 90% of the total population. Synchronous and dc motors constitute an additional 9% with the balance comprised of specialty applications. The percentage of motor failures of the total population in each category ranges from 2.4% for synchronous motors to 6.3% for dc motors. The dc motor failure rate

is higher than normal and attributable to commutator related problems. One of the data bases indicated that motors with ratings of 1 - 99.9 horsepower (hp) represent nearly 47% of the total motor population. Fractional hp (< 1.0 hp) motors and motors with ratings of 100 - 999 hp represent another 41% of the total population while large motors (> 1000 hp) essentially making up the balance. It can be deduced from the data analysis that failure rate typically increases with horsepower rating even though large motors are often equipped with sophisticated surveillance, monitoring and protection systems.

Three-phase induction motors are versatile and reliable, and speed can be selected to suit the load. Dc motors are reliable and have accurate speed control as well as efficient performance over the entire speed range but commonly require more maintenance. Where constant speed is an absolute necessity, the synchronous motor is available.

With regard to motor applications, valves and pumps constitute nearly 95% of the total motor population and are predominantly driven by squirrel cage induction motors.

An analysis of the major motor components and their respective materials of construction are summarized in the following table:

Motor Components	Materials	Effects of Aging
Stator	Copper, Steel, Silicon Steel,	Minimal
	Aluminium	Minimal
	Insulating Materials	Significant
Rotor	Copper, Steel	Minimal
	Insulating materials	Significant
Bearings	Steel, Brass, Bronze	Moderate
	Grease, Lube oil	Significant
Accessories	Steel, Cast Iron, Brass, Copper	Minimal
	Seals and Gaskets	Significant
	Mica, Plastics	Significant
	Cable Insulating Material	Moderate
	Graphite	Significant

The insulating system of a typical electric motor consists of various materials in association with conductors and supporting structural parts. Insulating systems are NEMA designated as A, B, F and H, in ascending order of maximum operating temperature for a given life. Class B insulation systems are consistently in the highest failure category while Class F and H exhibit significantly lower failures. This is partly because a large population of motors in a typical nuclear plant have Class B insulation.

S.3 STRESSORS - OPERATIONAL AND ACCIDENT RELATED

Motors are subjected to various operational stressors which originate both from system-level effects and from the environment, and as a result individual motor components are required to endure numerous types of service wear conditions. Abnormal or accident events tend to worsen these conditions while potentially introducing additional stressing effects. The selection of a particular motor type and rating for the performance of a specific system function therefore requires consideration of the predominant mode of system operation, whether continuous or intermittent, and prediction of the expected mild or harsh environment. System considerations are extremely important in motor specification and failure to adequately consider these aspects can result in excessive loading and premature aging.

The Residual Heat Removal Systems, Service Water Systems, and High Pressure Coolant Injection Systems were noted to experience the majority of motorized system failures.

All motor components are susceptible to degradation including the stator, rotor, bearings, and accessories. The two most significant stressors in motors are temperature and vibration-related, and while the potential for the occurrence of these stressors is multiple in nature, thermal effects commonly result from excessive current which imposes self-heating and thereby insulation failure, and vibrational effects which can originate from internal and external abnormalities.

Predominant failure modes for motors are associated with the stator and bearings. Stator related failures are the highest having nearly equal probability of occurrence for both pump and valve applications, whereas bearing failures are significantly higher for pump motors. Stators are highly inclined towards ground insulation burnout due to overheating and corresponding material degradation which occurs normally as well as at an accelerated rate under harsh environment conditions. Bearing failures result primarily from the deterioration of lubrication properties in grease or oil caused by high temperatures and foreign materials.

The stresses caused by normal operation as well as misoperation also degrade motors. Excessive starts and stops and backseating of valves are the two most common forms of operational stressors.

Operational and environmental parameters that are resultant aging mechanisms and therefore influence the degradation of insulation, lubrication, gaskets and seals, and other components made of organic materials are predominantly electrical, mechanical, chemical, thermal, environmental, and radiation. In order to fully assess the effect of aging degradation on motor components it was important that the material behavior of the various organic or inorganic components be characterized.

The extent of aging degradation for insulating materials is indexed by evaluating dielectric and mechanical properties: dielectric properties include dielectric strength, dielectric constant, dissipation factor, and volume/surface resistivity; mechanical strength is characterized by resistance to tensile or shear stress and the corresponding amount of material elongation.

The dielectric and mechanical strengths of most materials decline with increases in temperature, time, and thickness. Changes in the normal values of these can be indicative of abnormal conditions such as the presence of moisture, changes in temperature, short circuiting of conductors, or the grounding of terminal leads.

One of the most critical mechanical loads which can promote degradation is vibration and is often caused by coupling misalignment, rotor imbalance, loose parts, and seismic events.

Remaining stresses to be discussed have their most significant effects on insulation and therefore motor dielectric integrity. Chemical oxidation reduces the tensile strength of insulation while also making it brittle. High temperatures and moisture concentration reduce both electrical insulating properties and insulation tensile strength. Exposure to radiation adversely affects electrical and mechanical insulation properties by causing embrittlement.

Potential seismic damage to motor components is primarily mechanical and inertia-related. Inertial failures are always associated with the size of the mass and the vibration acceleration and consequently many small components of a motor can be excluded from seismic performance consideration. However, damage can also be caused by seismically-provoked conditions such as dislodged objects falling on the motor. Since aging-related degradation is complex in nature, the correlation of aging with seismic effects is difficult to qualify and quantify. A method has been suggested based on the mechanical failure of weak-link motor components in consideration of the environmental, service wear, and cyclic mechanisms. Based on the review of seismic test data and actual earthquake effects it appears that for small electric motors, seismic effects should be minimal providing motor dielectric, rotational, and mechanical integrities have been properly maintained.

S.4 DATA EVALUATION AND ASSESSMENTS

LER, IPRDS, and NPRDS data provide the most complete information available to date on actual nuclear power plant motor failure and therefore provide the primary basis for the assessment of common failure modes, mechanisms, causes, and the associated frequency. Other sources of information utilized include NPE, EEI, and EPRI reports as well as actual experience relayed by motor maintenance and design specialists and motor manufacturers. A thorough analysis of operating experience necessarily requires a review of incipient, partially degraded, and catastrophic losses of motor integrity.

Analysis of the LER data provided the following:

- Motor failures that occur inside of the defined motor boundary are significantly greater than those that occur outside the boundary.

- For BWR systems, pump and valve motors are equally prone to failure during normal plant operation, whereas for PWR systems pump failures are more likely to occur.

An IPRDS data review revealed the following:

- Pump motor failures are often control related.
- The stresses caused by continuous operation in a motor have less deleterious effect on aging and service wear than intermittent or infrequent operation.
- Vibration and moisture in-leakage are the prime causes of motor failure.
- Most reported pump and valve motor failures are catastrophic (Note: This indicated that incipient failures are not being identified.)

A comparison of NRC licensee SALP (Systematic Assessment of Licensee Performance) ratings with LER motor failures indicates that licensees receiving below average maintenance ratings also experienced a comparatively higher number of motor failures. This condition demonstrates that improved preventative maintenance could prolong motor life and reduce the overall number of failures.

A review of additional data sources utilized served to reinforce foregoing conclusions:

- Motor failures typically occur, and are detected, while the machine is in the operational modes.
- Most degraded motor conditions are either in advanced stages or have resulted in catastrophic failures.
- Stator grounding and bearing related problems are the primary causes of motor failures.

S.5 FAILURE MODES, MECHANISMS AND CAUSES

All of the previously outlined efforts enabled the identification of potential failure modes, mechanisms and causes. (Note: This information is detailed and the reader is encouraged to review Table 4-15 of the report. This table identifies the potential for aging and aging-seismic effects, and the probability of occurrence.)

S.6 CONCLUSIONS

During motorized system operation key parameters can be utilized to generally assess motor integrity. Various performance or functional indicators serve to characterize the behavior of any electric motor, and when normal values for these parameters are observed to adversely change, the incipient stage of degradation potentially leading to ultimate failure is occurring. Therefore, characteristic parameter performance can be linked to failure modes, mechanisms, and causes that are representative for all types of motors.

Predominant motor failure modes are associated with the stator insulation system and the bearings. The failure mechanisms for stator insulation include degraded mechanical and electrical strength, shorted windings, loose

laminations, wedges (etc.), overheating and burned windings, corona or ionization, and corrosion of electrical connections. Failure mechanisms for bearings are overheating, cracking, scoring, corrosion, and lubrication problems (i.e., too much, too little, loss of properties).

The performance or functional indicators for stator insulation include temperature, vibration, current, voltage, power factor, polarization index, and insulation resistance. The performance or functional indicators, for bearings are vibration, temperature, and lubrication properties (by analysis).

Another area of failures can be classified as miscellaneous. The items to be observed in this category include loose bolts, coupling or anchor bolts which could cause vibration, environmental contamination, damaged seals or gaskets which lead to oil or water leaks, faulty protective equipment settings which could cause overloading or overheating, malfunctioning space heaters which would allow moisture buildup, poor operation, and worn commutator brushes. The functional indicators in this category are (as applicable) vibration, evidence of corrosion and wear, cracks, and leaks.

Figures 6-2, 6-3 and 6-4 present the preceding discussion of failure modes, mechanisms and performance indicators in greater detail.

It has been established through analysis and independent testing that for at least certain small induction motors (approximately 10 hp), seismic effects should be minimal providing motor dielectric, rotational, and mechanical integrity have been properly maintained. However, the definition of proper maintenance remains as an area requiring further research as does motor aging-seismic susceptibility.

S.7 FUTURE WORK

As a natural outgrowth of the work performed to date, and in accordance with the NPAR program strategy, the following future work is planned:

- To finalize the identification of critical performance indicators.
- To review advanced inservice inspection, surveillance and monitoring techniques.
- To establish in-situ testing methods as necessary to corroborate other related findings.
- To identify and recommend acceptable motor maintenance practices which can be undertaken to mitigate the effects of aging.
- To expand Aging-Seismic correlation studies to assess all sizes and types of motors.
- To provide recommendations for standards and guides, with specific emphasis on IEEE Std. 323, 344 and 627.

1.0 INTRODUCTION

1.1 BACKGROUND

Nuclear power generating stations utilize electric motors as vital system components both for the performance of normal operations as well as for the accomplishment of safeguard functions when required for limiting the potential for radioactive release due to abnormal events. It is therefore, imperative that motors remain capable of driving required loads.

Despite on-going improvements in the design, manufacture, and maintenance of electric motors, failures continue to occur, often for "unknown" reasons. A necessary remaining requirement, then, is to detect defects in order that decline in performance be ascertained in the incipient stage rather than after the fact following catastrophic failure.

Research efforts to date by the Electric Power Research Institute (EPRI)[1-2] and the Edison Electric Institute (EEI)[3] as well as by others[4-11] have produced a wealth of statistical data and failure information relative to the endurance and stressors of electric motors in various industrial settings. However, a distinct focus on aging, service wear, and the potential for degradation due to seismic effects has remained as an unchartered topic of significant importance for consideration in the complete evaluation of operating reactor motor reliability.

Numerous motor types and sizes are required for a typical power plant including both alternating-current (ac) and direct-current (dc) types for Motor Operated Valve (MOV), pump, fan, and miscellaneous applications. This study includes all relevant types and sizes of motors critical to plant safety. Excluded are fractional horsepower motors, such as those used for control room strip-chart recorders.

The endurance of an electric motor is dictated by its ability to maintain dielectric, rotational, and mechanical integrity while withstanding the operational and environmental stresses. Although service wear is often visually evident, the time-related degradation effects of aging are not as apparent and furthermore, the ability of a naturally aged motor to withstand high-excitation seismic forces which was evaluated as part of this research effort has not been previously examined to a significant degree.

The NRC Office of Research, Division of Engineering Technology, Electrical Engineering Branch has instituted a comprehensive long-range research program intended for diagnosing and evaluating the effects of equipment aging. The program, entitled Nuclear Plant Aging Research (NPAR), ultimately seeks to improve the operational readiness of selected components that are vital to nuclear power generating safety.

This report encompasses an aging and seismic endurance assessment of electric motors based primarily on a review of operating experience. The portions of the NPAR scope that have been completed through this Part I effort are delineated in Figure 1-1.

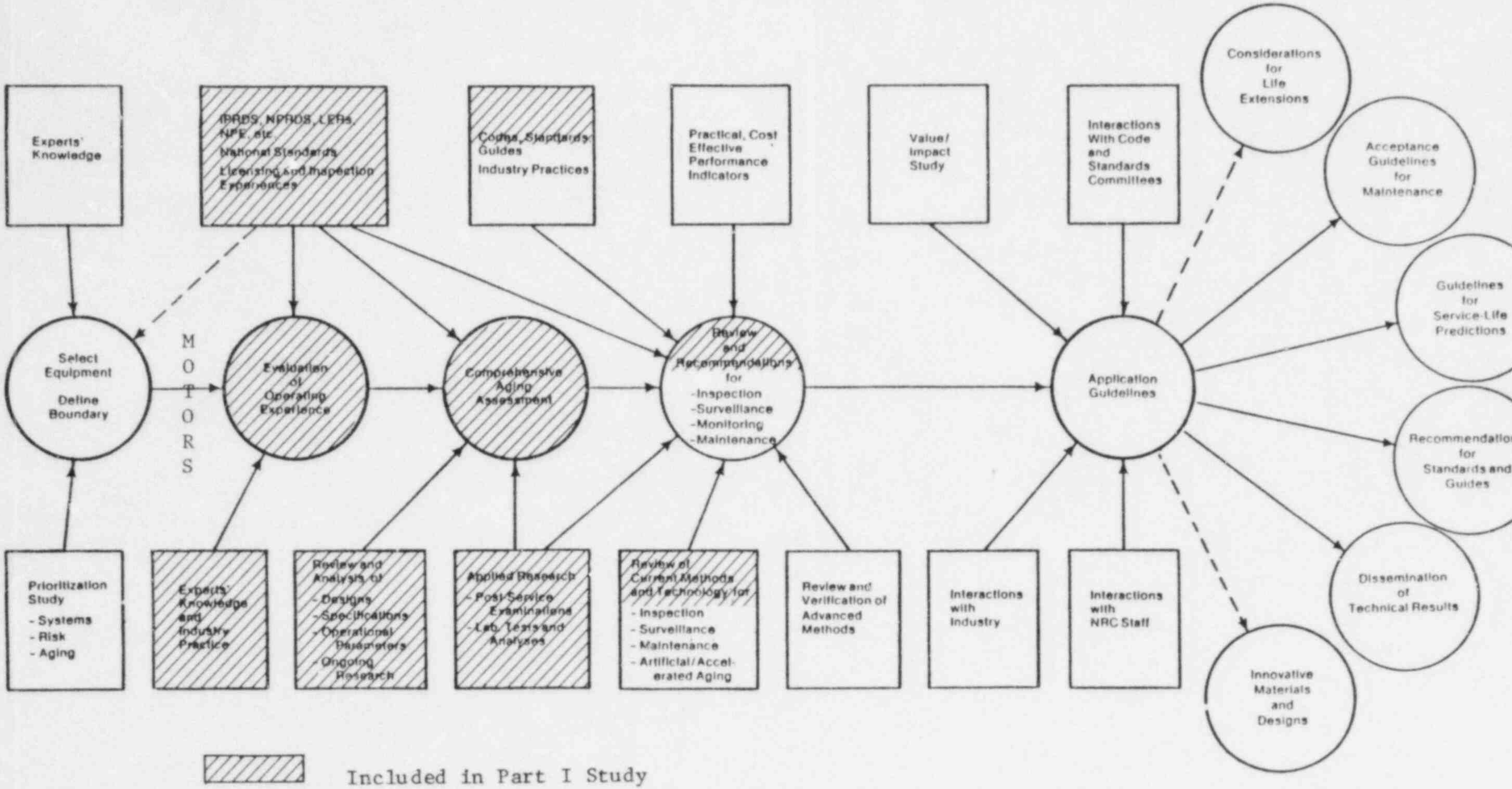

Figure 1-1: NRC-NPAR Strategy for Vital Component (Electric Motor)

1.2 OBJECTIVE

In accordance with the NRC - NPAR program plan, the following are the primary goals of the study:

1. To identify and characterize those aging and service wear effects associated with electric motors that are likely to impair plant safety.

2. To identify and recommend methods of inspection, surveillance, and condition monitoring that will be effective in detecting significant aging conditions such that proper maintenance or replacement can be implemented prior to loss of safety functions.

3. To identify and recommend acceptable maintenance practices that can be undertaken to mitigate the effects of aging, and to diminish the rate and extent of degradation caused by service wear.

Motor aging can be categorized as normal versus premature and it is therefore necessary to distinguish between those conditions caused by typical operating and environmental stressors as opposed to those resulting from misapplication, inadequate design, improper assembly, incorrect installation, abusive operation, or insufficient maintenance. It is to be noted that aging, within the context of this report, is defined as cumulative changes in motor integrity that occur with the passage of time. These changes can affect physical, electrical, and other properties, as well as component dimensions and corresponding relative positions within the motor housing.

1.3 SCOPE

Figures 1-2 and 1-3 depict the parts and components of typical ac & dc electric motors which consist of a stationary energized field (stator), a rotating element (rotor), alignment supports (bearings), and also various accessories which may include capacitors, instrumentation sensors, electric heaters, a cooling fan or heat exchanger, a terminal box, and a protective housing incorporating anchoring hardware. Throughout this report, the aforementioned components are considered to be within the motor boundary. The motor control center (MCC), service water system (where applicable), and the motor-driven application equipment are considered outside of the boundary but are included in the analysis of motor reliability to the extent that they can influence or directly contribute to motor failure. Figure 1-4 schematically depicts typical safety-related motor positions.

Environmental, operational, and accident-related stressors are considered for evaluating the system or component-level parameters that can affect motor performance. The environmental stressors include potential conditions of temberature, pressure, humidity, radiation, and chemical spray. Other effects include mechanical overloading, stator overheating, the introduction of moisture from external sources, and resulting insulation failure. The synergistic (combined) effects of stressors are addressed to the extent possible from existing literature. Aging-seismic correlation is discussed based on the Nutech report [12], EPRI findings[13], and the conclusions of the Senior

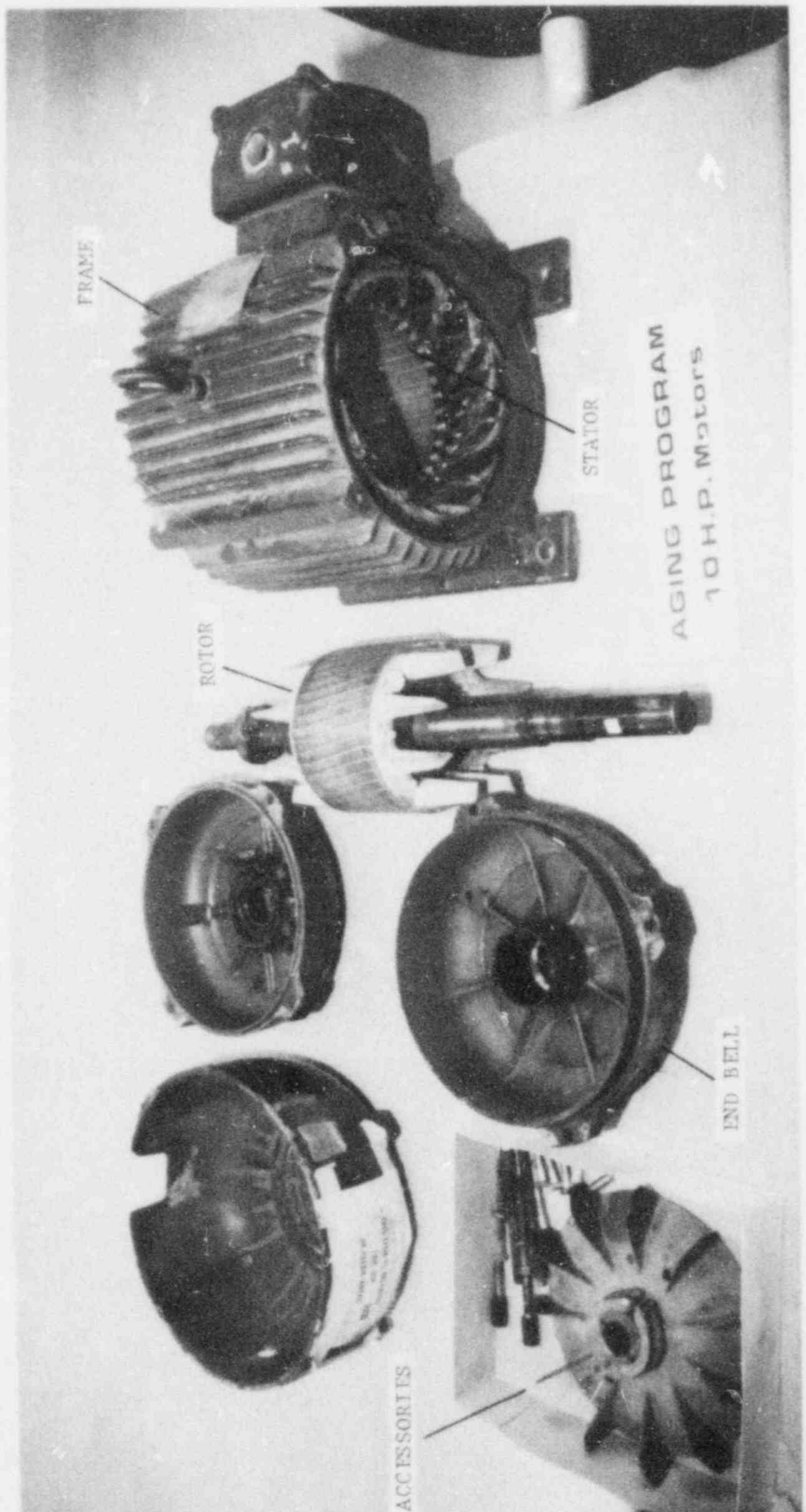

Figure 1-2: Motor Components

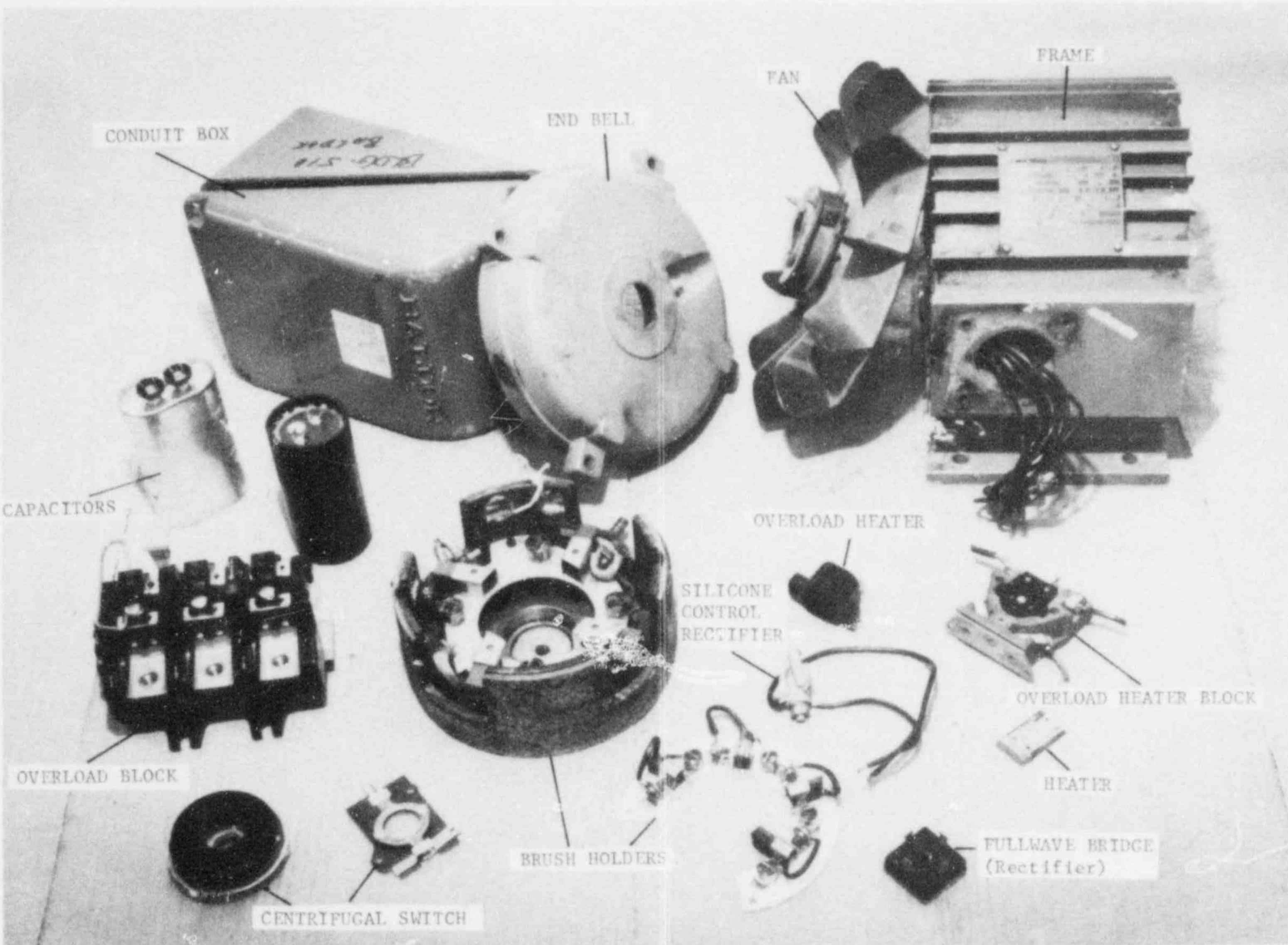

Figure 1-3: Motor Accessories

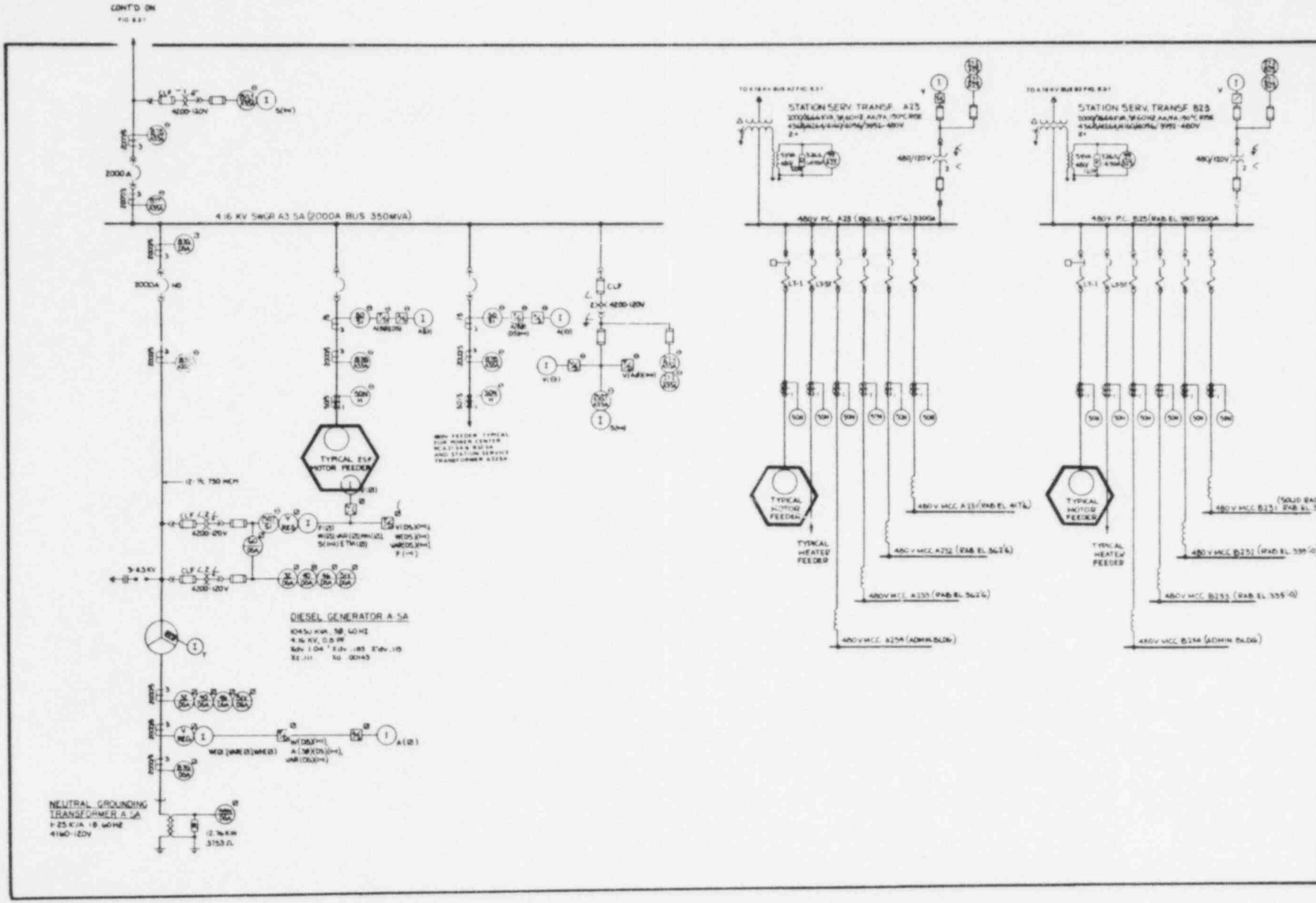

Figure 1-4: Electrical Line Diagram for Typical Motor Feeders

Seismic Review & Advisory Panel, SSRAP and the Seismic Qualification Utility Group, SQUG[14]. Test results for naturally aged motors and a review of recently published reports on the subject are included in the study as well.

The motor failure data base utilized for the evaluation of operating experience was extracted from the following sources:

1. Licensee Event Reports (LER)
2. In-Plant Reliability Data System (IPRDS)
3. Nuclear Plant Reliability Data System (NPRDS)
4. Nuclear Power Experience (NPE)

In evaluating the data from these sources, a failure was concluded for any event in which the motor was unable to deliver the required action upon demand. Based on the given description of the motor failure, subjective assessment of the reason was made wherever required due to a lack of adequate information so as to determine typical modes, mechanisms, and causes for the malfunctions.

Electric motor design and specification references utilized for analyzing the operating experience data base and for evaluating the suitability of existing standards included reports by the organizations given below:

1. Institute of Electrical and Electronics Engineers (IEEE)
2. National Electrical Manufacturers Association (NEMA)
3. American Society for Testing & Materials (ASTM)
4. American National Standards Institute (ANSI)

The standards and guides provide criteria for motor manufacturing and testing, although not specifically with regard to aging and seismic endurance design and on-line assessment. For example, ANSI, NEMA, and IEEE provide detailed information on terminal marking, component dimensions and tolerance, power ratings, inherent frequency limits and instructions for the performance of diagnostics such as high-potential tests, but the standards do not actually address time-related degradation effects and prescriptions for identifying fragility limits.

Other data sources employed for the evaluation of operating experience include maintenance recommendations provided by motor manufacturers, In-Service Inspection (ISI) reports, NRC-Inspection & Enforcement (I&E) plant and vendor inspection findings, and expert knowledge. A complete list of references is included with this report, and in addition, applicable standards, guides, and codes are given in Appendix A.

1.4 STRATEGY

Following the selection of motors as a vital component for safety analysis consideration and the subsequent identification of the relevant boundary, it was then appropriate to survey all possible data sources detailing motor failures. As noted, LER, IPRDS, NPRDS, and NPE data provides the most pertinent data base for nuclear power plant operating experience review. In the interest of obtaining as much information as possible on motor stressing conditions and resulting materials degradation, however, other data sources outlining nuclear as well as non-nuclear motor application failures were utilized

such as the EEI-Motor Malfunction Summary[3]. All relevant quantitative and qualitative information was systematically categorized by equipment application, and where possible for nuclear plant malfunctions, by safety system, Nuclear Steam Supply System (i.e., PWR or BWR)*, and by plant operating status at the time of failure (e.g., Mode-1; operational testing; etc.). To the furthest extent possible, reported failure instances were evaluated to deduce failure modes, mechanisms, and causes.

In order to adequately perform the evaluation of operating experience it was necessary to acquire a practical knowledge of motor design, construction, and testing in order that cited failure modes, mechanisms, and causes could be fully understood from the licensee point of view as described in the LER, IPRDS, NPRDS, and NPE data base. A tour of a motor manufacturing and service facility provided insight into the significance and imperativeness of ensuring dielectric, rotational, and mechanical integrity. Discussions with insulation testing specialists provided the perspective necessary for evaluation of condition monitoring and preventative maintenance options based on the identification of failure-prone critical sub-components and associated materials.

Expert knowledge and industry-practice experience was sought through discussions with Franklin Research Center, EBASCO services, Doble Engineering Company, and nuclear as well as fossil power station maintenance personnel. The objective of these discussions was to analyze and diagnose the aging and service wear causes of common-mode motor failure and to thereby identify suitable inspection, surveillance, condition monitoring, testing, and maintenance practices. As an additional measure for evaluating motor performance while under the influence of external forces, two 10-HP motors employed for 12 years in a nuclear power plant application were electrically and seismically tested[15].

The foregoing strategy and corresponding activities providing the fundamentals required for the evaluation of operating experience and comprehensive aging assessment will serve as the basis for the recommendations for inspection, surveillance, and monitoring methods and also for the application guidelines to be developed in Parts II and III of the study.

Motor construction is discussed in Section 2.0, and characteristic plots of material properties with corresponding endurance limits are given in Section 3.0 during the review of aging mechanisms. Section 4.0 discusses performance and functional indicators with emphasis placed on the importance of motor ventilation, insulation, temperature, lubrication, and on minimizing internal as well as external sources of vibration. An interim review of common inspection, surveillance, and condition monitoring techniques including a discussion of current technology and regulatory inspection requirements is given in Section 5.0. Conclusions and projections of the future work are presented in Section 6.0.

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* PWR: Pressurized Water Reactor
  BWR: Boiling Water Reactor

As noted, Figure 1-1 illustrates the approach employed to satisfy the NPAR objectives. During the first-phase of the research an evaluation of operating nuclear power plant experience, the performance of comprehensive aging assessment, an abbreviated treatment of current inspection, surveillance, and condition monitoring techniques, and a preliminary review of manufacturer-recommended maintenance practices is accomplished. An in-depth analysis of advanced inspection, surveillance, condition monitoring and maintenance practices will be fulfilled during the second-phase, and in the final report, component life for maintenance frequency, recommended guidelines, and a value impact study will be provided.

2.0 RESEARCH BASIS & MOTOR CHARACTERISTICS

This section identifies the sources of failure-related information, constituting the research basis and also describes materials, construction, and characteristics of motors. The analysis of the effects of stressors on motor components is outlined in Section 3, and the relevant evaluation of failure data is included in Section 4.

2.1 DATA AND INFORMATION SOURCES

Several nuclear power plant operating experience data sources are available at present. Although no single source contains all of the information required for the study, each has been examined to derive the most useful and pertinent elements related to motor failures. Due to limited access to all possible information sources as well as ever present time constraints encountered while accumulating the data, the following four previously introduced compilations were utilized to the greatest extent:

- Licensee Event Reports (LERs)
- In-Plant Reliability Data System (IPRDS)
- Nuclear Plant Reliability System (NPRDS)
- Nuclear Power Experience (NPE)

A detailed explanation of the analysis procedure performed on each of the above is provided in subsequent paragraphs. Other information sources (including studies sponsored by EPRI and EEI) are considered in the review. The aging-seismic correlation studies performed by SQUG and Nutech were evaluated in order to establish if any evidence of seismically-induced motor failure exists. The data base also includes numerous limited scope generic failure research findings. Motor manufacturer recommendations, responses from repair-facilities, in-service inspection data, expert knowledge, NRC-I&E audit reports, and standards and guides published by the Institute of Electrical and Electronics Engineers (IEEE), as well as by others, represents the balance of the data base.

2.1.1 Licensee Event Reports (LERs)

LERs[4-6] are reports of significant operational events at nuclear power plants submitted to the NRC by licensees in accordance with federal regulations. The requirements and procedures for reporting of events on an LER prior to January, 1984 were contained in individual plant Technical Specifications with additional guidance provided in NRC Regulatory Guide 1.16, "Reporting of Operating Information" and in NUREG-0161, "Instructions for Preparation of Data Entry Sheets for Licensee Event Reports". For events occurring after January 1, 1984, LERs are submitted in accordance with the rule 10CFR50.73, "Licensee Event Report System". Additional guidance on this new rule is given in NUREG-1022, "Licensee Event Report System - Description of Systems and Guidelines for Reporting". LERs submitted to the NRC under both old and the new systems are modified and processed into the computerized LER data file of the Nuclear Safety Information Center (NSIC) maintained by Oak Ridge National Laboratory.

The old LER system was judged to be inadequate for data collection due to a number of reasons, which included non-uniform reporting requirements for various plants and a lack of information in the LER on the cause of component or system failure. The new system requires more detailed and more uniform reports of events judged to be reportable. However, a number of component failure events previously reportable under the old LER rules are no longer reportable under the new rule. These events are to be reported to the Nuclear Plant Reliability Data System (NPRDS) under INPO direction. The NRC is currently evaluating the performance of NPRDS for providing equipment reliability data.

This study utilized computer-sorted LER abstracts from the NSIC LER data files covering the 10 year time period from 1974 to 1983 inclusive. The file was sorted to obtain motor failures and produced 190 LERs for Motor-Operated Valves (MOVs), 242 LERs for motor-driven pumps, and 123 LERs for miscellaneous motor-operated equipment (including fans and small samplers). Figure 2-1 illustrates the format and typical given information of two LER's for MOVs.

The motor-failure-sorted LER data base was reviewed by BNL and categorized according to NSSS type (i.e., BWR or PWR), plant status at the time of failure, operational characteristic of the motor and application equipment (i.e., intermittent or continuous duty), and common failure mode. This data base covers the wide range of horsepower ratings and overall motor sizes that are utilized in the various U.S. nuclear plant systems. Lacking, however, is the total motor population of the power plants needed to determine failure rates. Each LER description has been studied and based on subjective conclusions drawn from the narrative, the failure has been classified as to failure mode, effects from either outside or within the motor boundary, and as to a number of other characteristics described later in the report.

2.1.2 <u>In-Plant Reliability Data System (IPRDS)</u>

The ORNL-IPRDS data base [7-8] was developed primarily for use in nuclear power plant probabilistic risk assessment (PRA) and reliability studies. The source of the data was a representative sample of commercial operating reactor maintenance work request records.

Unlike other data accumulation systems, IPRDS is essentially a complete failure record that delineates levels of severity (i.e., catastrophic, degraded, and incipient conditions) and includes both safety and non-safety class equipment. The component identification, size, system, environment, and operational mode are also included in the information, and the pump-related data provides the repair record and category as shown below:

1. COMPONENT REPLACEMENT.
2. MINOR REPAIR.
3. MAJOR REPAIR.
4. RESET/ADJUST.
5. RECALIBRATE.
6. UNKNOWN.

Specific age-related failure information is not available from the IPRDS data base. In fact, the failure and repair descriptions in this system are in some instances condensed to the extent that considerable expertise is required

```
 11/0/0000001-0000190//        137
ACCESSION NO.     0020105294
TITLE             HPCI PUMP SUCTION ISOLATION VALVE FAILS TO OPEN AT FITZPATRICK
CORPAUTH          NIAGARA MOHAWK POWER CORP., SYRACUSE
DATE              1975
TYPE              Q
MEMO              2 PGS. LTR W/AOR 75-69 TO NRC DIR. OF LICENSING. AUG. 18. 1975.
                  DOCKET 50-333, TYPE--BWR, MFG--G.E., AE--STONE & WEBSTER
AVAIL             AVAILABILITY - NRC PUBLIC DOCUMENT ROOM, 1717 H STREET.
                  WASHINGTON. D. C.   20555. (08 CENTS/PAGE -- MINIMUM CHARGE
                  $2.00)
CATEGORY          170000;120000
EDITION           0062
CORP CODE         NMP
COUNTRY           A
ABSTRACT          CAUSE - MOTOR BURNED UP.  THE HPCI PUMP SUCTION FROM TORUS
                  OUTBOARD ISOLATION VALVE FAILED TO OPEN ON SIGNAL DURING
                  TESTING.  THE VALVE MOTOR WAS BURNED UP.  IT WAS SENT OFF-SITE
                  FOR REPAIR.  THE VALVE WAS MANUALLY OPENED.  IT WILL BE
                  MANUALLY CLOSED IF REQUIRED.
KEYWORDS          REACTOR, BWR;FAILURE, EQUIPMENT;FAILURE;CONTAINMENT ISOLATION;
                  FITZPATRICK (BWR);TEST, SYSTEM OPERABILITY;VALVE OPERATORS;
                  MOTORS;VALVES;HPCI
 11/0/0000001-0000190//        138
ACCESSION NO.     0020104083
TITLE             HIGH PRESSURE SERVICE WATER VALVE MOTOR TRIPS AT PEACH BOTTOM 3
CORPAUTH          PHILADELPHIA ELECTRIC COMPANY, PA.
DATE              1975
TYPE              Q
MEMO              2 PAGES, LETTER TO NRC DIVISION OF REACTOR LICENSING. JUNE 30,
                  1975, DOCKET 50-278, TYPE--BWR, MFG--G.E., AE--BECHTEL
AVAIL             AVAILABILITY - NRC PUBLIC DOCUMENT ROOM. 1717 H STREET.
                  WASHINGTON. D. C.   20555. (08 CENTS/PAGE -- MINIMUM CHARGE
                  $2.00)
CATEGORY          170000;120000
EDITION           0061
CORP CODE         PEC
COUNTRY           A
ABSTRACT          CAUSE - WATER IN THE MOTOR.  DURING TESTING OF THE HIGH
                  PRESSURE SERVICE WATER SYSTEM WITH THE REACTOR AT 50% POWER.
                  THE RHR HEAT EXCHANGER OUTLET VALVE MOTOR TRIPPED ON THERMAL
                  OVERLOAD.  MOISTURE HAD ACCUMULATED IN THE MOTOR CAUSING IT TO
                  TRIP ELECTRICALLY.  A PREVIOUSLY REPAIRED VALVE STEM LEAK IN
                  THIS VALVE IS SUSPECTED TO HAVE CAUSED THE WATER ACCUMULATION.
                  THE MOTOR WAS DRIED OUT AND RETURNED TO SERVICE.
KEYWORDS          REACTOR, BWR;FAILURE, EQUIPMENT;FAILURE;WATER;TEST. SYSTEM
                  OPERABILITY;FAILURE, MAINTENANCE ERROR;AUXILIARY COOLING;
                  SHUTDOWN COOLING SYSTEM;PEACH BOTTOM 3 (BWR);VALVE OPERATORS;
                  MOTORS;HEAT EXCHANGERS
```

Figure 2-1: Typical LER Data sorted by Motor Failures

to make an assessment of the event that occurred. Additionally, since the information applies to valve or pump failures overall, often it is difficult to determine whether a reported malfunction is directly applicable to the motor itself. For example, when a bearing failure condition is reviewed, the reported occurrence may be undistinguished between the motor bearings and the pump bearings. In some IPRDS cases it is possible to retrospectively identify the incipient stage of degradation from maintenance work requests. The data specifically addresses particular generating units on a case-by-case basis in contrast to the other motor failure information sources utilized. A total of four nuclear power plants was included in the sort which represented two stations, each having a single Pressurized Water Reactor (PWR), and two other stations having Boiling Water Reactors (BWRs) including a single station comprised of three units.

The IPRDS information used in this study addresses motor failures only. The pump motor sort applies to all four plants while the valve motor (MOV) sort applies to two of the plants, each having a single PWR or BWR unit. No other motor-driven components were included in the IPRDS data base.

2.1.3 Nuclear Plant Reliability Data System (NPRDS)

NPRDS[9], compiled by the Institute for Nuclear Power Operations (INPO), contains both component engineering and failure information. The INPO annual reports relay cumulative system reliability, and those used for this study range from July 1, 1974 through December 31, 1982.

The primary purpose of the information is to provide safety-related system operating statistics for the purpose of evaluating and comparing reliability performance based on modes and rates for components which in turn can be used in the development of failure-mode-effects analysis, fault hazard analysis, and PRA studies. The NPRDS data base is designed to organize operational behavior information for nuclear plant safety systems and components. The motor performance data includes type/category, application/function, failure detection method, and reactor status at the time of the failure. In addition to the annual reports, quarterly NPRDS component failure listings for the year 1983 were examined. A sample copy of these data is shown in Fig. 2-2.

2.1.4 Nuclear Power Experience (NPE)

NPE[10] is a comprehensive accumulation of operating experience for U.S. Light Water nuclear power plants compiled by S.M. Stoller Corporation. The data are contained in several volumes which are cross-referenced and keyworded for direct access and information retrieval. The summaries narrate the entire sequence of a motor failure event which includes the date, source, or cause of the failure and the repair record detailing corrective action. A typical NPE motor failure report is shown in Fig. 2-3. The data is subdivided under components failure headings such as air deflectors, bearings, brushes, end bells, fans, insulation, lubrication, overloads, starters, vibration, and windings. A total of 163 BWR and 193 PWR events related to motor failures were examined. Of all the data sources utilized, NPE contains the most in-depth background information concerning specific failures.

```
MOTOR    6080                                   E 03

              NPRDS COMPONENT FAILURE (A02C) REPORT- NUCLEAR PLANT RELIABILITY DATA SYSTEM            83-3
                                           "lant Type" GENERAL ELECTRIC
-----------------------------------------------------------------------------------------------------
        FAILURE REPORT                           |          COMPONENT ENGINEERING DATA
                                                 |
                           ENTERED ON 08/11/83   |
                                                 |
NPRDS Component Code..............MOTOR          |  Location................REACTOR RECIRCULATION SYS.
                                                 |
Discovery Date................830405             |  Data Start Date.........760401
Discovery Number..............1                  |  In-Service Date.........751103
Report Date...................830628             |  Out-of-Service Date.....
                                                 |
Affected System...............CBB-REACTOR RECIRCULATION SYS.  |  Safety Class............2
                                                 |  Critical Operation Mode.OPERATING
Start Date....................830405             |
Start Time....................13:00              |  Manufact   r............G080
End Date......................830412             |                          GENERAL ELECTRIC COMPANY
End Time......................13:00              |  Manufacturer Model No...5K26375A61-3
                                                 |  Manufacturing Std.......
Status Code...................E-SUBSYS/CMPNT IN SRVC (OP/STANDBY)  |
Type of Failure Codes.........A-MECHANICAL       |  Internal Environment....AIR
Mode Code.....................AA-LEAK            |  External Environment....TEMP & HUM CONTROLLED
Type of Detection Codes.......E-SPECIAL INSPECTION  |                        AMBIENT TEMP(-10F-120F)
Cause Category Codes..........K-UNKNOWN          |
                              F-MAINTENANCE/TESTING  |  Vendor..................GENERAL ELECTRIC COMPANY
Cause Codes...................XX-OTHER (SEE REMARKS)  |
                              GA-EXCESS VIBRATION  |          Engineering Codes
                              AM-IMPROPER PREVIOUS REPAIR  |
System Effect Codes...........E-NO SIGNIFICANT EFFECT  |  A. Type...................SYNCHRONOUS
Plant Effect Codes............G-NO SIGNIFICANT EFFECT  |  B. Rating.................3000 HP AND OVER
Corrective Action Codes.......AH-REPLACE PART(S)  |  C. Capacity-Line Voltage..3 500-4 999 VAC POLYPHASE
                              AG-REPAIR PART(S)  |  H. Voltage Rating..........3920 VAC
Documentation Codes...........Z-NONE             |  J. Rotational Speed........1680 RPM
                                                 |
Failure Description..WHILE ADDING OIL TO 2B RX RECIRC PUMP LOWER MOTOR  |  % Time Operating When Reactor is Critical...100 %
                     BEARING , OIL WAS FOUND LEAKING FROM DRAIN LINE   |  % Time Operating When Reactor is Standby....100 %
                     FITTING AND THE DRAIN VALVE .                     |  % Time Operating When Reactor is Shutdown...70 %
                                                 |
Cause of Failure.....UNKNOWN , HOWEVER VIBRATION OR IMPROPER   |  Testing Performed    Frequency/Period    Hrs Out of
                     MAINTENANCE COULD HAVE BEEN A FACTOR (DRAIN VALVE  |  -----------------    ----------------     Service
                     WAS MISSING THE PACKING NUT) .            |
                                                 |  Check Testing         1 / DAY                0
Corrective Action....REPAIRED LEAKING FITTINGS AND REPLACED DRAIN VALVE  |  Functional Testing    0 / NOT DONE           0
                     THAT WAS MISSING PACKING NUT .  TT #2-M-83-1182 .  |  Calibration Testing   0 / NOT DONE           0
-----------------------------------------------------------------------------------------------------
```

Figure 2-2: NPRDS Motor Failure Data (Sample)

2.1.5 Published Reports

Electric Power Research Institute (EPRI)

An EPRI report[1] prepared by General Electric Company has evaluated the reliability and performance of state-of-the-art power plant motors with regard to design and operational characteristics which offer the potential for increased dependability and efficiency. The study surveyed 132 generating units constituting 4800 low-to-medium voltage motors having ratings greater than 100 HP. The results link failure causes to plant designers, utility companies, and motor manufacturers and to the specific hardware applications. However, the information is not exclusive to nuclear power plants.

Another useful and related document prepared for EPRI by NUS Corporation[2] provides the nuclear industry with motor lifetime predictions under typical mild environment conditions. The report covers the period 1969 through 1979 and includes such information as annual motor malfunction trouble rate and average motor service life.

45. EXCESSIVE CURRENTS DAMAGED RCP MOTOR - REPLACEMENT REQUIRED

Zion 1 - June & July 75 - shutdown

The RCP's were being started periodically to assist in venting the primary system. The 1A RCP had been running for ~ 3 hr and then was secured. After about a 3 hr shutdown period it was restarted; it was manually tripped ~ 1 min later because the operator observed an apparent abnormality in pump seal leakoff flow. The problem was resolved and the pump was restarted ~ 5 min later. Startup current was observed to drop off and stabilize properly at the running value on the control board meter. After a 34 sec run, the motor tripped on instantaneous phase overcurrent; a phase unbalance relay also operated. Initial inspection of the motor indicated some possible coil displacement and the presence of what appeared to be pieces of insulation on top of the windings. Examination showed A Ø to be grounded.

Because there were too many unknowns associated with a repair they decided to replace the motor. W located a 7000 hp motor at Salem that could be adapted to Zion. The motor arrived on site 6 days after the failure. To adapt the Salem motor several alterations were required; among them were:

- rerouting of the 4 kV leads.
- repiping of cooling water to oil cooler.
- mating the Salem motor bearing T/C's to the Zion RTD system.
- accomplishing 3 pump modifications.
- an 18 ft square hole had to be mined through a 4ft concrete shield to allow for replacement.

The motor was installed and they were ready for startup within 10 days.

The failed motor was disassembled, decontaminated and shipped to W for evaluation of the failure. The damage included:

- > 50% of the upper end-ring rotor bar connections were broken. They were brazed connections and extensive melting of the brazing had occurred. The appearance of the puddles suggested that they were molten when the rotor was at rest.
- The noise suppression bands over the upper rotor bar were missing and had come off in operation.
- Several stator coils had moved radially and circumferentially and had strands burned through adjacent to the iron.

W postulated that sometime in the motor's life a start was attempted under locked rotor conditions. The excessive currents caused the brazing alloy to melt and weakened the noise suppression banding. The banding became loose during subsequent starts and then whipped around and stripped or abraided insulation off the stator coils. Arcing ultimately occurred in A phase between the coils and the stator iron fingerplates.

Zion personnel could find no physical evidence to support ever having had a locked rotor; the seals and motor bearings showed no such evidence. Plans were to disassemble and inspect a motor in the future to determine the specific cause of the failure.
(czr, czs, dem)

Figure 2-3: NPE Motor Failure Description (Sample)

Edison Electric Institute (EEI) Report

EEI has developed a data base of motor malfunctions for various industries[3], including nuclear power generation, which focuses on motor sizes ranging from 250 HP and above. The 1982 annual report on apparatus trouble summaries which has been utilized for this includes detailed information pertaining to motor failures and the results given are in full agreement with trends observed from other data sources.

Society for Reactor Safety, Germany - (GRS)

The objective of the GRS report[11] was to develop data on foreign components and systems to the degree of detail necessary for risk and reliability analysis. This information includes equipment items such as valves, valve drives, gears, electric motors (including solenoids), and pumps. Characteristic operational conditions have been evaluated in this report so as to assess the extent of the influence on failure rates and modes.

For electric motors, the data includes six specific motor types pertaining to 1062 pieces of operating equipment from 38 manufacturers. Out of the total population, 979 are either low-voltage polyphase-asynchronous motors, short-circuit rotors, or generators.

Aging-Seismic Correlation Studies

An original aging-seismic correlation evaluation was performed for EPRI by Wyle Laboratories[13]. The study was conducted to evaluate (for selected electrical and electronic components with the exception of motors) the effects of aging on the ability of the equipment to perform during seismic conditions. This was accomplished by subjecting new and used components to endurance testing. The results of this study provide suitable justification for exempting certain components from the requirement for accelerated artificial aging prior to seismic qualification testing. With the exception of relays, all components including resistors, diodes, integrated circuits, transistors, optical couplers, capacitors, and terminal blocks demonstrated suitable integrity for withstanding seismic forces.

A Sandia National Laboratories (SNL) report produced by Nutech Engineers[12] presents a new method of analysis for evaluating the effects of aging on electrical equipment for the purpose of assessing seismic endurance capacity. The study is based on the probability of failure occurrence due to weak link (component) materials subjected to loads during an earthquake. The underlying assumption in the methodology is that the only failure mode for which an aging-seismic correlation exists is the mechanical failure of the weak link component. The motor sizes addressed in this report are relatively small (e.g., 2 HP) and are primarily used in MOV, fan, and low-capacity compressors all of which are squirrel-cage induction motor-driven.

The Seismic Qualification Utilities Group (SQUG)[14] studied the likelihood of operating reactor equipment to fail during seismic events by utilizing data compiled for naturally aged equipment installed in conventional (fossil) power plants. Seven classes of equipment were assessed, including motorized pumps and valves, and from the findings it is claimed that these equipment items are inherently sufficiently rugged and therefore are not

susceptible to seismic effects. Thus, SQUG results indicate that equipment will continue to perform the intended functions, as currently designed, despite earthquake induced loading.

2.1.6 Industry Standards & Guides (IEEE, ANSI, NEMA, ASTM, etc.)

Industry practice for the design and maintenance of electric motors has traditionally been based on the standards and guides developed by IEEE, ANSI, NEMA, and ASTM [note: see Appendix A]. While these references do not specifically address the aging and seismic correlation issues, operating experience has proved that electric motors are inclined to maintain suitable reliability following design adherence to the standard requirements. This condition is due in part to the fact that actual service duty and performance demands are generally less severe than those projected worst case conditions that are used to establish motor endurance upper limits.

Design and construction standards for electric motors primarily include those developed by ANSI and NEMA. The materials used in motor design are specified according to ASTM standards, IEEE standards are mainly suited for testing and maintenance purposes, and guidelines published by ANSI and AFBMA (Anti-Friction Bearing Manufacturers Association) relate to various motor design aspects including bearing load ratings.

2.1.7 Seismic Testing of Naturally Aged Motors

Two 10 hp, 480-V, 60 Hz electric motors, obtained from an east coast Nuclear Station for laboratory evaluation purposes, were tested in a no-load as well as loaded condition, and dielectric parameters including current, voltage, horsepower, and insulation resistance were checked before, during, and after imposing simulated seismic effects. Tests were conducted at excitation levels equivalent to those that bound the response for a safe shutdown earthquake at any plant location anywhere in the United States. The Generic Floor Response Spectra, GFRS[16], were used as the basis for the excitation levels of the aging tests, and the procedure and results will be included in a separate report[15].

2.1.8 Other Sources

Considerable effort was made to review, discuss, and evaluate common modes of motor failure with experts and concerned organizations which included:

- The discussion of aging problems with Franklin Research Center,Philadelphia, PA

- A tour of the manufacturing facilities of Westinghouse Electric Corporation, Large Motor Division, Buffalo , N.Y.

- A general discussion of motor design and maintenance issues with Ebasco Services, New York, N.Y.

- Tour and evaluation of motor service and repair with:
    - Westinghouse Electric Motor Service Center at Buffalo, NY
    - Brookhaven National Laboratory Motor Service Shop, Upton, L.I., N.Y.
    - IMC Magnetics, Westbury, N.Y.
    - Wagner Electric, Riverhead, N.Y.

- A discussion of motor maintenance procedures during a site visit to Port Jefferson Fossil Power Station, Long Island Lighting Company, Port Jefferson, N.Y.

- Tour and presentation on large motor (>1000 hp) preventive maintenance testing at Doble Engineering Company, Watertown, MA

2.2 MOTOR TYPES

Only a few categories of electric motors are of direct significance for nuclear power plants[17] and are classified as follows:

- three-phase induction motor
- direct-current motor (dc)
- three-phase synchronous motor.

(Figure 2-4 depicts the motors that were of particular significance to this study and a brief characteristic description of each type is provided in the latter part of this section). Single phase motors are generally used as strip chart indicator drives.

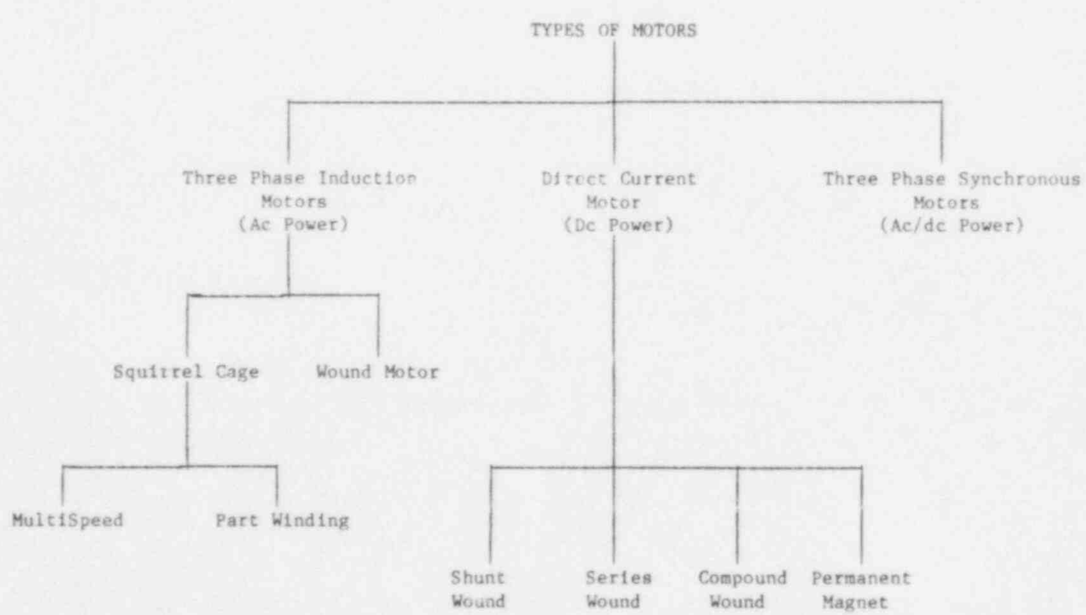

Figure 2-4: Predominant Types of Nuclear Power Plant Electric Motors

Other motors, especially small non-safety-related types are not included in the present study. These motors may include: universal motors, stepping motors, capacitor-start motors, hysteresis motors, resistance split-phase motors, reluctance motors, torque motors, shaded pole motors, and servomotors in both ac and dc versions.

It is evident from the NPRDS data base (Figure 2-5) that induction motors are the "workhorse" of the nuclear industry, comprising nearly 90% of the total population, which includes squirrel cage (approximately 97% of all induction motors) as well as stepping and repulsion-start types. Synchronous and dc motors are equally represented by 9% of the total population while the balance includes capacitor-start, split-phase and pneumatic motors.

Figure 2-5 provides comparative percentages of failures in each motor category. Direct-current motors are noted to have a larger than normal failure percentage with (6.3%) which is usually attributable to commutator-related malfunctions.

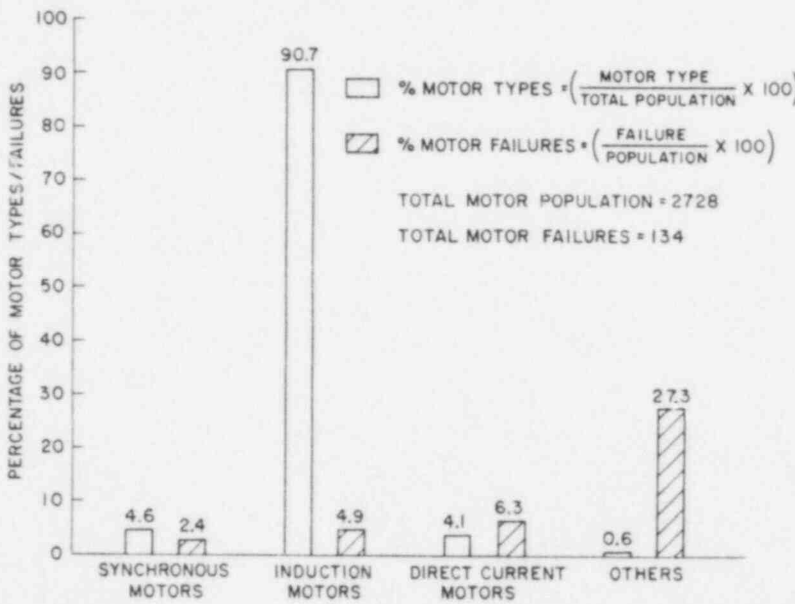

Figure 2-5: Motor Types and Corresponding Percentage Failure
(NPRDS DATA: 7/74-12/82)

NEMA has classified electric motors with regard to size, application duty, electrical type, environmental protection and methods of cooling, variability of rotational speed, and mounting arrangement. Based on size, motors are designated as fractional-horsepower, integral-horsepower (up to 500 hp and 3600 rpm) and large (having a horsepower/speed rating greater than 500/3600 RPM). In addition there exists general purpose ac motors, general purpose dc fractional horsepower motors, industrial dc motors, definite purpose motors, general industrial motors, special purpose motors, etc. Under the electrical type classification, motors are denoted as ac, polyphase, single phase, universal, and dc. With respect to environmental protection and methods of cooling, motors are classified as open, totally enclosed, and encapsulated (sealed windings). Motors are also categorized according to speed, including constant-speed, variable speed, adjustable speed, base speed of an adjustable speed, adjustable varying speed, and multispeed motors. Motors are also designated according to mounting configuration including floor, ceiling, and wall anchoring which implies horizontal, vertical, and angle mounting.

Figure 2-6 illustrates the population of failures corresponding to horse power ratings for motors utilized in the nuclear industry. Integral motors with ratings of 1 to 99.9 hp represent nearly 47% of the total population. These motors are commonly used to drive MOV's, small pumps, fans, and dampers. Fractional motors and motors with ratings of 100 to 999-hp represent another 41% of the total population, while large motors with ratings above 1000-hp represents only 9.2%. Figure 2-6 indicates that integral size motors (1-99.9 hp) have the lowest failure rate, and it can be deduced that failure percentage based on the total population within the range increases with horsepower rating even though large motors are often equipped with sophisticated surveillance and monitoring systems as well as electrical breakers and protective relays.

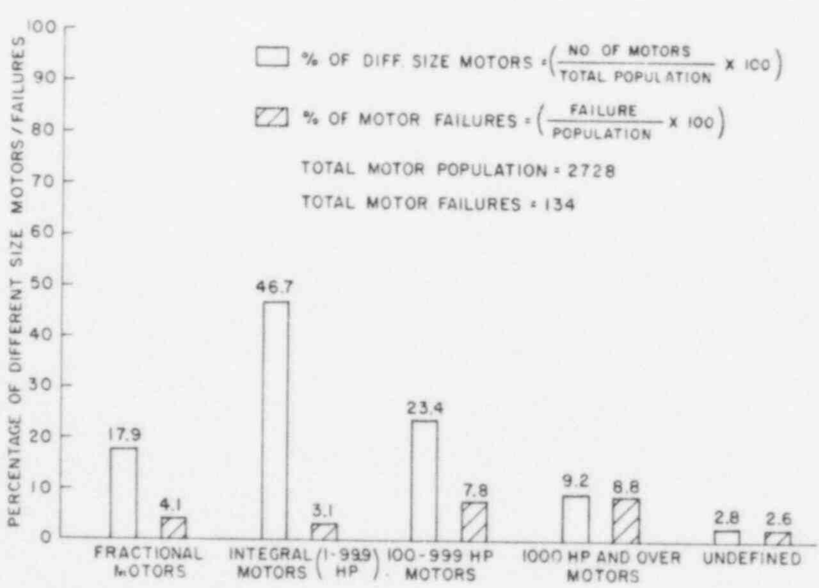

Figure 2-6: Motor Sizes and Corresponding Percentage Failures (NPRDS DATA: 7/74-12/82)

2.2.1 Three-Phase Induction Motors

Induction motors operate on the principle of a transformer whereby a voltage applied to the primary winding induces a voltage in the secondary winding. All induction motors have a stator winding (primary) connected to an ac power source which produces an electro-magnetic field, and since the rotor is free to turn, motion is produced by the interaction of magnetic flux.

Squirrel Cage Induction Motors -- The term "squirrel cage" denotes the type of construction employing solid-bar copper or aluminum conductors embedded in the rotor steel and connected at each end by a shorting ring. This type of motor is the most commonly specified for power plant applications due to the fact that it is ruggedly built and very reliable. A fundamental characteristic of most squirrel cage induction motors is the ability to maintain almost constant speed from no load to full load.

Squirrel cage induction motors are further divided into multi-speed and part-winding machines. The former type has pole configurations which can be changed by altering the winding connection at the motor controller. The latter type has the winding so arranged that part of the winding is energized on start-up and the remaining portion is energized in one or more steps.

Wound-Rotor Induction Motors -- The stator of a wound rotor machine is similar to that of the squirrel cage motor with the exception of the rotor circuit which has wound coils instead of solid-bar conductors. These coils are connected to slip rings on the rotor shaft and by the contact of carbon brushes are connected to a variable-resistor-bank external to the machine. Both slip and torque characteristics of the motor are dependent on varying the resistance of the rotor electrical circuit in the bank. Resistance in the circuit reduces the surge in starting current, which in the case of no external resistance the starting current can be as high as five times full-load current and can overheat the winding and subsequently burn out the motor.

2.2.2 Dc Motors

The primary advantage of the dc motor is accurate speed control and efficient performance over the entire range from zero to full speed. Direct-current machines are generally less tolerant of severe environmental conditions than are alternating-current machines in that the commutator and brushes require periodic maintenance. Direct-current motors have high temporary overload capacity and can withstand substantial operating abuse. Because of a larger air gap and interpolar space between field poles, the dc motor receives more forced cooling than other motor types.

There are four basic types of dc motors of which the first three are classified according to the connection of the field coil with respect to the armature coil. These are the shunt-wound, series-wound, compound-wound, and permanent magnet. Field poles are installed in the motor frame, and current is introduced into the armature through brushes riding on the commutator surface.

The speed of a dc motor is controlled by varying the strength of the magnetic field or by varying armature voltage. As field strength decreases with reduced armature current, speed of a series motor increases, and vice-versa. The rotational direction of a dc motor is changed by reversing the polarity of the field with respect to the armature.

In the case of shunt-wound motors, the field is connected in parallel (shunt) with the armature. Speed is controlled by changing the current in the field circuit by means of a rheostat, and as the term denotes, series-wound motors are constructed with a field placed in series with the armature. Field strength increases as armature current increases (with load) and therefore speed decreases. These motors exhibit a high torque characteristic at low speeds, and have particularly high starting torque and acceleration. The compound-wound motor represents a compromise between the shunt and series-wound types since this motor has both a shunt field as well as a series field, and the torque characteristics are also a compromise between the two types. Another dc type is the permanent magnet motor which is designed to permit very high magnetic flux densities. Permanent magnet motors are typically fractional horsepower, but includes other small, integral sizes that offer the advantage of simpler construction and high reliability. Since the field strength of a permanent magnet motor cannot be varied, speed control is achieved by varying armature voltage.

2.2.3 Synchronous Motors

Unlike the ac induction or dc motor, the synchronous motor is a dual-electrical-input rotating machine which requires both ac and dc power and operates precisely at synchronous speed over a full range from no load to full load. Another feature of the synchronous motor is the ability to vary power factor while driving a given load.

The dc field winding for the synchronous motor is located within the rotor and the ac armature winding is located on the stator. This motor is usually started exactly like an induction motor. Since there exists a separate dc supply to the field winding, the air-gap length is larger than that found in induction motors of comparable size and rating. The synchronous motor is more expensive and less rugged than comparable induction motors in the smaller horsepower ratings, due mainly to the slip ring and brush arrangements in older motors or the brushless exciter arrangement in newer designs, which feed the dc supply to the rotor.

2.2.4 Motors Considered for the Aging Research

For the purposes of this study, motors of all sizes (according to horse power rating) are included, with the exception of fractional horsepower motors which have been omitted for reasons previously cited. In addition to the horsepower rating, corresponding motor voltages ranging from 100V ac and dc to 14000V ac are included. High voltage motors, which are discussed later, introduce the potential for additional and unique failure modes including those due to corona effects (or ionization).

All motor mounting configurations are included in the study although most nuclear power plant motors are in fact mounted horizontally. The primary distinction between horizontally and vertically mounted motors is in the bearing

design. The bearing assembly design for vertical pump motors may be either normal-thrust or high-thrust. In the case of normal thrust motors, both the guide (upper) and the thrust (lower) bearings are ball bearings, with thrust bearings requiring periodic lubrication. For high-thrust motors, the location of guide and thrust bearings are reversed. There are many other variations in the design of bearings as well as other components for vertically-mounted versus horizontally-mounted motors.

For the common nuclear power plant motor system applications which include valve operators, pumps, fans, compressors, dampers, and strip chart indicator drives, valves and pumps constitute nearly 95% of the total motor population. While most MOVs can be categorized in either the small or medium-size range (with respect to horsepower classification and low-voltage ac supply), pump and fan motors cover the full spectrum of sizes as required for equipment output and duty cycle.

2.3 MATERIALS AND CONSTRUCTION

Prior to the assessment of failure modes, mechanisms, and causes, the construction and material characteristics associated with each motor component were evaluated. Since construction plus materials determine the overall integrity of the equipment, these factors obviously have significance and an effect on motor reliability.

The detailed design aspects of electric motors[18] is beyond the scope of this study since it would require addressing all possible types of motor construction. However, as an example, the construction of a squirrel cage induction motor is outlined below and it should be noted that similar components and features are used in the construction of other motor types as well.

The major components of a typical squirrel-cage induction motor consist of the following:

1. stator (the stationary part)
2. rotor (the rotating part)
3. bearings
4. frame and end brackets.

Secondary components vary but can include:

1. junction box
2. seals and gaskets
3. fan coolers
4. heat exchangers
5. terminal block
6. heaters
7. capacitors
8. temperature or vibration detectors

Failure of any of these components has the potential to affect motor capability to perform at the time of demand. Note that the above components consist of both metallic and non-metallic materials. Table 2-1 includes some of the typical materials used in motor construction in relation to aging sensitivity

for motors in general. Effects of aging for each material is subjective to the operating experience findings and the material sensitivity to the exposed stressors.

2.3.1 Stator

The assembly parts of a stator include the ferro-magnetic silicon steel core, coils, insulation, and a steel or aluminum housing. The core is made of many steel laminations, and insulated coils are wound together to form the core as shown in Fig. 2-7. The entire assembly is then inserted into a frame, as shown in Fig. 2-8. For small motors, the core is inserted into the frame prior to winding the coils and the converse is true for large motors. Note that it is necessary to have sufficient copper or aluminum and iron in the motor in order to induce and develop the required torque (the core consists of iron whereas the coil itself is made of copper or aluminum).

Table 2-1 Typical Materials used in Motor Construction

Motor Components	Materials	Effects of Aging
Stator	Copper, Steel, Silicon steel,	Minimal
	Aluminium	Minimal
	Insulating Materials*	Significant
Rotor	Copper, Steel	Minimal
	Insulating materials*	Significant
Bearings	Steel, Brass, Bronze	Moderate
	Grease, Lube oil	Significant
Accesories	Steel, Cast Iron, Brass, Copper	Minimal
	Seals and Gaskets	Significant
	Mica, Plastics	Significant
	Cable Insulating Material	Moderate
	Graphite	Significant

*Includes mica, glass, resins, enamels, mylars, fiber, varnish, and nonhygroscopic materials.

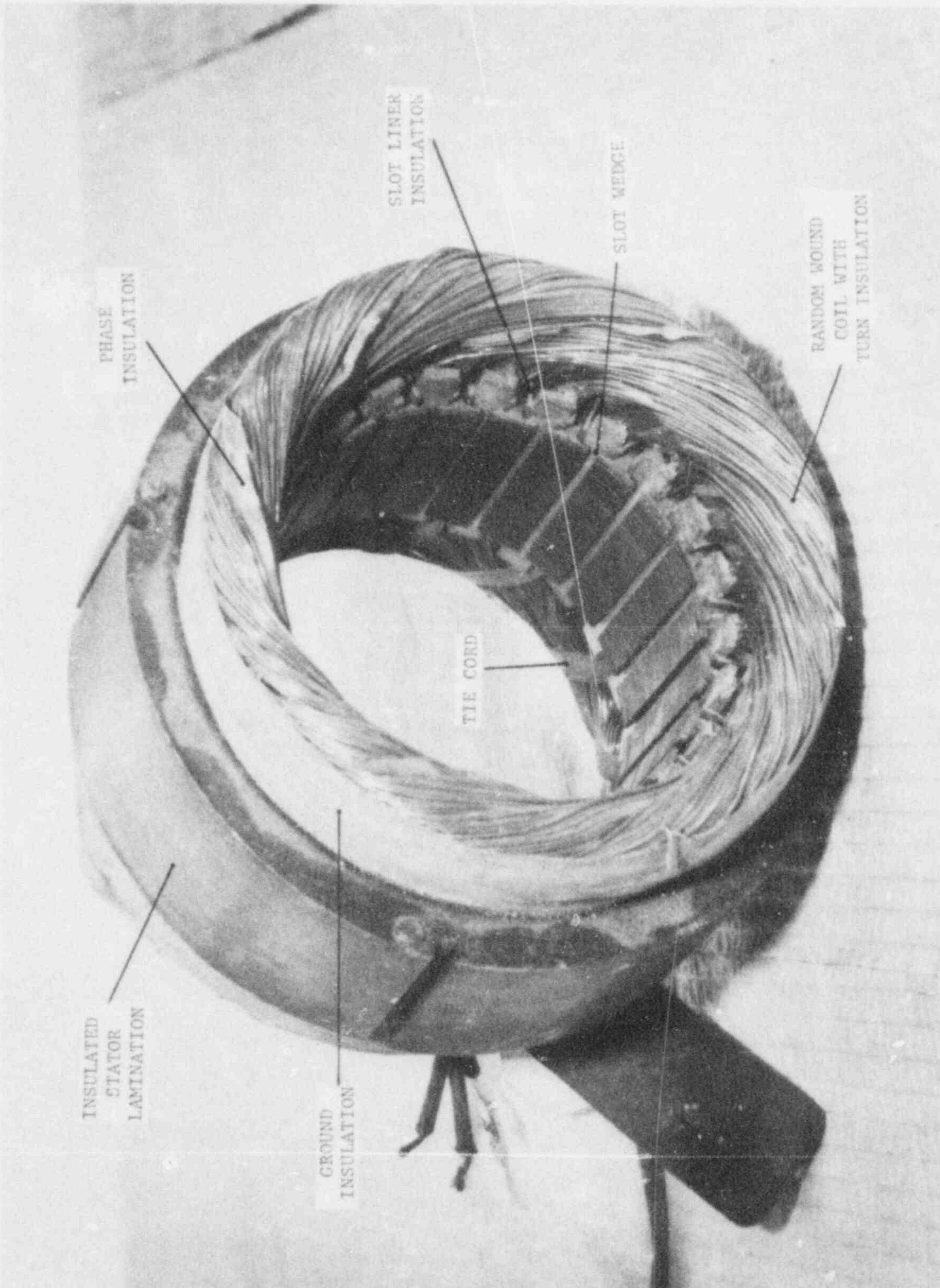

Figure 2-7: Stator Winding Insulating System

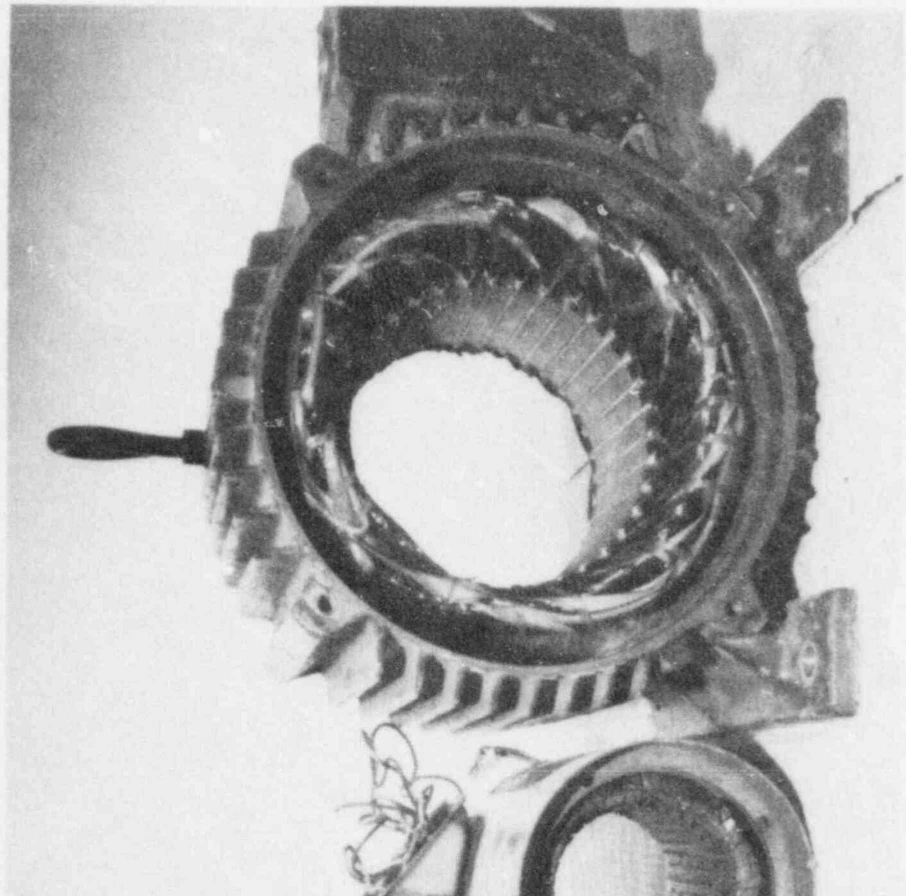

Figure 2-8: Motor Stator Assemblies

Stator Core -- Steel laminations, made of sheets, are insulated on both sides with a baked coating having a uniform thickness which prevents shorting of laminations and reduces eddy current losses inside the core. The stator core final assembly consists of stacking the laminations, secured with a number of locking bars pressed into notches spaced around the periphery, followed by annealing and oxidizing the stator in a controlled atmosphere.

Stator Winding Coils -- Two basic winding types are utilized in stator construction: for motors up to 250 HP random wound coils are used while form-wound coils (see Fig. 2-9) are adapted to larger size motors. The copper wires (or conductors) used in the winding coils have an enamel coating to provide turn-to-turn insulation and composite synthetic glass insulation over enamel is also used for severe duty applications. The straight portion of the form-wound coil which lies in the stator core slots is then insulated with a mica wrapper to provide ground insulation, and the end turns are insulated with mica tape. After the coils are wrapped with the mica insulation, a glass binder or nylon tape is applied over the complete coil to provide mechanical protection and better absorption for the epoxy resins during impregnation of the stator assembly. Fig. 2-10 illustrates the cross section of insulated stator coils.

Phase-to-phase insulation is required to separate phase groups. In the case of random-wound motors, mylar or mica sheets are used between the phase windings. For form-wound stators, the space between phases is more heavily (mica) wrapped since full phase voltage is applied in this area and not between the coils.

Slot wedges made of wood or fiber are inserted into the stator core to hold conductors firmly in the slot. For form-wound coils, synthetic fiber felt pads are inserted between the coil extensions for arch bindings. During the varnish impregnation process, which binds all insulation components together while eliminating air spaces, these felt pads absorb the epoxy resins. After hardening, these insulators provide mechanical protection, inhibit contamination, and also help to limit coil movement during motor operation.

Phase to phase insulation, combined with wedge materials, adds to stator insulation properties. After the stator is wound and all lead connections are properly terminated, the wound stator and stator core are prebaked to eliminate moisture prior to vacuum pressure impregnation in solventless, epoxy resin, which is followed by curing. After the final impregnation and initial bake, the stator is dipped in epoxy varnish and re-baked. The entire insulation system then undergoes qualification and verification via an underwater testing process which includes subjecting the assembly to accelerated conditions of heat, aging, moisture, mechanical shock, transient voltage stress, and thermal shock. Resistance is then tested and an evaluation is made for eddy current leaks.

Stator Frame -- The frame housing the stator core and coils is generally made of steel, cast iron, or aluminum. As noted for small motors, the stator core is first pressed into the frame prior to adding windings where it is held either by ridges on the inner bore of the frame or by tack welds. For large motors, with form-wound coils, the frame is assembled after the windings are set in the stator core.

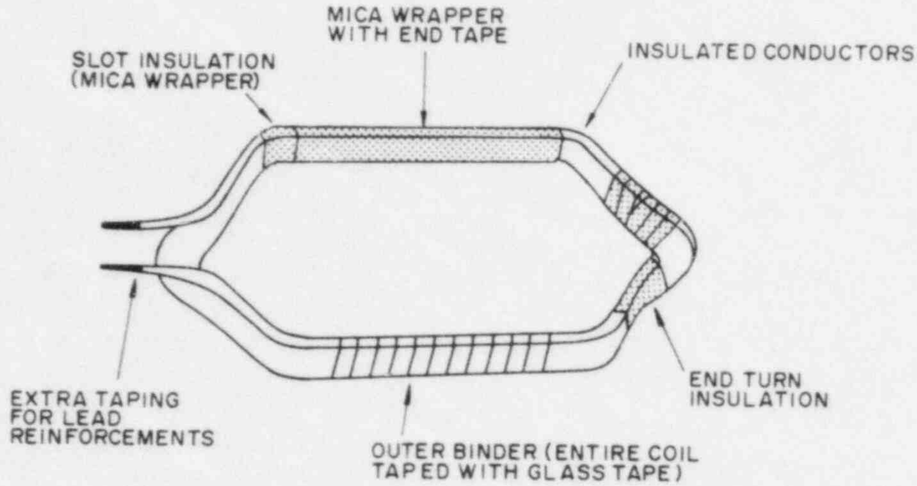

Figure 2-9: Typical Insulation Construction for a Form-Wound Coil (Ref. 18)

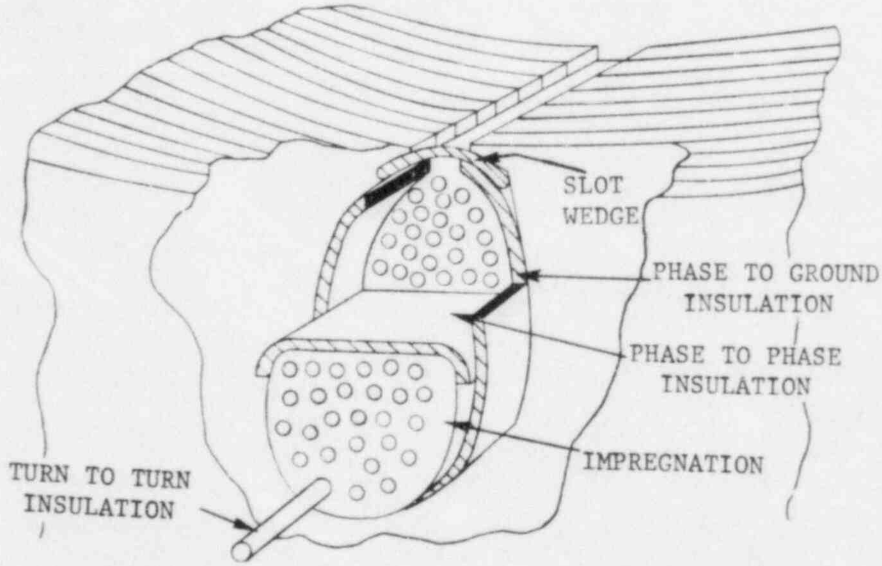

Figure 2-10: Random-Wound Stator Coil Insulation Cross-Section (Ref. 18)

2.3.2 Rotor

The rotor design shown in Fig. 2-11 consists of laminations, conductors, end rings, a shaft, and a cooling fan. In the case of dc motors, a commutator assembly or slip ring while for synchronous and wound-rotor motors, a brushless exciter arrangement is a component of the rotor assembly. The rotor core is made of laminations similar to that of the stator core, and the rotor assembly can be either die cast or brazed where the former is typical for small, heavy-duty motors while brazed rotors are common for larger motors intended for special types of duty.

Rotor Core -- Unlike the stator lamination assembly, the rotor slots in some induction motors are not formed in a straight line. Instead, each lamination is turned slightly with respect to the next one such that at the end there exist skewing in the slot which provides better starting and running characteristics. Heavy end plates are necessary for holding the rotor lamination stack together and the ends of the rotor core are reinforced with stiffener bars to prevent tooth vibration and breakage resulting from any occurrence of the radial flux and axial flux.

Rotor Coils and Insulation -- Depending on the slip characteristics and speed-torque curves desired (Reference Fig. 2-12), NEMA has categorized squirrel-cage induction motors for five basic designs known as Design A, B, C, D, and F. As illustrated in Fig. 2-12 each of the designs has a distinct speed-torque characteristic achieved by control of resistance and reactance of the rotor winding and thus the design of the rotor slot and bar are different for each design. Designs A and B have fairly low rotor resistance, C has high resistance on starting and low resistance when running, while D has high resistance at all times. Design F has a very low starting torque and moderate breakdown torque, and is seldom used.

In large induction motors, aluminum, copper or copper alloy bars are pressed into the slots of the rotor stack depending on the particular design. Copper or aluminum in the rotor improves thermal capacity and increases motor life. The end or resistance rings are made of the same material as the bars and are centrifugally cast to ensure a uniform cross section. These rings are usually attached to the rotor bars by high frequency induction brazing which provides high strength as well as high electrical conductivity in all joints.

Most rotor assembly failures do not result from thermal expansion and contraction of the end rings or centrifugal force due to rotation but rather are caused by repeated application of current-imposed forces that occur during each motor start. State-of-the-art designs employ a technique known as swaging to tighten the bars (axially aligned in the slots through the core) to eliminate space for movement. It also prevents outward movement during running.

In the case of die cast rotors used in small squirrel cage motors, the core stack is inserted into die rings and the bars are cast into the closed rotor slots in a manner that is inherently tight and therefore no swaging is required. The construction of die cast rotors is consequently more rugged than that for brazed rotors.

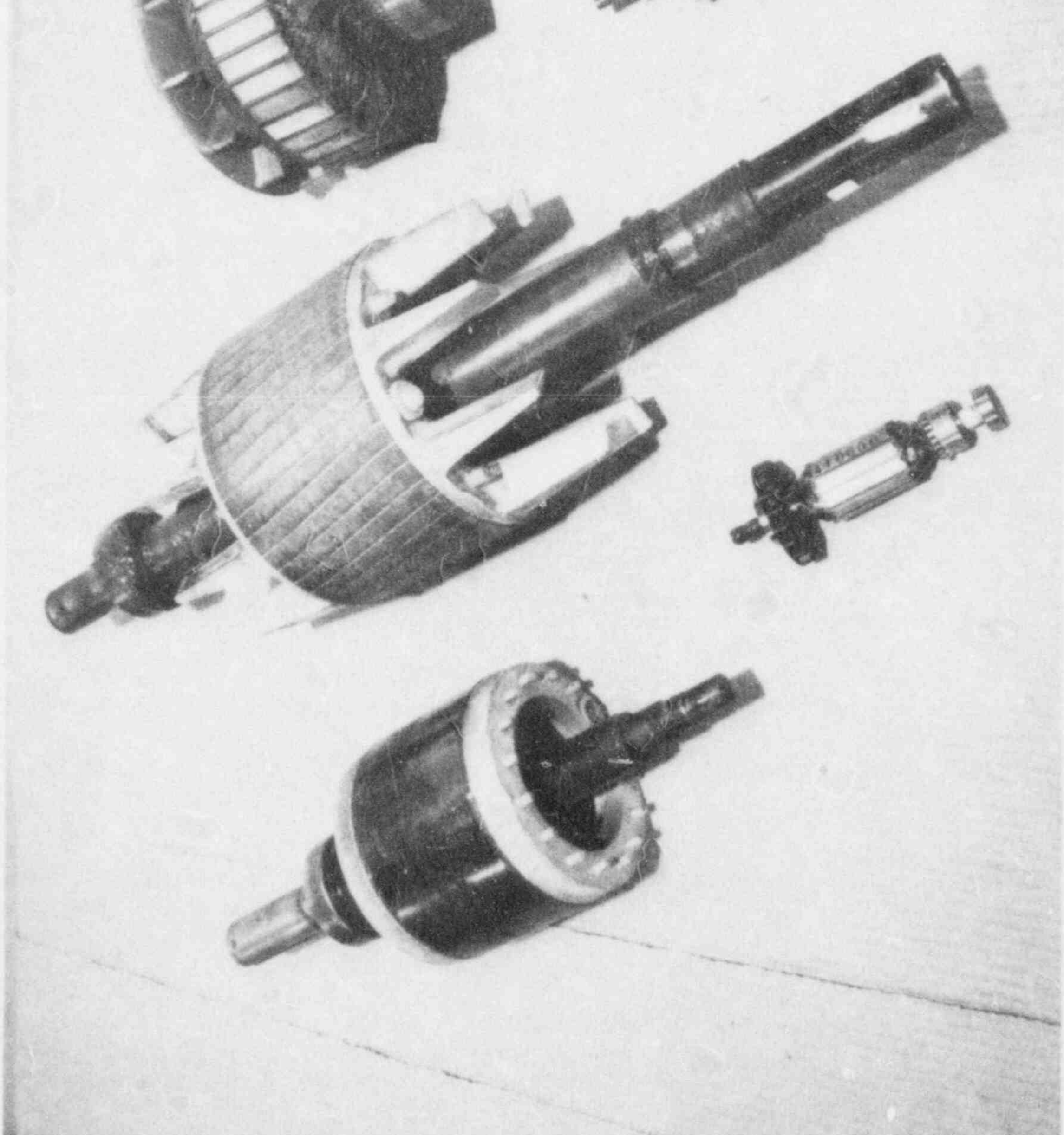

Figure 2-11: Motor Rotor Assemblies

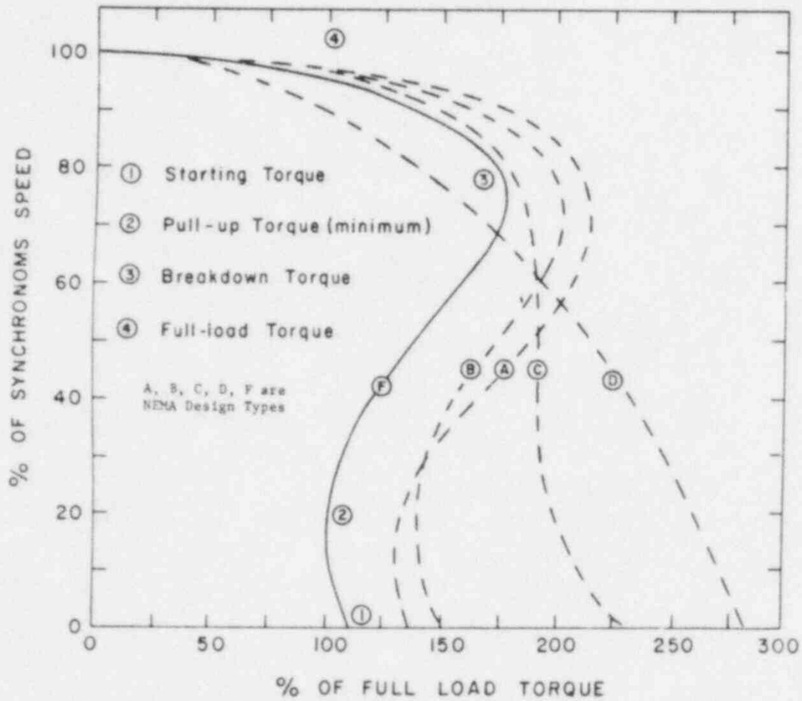

Figure 2-12: Speed-Torque Characteristics for typical NEMA Design Classifications (Ref. 18)

Rotor Shaft -- The rotor core and bar assembly is keyed and shrunk to the shaft. The shaft and support system is designed to prevent excessive deflection that would otherwise occur due to rotor weight and induced magnetic forces. When needed, such as in the case of large motors, stiffeners are added to lend rigidity to the shaft. Note that rotor critical speed is always designed well above motor speed in order to avoid the potential for coincident frequency vibration damage.

Commutator (dc motors) -- The commutator is assembled by alternating mica insulation segments with silver-bearing copper V-Ring commutator segments. The actual size and overall design of the assembly is dependent on the required electrical and mechanical characteristics of the motor being built. The commutator assembly is typically mounted on the shaft with the armature or rotor core and the conductor leads from the rotor are inserted into slots in the commutator bars.

2.3.3 Bearings

Motor bearings (shown in Fig. 2-13) are necessary for enabling the rotor assembly to turn freely within the stator when the magnetic fluxes from the energized field and armature windings interact. Bearings are installed on each end of the motor shaft and in small motors, are hydraulically pressed into the frame housing in order to avoid slippage when the rotor turns.

The most commonly used types of motor bearings include anti-friction and sleeve bearings. The anti-friction types are available as either ball or roller bearings. Selection of the particular type of bearing depends on the predicted load and overall service conditions expected for the motor. Note that bearings are subjected to either a radial load such as that produced by belt

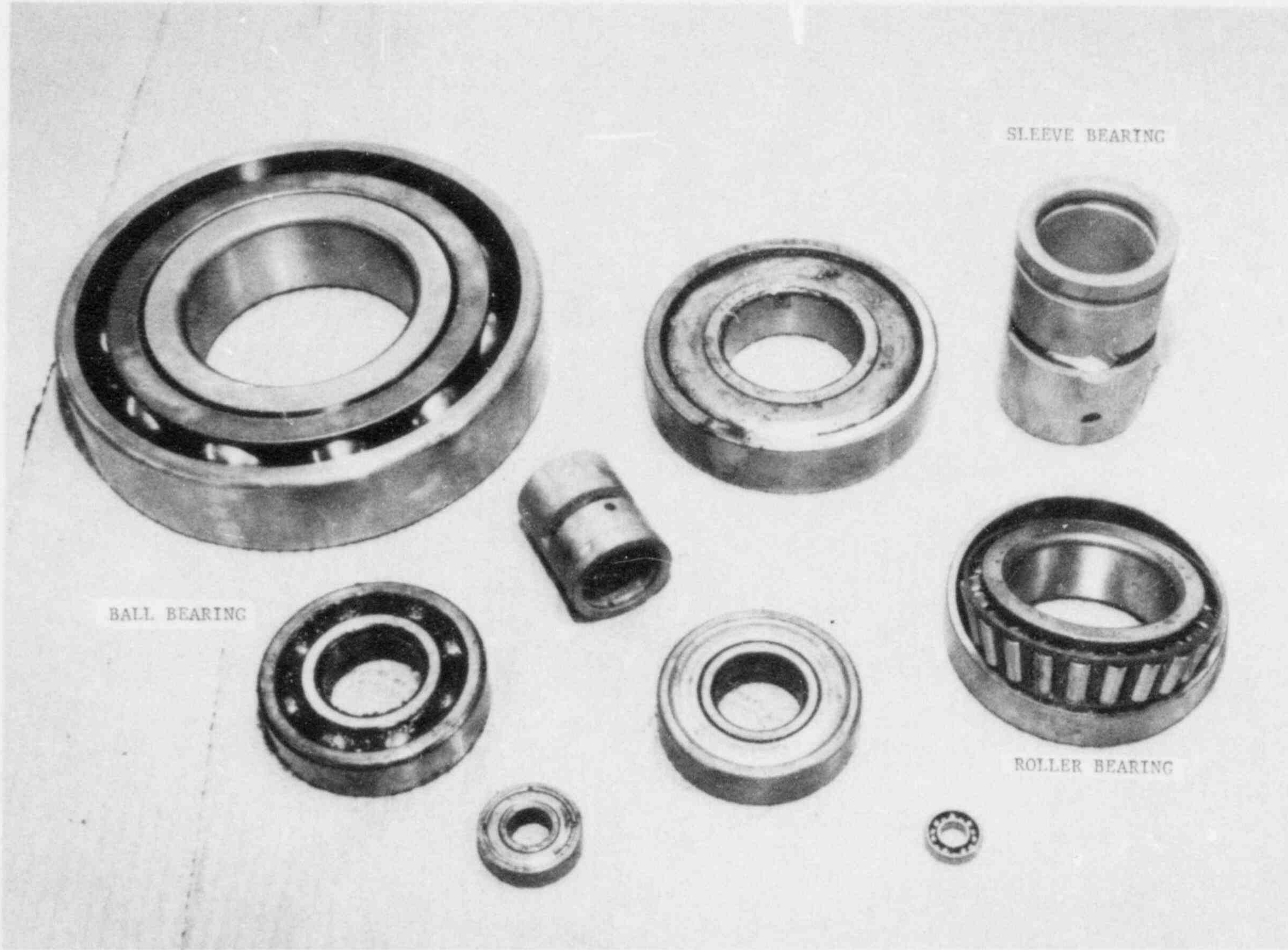

Figure 2-13: Typical Motor Bearings

and pulley drives, or to axial loads, which are also known as thrust loads and are developed by the pressure from the blades of a pump or the vanes of a fan, plus the rotor weight in the case of a vertical motor.

Sleeve bearings can accommodate radial loads only and no axial load capacity is available. (Note: by "end float couplings", a bearing can be relieved of all end thrust.) The radial load endurance of these bearings is directly related to dimensions and to the viscosity of the oil film. Larger than recommended loads can force out the oil resulting in bearing failure. On some horizontally mounted motors the lubrication is supplied to the bearing journal by an oil ring rolling on the shaft which reaches an oil reservoir during shaft rotation. Vertically mounted motor sleeve bearings are continuously immersed in an oil reservoir.

Anti-friction ball or roller bearings are formed by enclosing a number of hardened steel balls or rollers between inner and outer races of hardened steel. Depending on the design of the groove in the races, these bearings can take some axial (thrust) loads as well as radial loads. Typically these bearings are grease lubricated.

For large motors, typically each bearing is enclosed in the main housing and a sight glass is provided for monitoring oil level. Additional devices may be installed to measure temperature, vibrational amplitude, and other critical parameters. In some cases cooling systems are part of the bearing design which are intended for dissipating the heat generated by friction forces encountered by a turning rotor.

2.3.4 Frames and End Brackets

The design of motor frames and end brackets requires consideration of the environment, the equipment application, and general or specific operational needs. The frame and end brackets in large motors are usually constructed of steel having very conservative design tolerances. Brass rings are inserted inside the bearing bracket (to prevent rotor misalignment which could occur due to corroded end brackets if a material other than brass is used) and this precaution minimizes the potential for catastrophic mechanical damage to the stator, rotor laminations, and insulation system.

In accordance with NEMA standards, motors are classified into three general categories based on the specified cooling method and the levels of protection afforded for enduring the predicted operating environment. The following list specifies different types of motor enclosures; detailed descriptions of each are available in the NEMA standards:

Open Motors	Totally Enclosed Motors
Drip-proof	Totally enclosed pipe ventilated
Splash-proof	Totally enclosed fan cooled
Guard or semi-guarded	Totally enclosed air-to-air cooled
Open pipe-ventilated	Totally enclosed water-air cooled
Weather-protected (Types I&II)	Totally enclosed water-inert gas cooled
	Explosion-proof

The purposes of the motor enclosure are summarized below:

- to provide strength and rigidity.
- to provide an accurate mounting plane.
- to provide correct and uniform air gap (for smooth and quiet operation).
- to protect motor components and accessories from environmental stresses including foreign particles, and corrosion.
- to provide protection for motor loads via the design of a proper terminal box.

2.3.5 Classification of Insulating Systems

The insulating system of a typical electric motor consists of various insulating materials in association with conductors and supporting structural parts. These materials are classified according to tested performance under operation at conditions of maximum permissible temperature. NEMA insulating systems are designated as A, B, F, and H, in ascending order of maximum operating temperature for a given life. Fig. 2-14 illustrates the life-temperature relationships for the above classes of insulation.

Class A insulation consists of cotton, silk, paper, or other organic materials impregnated with insulating varnish, molded or laminated phenolics, films or sheets of synthetic resins and enamels applied to conductors. The hot spot temperature limit for this class is 105°C, which consists of 40°C ambient temperature, 40°C rise by heating, 15°C hot spot allowance, and 10°C allowance for service factor. It is believed that a 10°C allowance for a service factor of 1.15 (recognized by NEMA for motors above 2 hp) is sufficient to accomodate a 15% overload.

Class B insulation consists of mica, asbestos, fiberglass, or other materials, not necessarily inorganic, and synthetic resins. The maximum hot spot temperature is 130°C. Table 2-2 provides different temperature allowances and the temperature rise for various motor types. Table 2-3 outlines the temperature relations for drip-proof and totally enclosed fan cooled ac motors.

Typical materials used in a Class F insulating system also include mica, glass fibre, and asbestos, as well as other materials not necessarily inorganic, combined with compatible bonding substances having suitable thermal stability. A total temperature of 155°C is the hot spot limit for this class.

For Class H insulation typical materials include mica, glass fibre, asbestos, and again other materials not necessarily inorganic, also combined with compatible bonding substances such as silicone resins which have suitable thermal stability. This insulation class is designed for motor operation at a maximum total temperature of 180°C although a higher temperature limit of 220°C is available under this classification for special use under extreme temperature conditions.

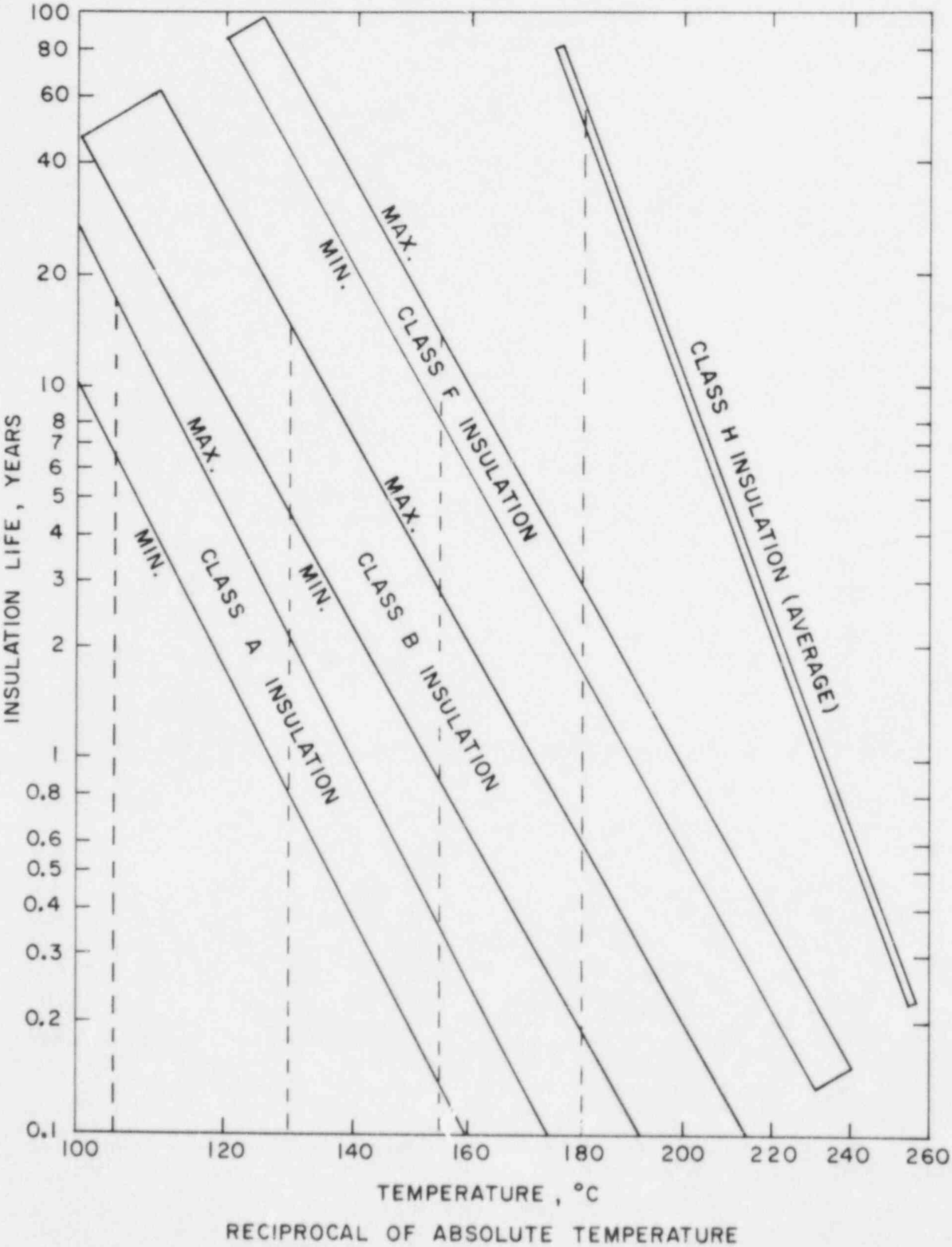

Figure 2-14: Life-Temperature Relationship of NEMA A, B, F and H Insulation Classes

Table 2-2: Temperature Rise of Various Motor Types With B, F, and H Classes of Insulation

	Temperature Rise °C		
Insulation Class:	B	F	H
Open, nonencapsulated, 1.0 service factor	80	105	125
All 1.15 service factor motors (while motors operating at service factor load)	90	115	-
Totally enclosed fan-cooled (TEFC) motors	80	105	125
Totaly enclosed non-ventilated (TENV) motors	85	110	135
Encapsulated motors, 1.0 service factor, all enclosures	85	110	-
Fractional horsepower (Frame 42 and larger) open motors, 1.0 service factor	80	105	125

Table 2-3: Temperature Relations for Drip-proof and Totally Enclosed Fan Cooled AC Motors

	Temperature °C (1.0 Service Factor)			
Insulation Class:	A	B	F	H
Ambient Temperature	40	40	40	40
Temperature Rise by Resistance	60	80	105	125
Hot Spot Allowance	5	10	10	15
Hot Spot Temperature	105	130	155	180

Based on the EEI Trouble Report for motors 250 hp and above and as shown in Table 2-4, Class B insulation systems are consistently in the highest failure category each year while Class F and Class H insulation exhibit significantly fewer failures. Table 2-4 also includes the average service life at the time of failure detection: with the exception of the year 1982 (in which case it is 12 years) the average service life of a motor varies from 3 to 6.5 years. It may be useful to note that class B insulation was used in both safety-related and non safety-related applications in older plants, and in non safety-related applications in newer plants. Most new plants are now using F or H insulation in safety-related applications, and older plants are using F and H as replacement insulations. Type A insulation is generally no longer used in large motors.

Table 2-4 Large Motor Failures Classified by Insulation Types
(EEI Trouble Report, Reference [2-3])

Year	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1982
Insulation Class												
A	–	4	13	2	4	1	1	1	–	–	–	1
B	19	19	28	13	26	20	21	53	26	29	34	42
F	3	2	4	4	2	7	8	3	13	9	7	19
H	1	–	3	2	1	1	1	1	–	4	–	1
Other	–	1	5	2	2	–	2	1	6	1	3	3
Total	23	26	53	23	35	29	33	59	45	43	44	66
Average * Service Life	4.7	–	5.68	6.22	5.66	3.55	4.33	3.19	5.07	6.14	6.16	12.02

*Average Service Life (Average Age at time of Failure) = $\frac{\text{Total In-Service Years of Motors with Failures Reported This Year}}{\text{Number of Failures Reported This Year}}$

3.0 OPERATIONAL STRESSORS AND CORRELATION WITH ACCIDENT EVENTS

Motors are subjected to various operational stressors which originate both from system-level effects and from the environment and therefore, individual motor components are required to endure numerous types of service wear conditions. Abnormal or accident events potentially tend to worsen these conditions while introducing additional stressing effects. The selection of a particular motor type and rating for the performance of a specific system function therefore requires consideration of the predominant mode of system operation (whether continuous or intermittent) and prediction of the expected mild or harsh environment. Potential worst case conditions imposed by synergisms and seismic events must also be considered, and a supplementary requirement to be addressed concerns the impact of human factors on system operations during routine as well as emergency conditions.

3.1 SYSTEM-LEVEL PARAMETERS

In addition to other parameters, control systems regulate motor output levels and the required motor endurance limit is dictated primarily by the application equipment load. When load torque demand exceeds motor output capability overheating commonly occurs, and severe overloading results in motor disconnection and potential system failure.

Tables 3-1 and 3-2 represent failures of motor-driven pumps and valves for major and auxiliary systems obtained from the LER and IPRDS data base. It should be noted that the number of indicated failures must be associated with the total motor population (which was not available from the LER and IPRDS data base) for each system in order to establish a failure rate. Improper operation and motor misapplication are the apparent main causes of system-related failure.

Certain pump and fan systems are designed for initial operation against a closed (pressure) head while other arrangements require recirculation during start-up for the gradual development of system pressure. The incorrect positioning of valves and dampers caused by operator error or by the malfunction of system interlocks can promote motor overloading, and if an inadequately rated motor has been specified for the system function the likelihood of overheating is further increased.

Since motor winding current increases with conditions of low voltage and low frequency, it is evident that degraded power supply conditions can also affect motor longevity. However, during normal plant operation, voltage and frequency, and therefore current fluctuations are typically not of concern since motors are rated for a 10% drop in voltage and a 5% drop in frequency. The effects of under voltage on (ac) valve-operator induction motors can be critical since the torque varies with the square of the voltage and as a result proper application requires motor oversizing to avoid stalling and burnout or tripping. Conditions of low voltage and low frequency are usually associated with the loss of offsite power which can be concurrent with accident conditions.

Table 3-1: Reactor Fluid System Motor Failures
(LER Data: 1974-1983)

*Residual Heat Removal (RHR)	41
Service Water (SW)	38
*High Pressure Coolant Injection (HPCI)[1]	35
Gas Radiation Waste Management	20
Containment Heat Removal (CHR)	19
Emergency Generating System (EGS)	18
Chemical Volume and Control System (CVCS)[2]	16
Heating Vent. Air Conditioning (HVAC)	12
Containment Isolation System (CIS)	11
Containment Gas Control (CGC)	11
*Reactor Core Isolation Coolant (RCIC)[1]	10
*Core Spray (CS)[1]	9
Reactor Coolant Recirculation[1]	9
Fire Protection	8
Radioactive Monitoring	8
Control Room Habitability	8
Others	<6

* Emergency Core Cooling System (ECCS)

1 BWR Application only

2 PWR Application only

(unmarked) Both BWR and PWR application

Table 3-2: Fluid System Failures
(IPRDS Data: 1974-1981)

	Plant 1		Plant 2*	Plant 3* Units			Plant 4	
	Pump	Valve		1	2	3	Pump	Valve
Containment Spray		6						
Reactor Coolant	5						7	
CVCS	16	6						
Condnsr. & Condst.	31	5				5		
Feedwater		5						
Circ. Water	14		16	9				
Stm. Gen. Blwdn.		17						
Auxiliary Stm.			8					
Safety Injectn.		10				5		6
Radioactive Wst.	21		8	32	7	13	14	
Service Wtr.	11		12	10		5	15	
Pot. & Sanit. Wtr.	5							

* Pump Motors Only
Note: System idents according to IPRDS definitions (Ref. 7)

System-level stressors also include the effects of vibration which can be driven component or seismically/hydrodynamically induced. If a motor is not dynamically balanced with the interconnected load, operational vibration can damage the bearings.* Alternatively, high excitation to the motor and attached hardware transmitted through supporting structures can potentially affect numerous motor components including both the bearings and mounted accessories (e.g., in the case of a large motor, the lube oil cooler heat exchanger). Any form of obstruction to rotor movement can cause electrical insulation damage when and if excessive current is realized from the power source resulting in an overload condition. Motor and overall system failure is further probable under conditions of machine dislodged mounting and/or separation from the power supply.

3.2 COMPONENT-LEVEL PARAMETERS

All motor components are susceptible to degradation[19-21], including the stator, rotor, bearings, and various accessories. The two most significant stressors in motors are heat and vibration-related, and while the potential for the occurrence of these stressors is multiple in nature, thermal effects commonly result from excessive current (which imposes self-heating and therefore possible insulation failure) and vibrational effects can originate from the internal and external abnormalities previously cited.

Regardless of rating size and the system application, all motors are subject to stresses which may eventually cause failure. Figures 3-1 and 3-2 illustrate relative failure proportions for basic motor components. Stator-related failures are the highest having nearly an equal probability of occurring for both pump and valve motors. Bearing failures are observed to be significantly higher for pump motors than for valve operators, while all other component failures are comparatively low. It should be noted that motor size is a factor to the extent that certain failures are more likely to occur in large motors than in small motors (e.g., valve operator motors).

The predominant modes of motor performance degradation are attributable to stator insulation damage. Other effects include the shorting of iron lamination edges which cause localized heating due to the presence of eddy currents thereby creating "hot spots". This condition has been reportedly caused by loose parts travelling through the air gap between the stator and rotor, and by damage that can occur during maintenance and inspection activities, as well as by other factors. Another mechanism for coil electrical failure is the loosening of slot wedges occurring as a result of material shrinkage or machine vibration. Traces of powder in the vicinity of a dead air space indicates winding chafing, and unrestrained stator parts are particularly conducive to motor damage during start-up when electrically induced vibration and current are at maximum levels. Insulation that has become porous with age is very prone to failure, and the condition is more critical during motor starting than during normal sustained operation, when heating tends to remove residual water vapor and so dry out the insulation.

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* Ac machinery inherently has vibratory stresses due to the alternating flux in the core.

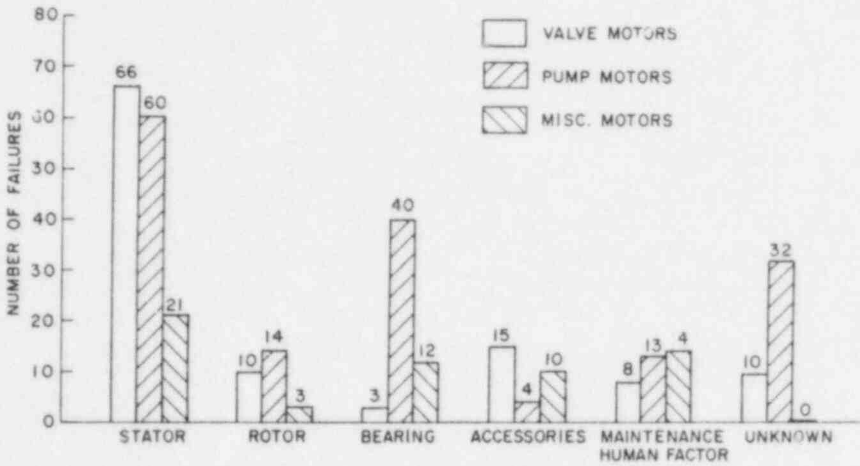

Figure 3-1: Motor Component Failure Distribution (LER DATA: 1974-1983)

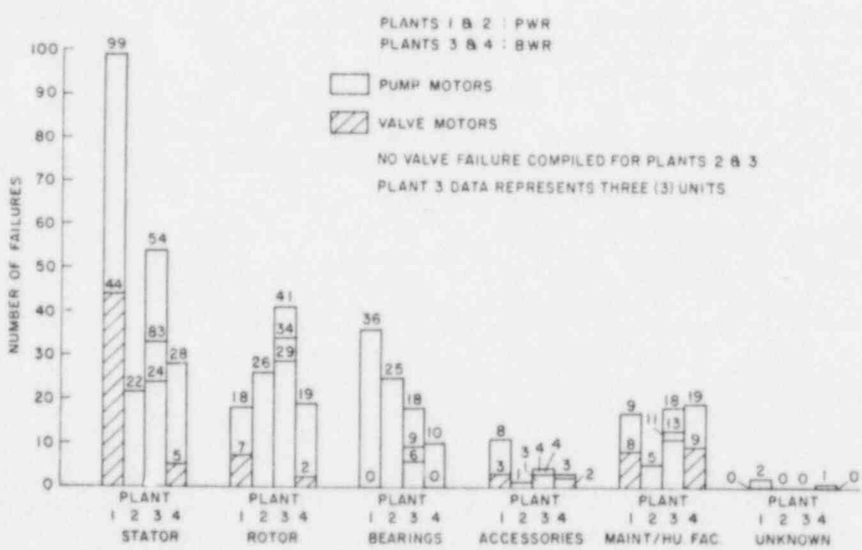

Figure 3-2: Motor Component Failure Distribution (IPRDS DATA: 1974-1981)

Relatively similar failure causes are apparent within all motor classes as shown in Table 3-3. Stators are highly inclined towards ground insulating system burnout due to overheating and due to material degradation which occurs normally as well as at an accelerated rate when a motor is exposed to hostile environmental conditions such as humidity, radiation, high temperature, and chemical spray. Rotor damage commonly occurs due to excessive vibration which is often attributable to coupling misalignment or the loss of balance weights from the (rotor) assembly. Bearing failures result primarily from the loss of lubricating oil or grease although corrosion also has a significant effect on performance deterioration. Mounting related failures are the highest reported accessory malfunctions. The disintegration of seals and gaskets represents an additional common accessory failure that can result in the degradation of housed internals (e.g., cable terminations in a motor junction box), the leakage of lubricant, and the overall elimination of hermetic properties.

Combined rotor and stator damage is noted to occur when bearings completely fail and rotational clearance is lost. For motors that are not equipped with bearing temperature detectors and alarms, particular care must be taken to ensure that rotational integrity is maintained.

3.3 APPLICATION AND OPERATIONAL STRESSES

The most significant application problems associated with power plant motors are undersizing and the general mismatching of load and duty cycle requirements. These conditions usually do not occur during the original design specification process but rather as a result of system modifications and subsequent equipment additions.

The most damaging operational stress results from exceeding motor duty cycle by attempting too many starts in too short a period. Inrush current during motor start-up causes considerable heating and sufficient time must be provided to permit heat dissipation. Manufacturers usually impose time limitations on starts, particularly for large motors, and frequent starting would be expected to occur at times when motor auxiliary or control system problems are being investigated and typically not during emergency operations.

The most probable source of operationally induced damage for valve operator motors is thermal overload due to backseating which can be caused by forcing the back of the valve seat against the valve body in the area around the stem in order to reduce valve stem leakage while the valve is in the open position. Nuclear power plant fluid system valve backseating is usually performed when leakage of undetermined origin occurs inside the primary containment structure. Operators strive to backseat valves as an alternative measure to shutting down the reactor and the process can require bypassing torque and limit switches. Unless a catastrophic failure occurs, the degree of deterioration caused by backseating can be difficult to determine but it is almost certain that aging will be accelerated as a result of this excessive service wear condition. Pump motors operating in the alternating mode can undergo numerous starting current surges (of short duration) which are often 5 to 10 times the full load current. This condition overheats windings and deteriorates the insulating system and thereby represents another form of excessive duty cycle that advances the aging process.

Table 3-3: Motor Component Related Failures

(A) STATOR RELATED FAILURES:

	LER DATA (1974-1983)	IPRDS DATA (1974-1981)** PLANT 1	PLANT 2	PLANT 3			PLANT 4
UNITS		1	1	1	2	3	1
ELECTRICAL							
MOTOR SHORT*	20	28	1	-	-	-	1
GND. INSUL. BKDN.	8	7	2	3	-	1	8
PHASE INSUL. BKDN.	2						
OPEN DC WINDING	9						
EXCESS CURRENT	8						
CRACKED INSUL.	2						
LOOSE CONNECTIONS	5	22	5	1	1	5	2
FLOODING/LEAKS							
VALVE/PUMP PACKING	10	3					
HUMIDITY	4						
SUMP WATER	3	4	3	-	-	-	1
EXT. WATER/STEAM	9	18	1	4	2	-	6
OIL/LUBE LEAK	4	8					1
DESIGN & WORKMANSHIP							
MANUF. DEFECTS	9						
DESIGN ERROR	2	2	-	-	1	-	-
LARGER DUTY CYCLE	5						
INCORRECT INSUL. CLASS SPECIFICATION	2						
UNKNOWN							
BURNED MOTORS*	47	7	10	16	5	15	9

* THESE CONDITIONS MAY HAVE BEEN INDUCED BY OTHER COMPONENT FAILURES

** PLANT 2 & 3 DATA EXCLUDES VALVE MOTOR FAILURES

Table 3-3: Motor Component Related Failures (Cont'd.)

(B) ROTOR RELATED FAILURES:

	LER DATA (1974-1983)	IPRDS DATA (1974-1981)** PLANT 1	PLANT 2	PLANT 3			PLANT 4
UNITS		1	1	1	2	3	1
ELECTRICAL							
ARMATURE SHORT	2	2	2	-	-	1	-
LOOSE BRUSH CONN.	3						
SHAFT MISALIGNMENT	6	1	-	1	-	-	-
SHUNT LEAD SHORT	3	-	-	1	-	-	-
MECHANICAL							
LOOSE DRIVER PINION	4						
MOTOR COUPLING	7	4	17	25	4	4	9
VIBRATION	-	11	7	2	1	2	10
MOISTURE IN AIR	1						
UNKNOWN	1						
(C) BEARINGS RELATED FAILURES:							
CORROSION	3	25	9	5	2	7	8
LOSS OF LUBE	42	11	16	1	1	2	2
VIBRATION	5						
UNKNOWN	5						
(D) ACCESSORIES RELATED FAILURES:							
COOLER LEAKS	4						
MOUNTING	11	7	1	1	1	-	-
COMMUTATOR	2						
LEAD WIRE BREAK	1	2	-	-	-	-	-
THERMISTOR	1						
CRACKED CASING	1	1	-	-	-	-	3
MOTOR BRAKE COIL	5	1	-	2	-	-	-
LOOSE FAN	4						

Table 3-3: Motor Component Related Failures (Cont'd.)

	LER DATA (1974-1983)	IPRDS DATA (1974-1981)** PLANT 1	PLANT 2	PLANT 3			PLANT 4
UNITS		1	1	1	2	3	1
(E) <u>MAINTENANCE AND HUMAN FACTORS RELATED FAILURES:</u>							
LACK OF CLEAN OIL/DIRT DEP.	5	10	5	3	-	1	6
USE OF OVERSIZED TEST INSTR.	1						
MISAPPLICATION/OPERATION	4	1	-	-	-	3	
WATER SPLASH	4						
IMPROPER LUBRICATION	4						
PROCEDURAL ERROR	3						
MISCELLANEOUS ERRORS	14	1					
REPAIR MOTOR/VALVE	-	5	-	8	2	1	13

Figure 3-3 provides an indication of operating modes at the time of pump motor failures for four (4) plants extracted from IPRDS reports. Table 3-4 expands on this information by illustrating the effects of duty cycle (A), annual operation in terms of the number of motor starts per year (B), and provides the relative level and extent of required motor repairs (C).

3.4 HUMAN FACTORS

The performance of an electric motor can be affected by the human element at many stages both before and during its operating lifetime. This includes the stages of specification and design, manufacturing and shipping, as well as during installation, preoperational testing, operation, and periodic maintenance.

In modern motor manufacturing much of the work is done by machines. Nevertheless the windings and insulation (especially for large motors) are usually manually assembled. The improper installation of these components or most any other component can jeopardize motor performance. For example, improper fit between bearings and other mating parts (such as the inner and outer races or the internal clearance in the bearing itself between the balls and races) can result in faulty operation or failure.

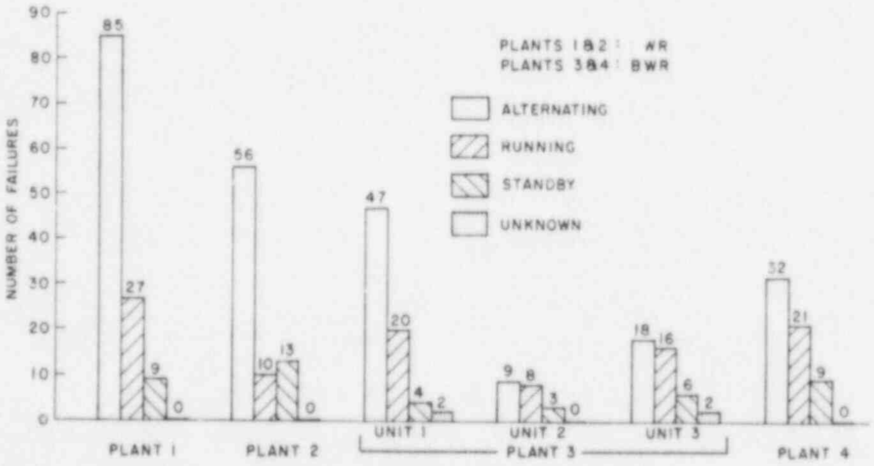

Figure 3-3: Pump Motor Operating Modes (IPRDS DATA: 1974-1981)

Table 3-4: Failures Based on Pump Duty Cycle, Annual Operation, and Repair Catagory (IPRDS DATA: 1974-1981)

UNIT	PLANT 1	PLANT 2	PLANT 3			PLANT 4
			1	2	3	
(A) DUTY CYCLE (% pump operating time)						
≤ 20	47	30	44	10	18	29
21 - 50	37	20	3	1	3	9
51 - 80	17	16	16	5	18	17
81 - 100	20	13	10	4	1	7
(B) ANNUAL OPERATIONS (starts/year)						
≤ 12	45	54	17	9	14	34
13 - 100	68	18	56	11	26	28
> 100	8	7	-	-	-	-
(C) REPAIR CATEGORY						
Component Replaced	10	16	14	3	15	5
Minor Repair	57	42	25	6	10	32
Major Repair	50	18	25	9	5	19
Reset/Adjustment	1	3	-	-	-	6
Recalibration	-	-	-	-	-	-
Unknown	3	-	9	2	12	-

Specification and application errors, such as undersizing or incorrect duty cycle considerations can be causes of operational failures. Also, motor insulation and bearing systems that are highly vulnerable to moisture often fall victim to inadvertent spray or leakage of water. In addition during routine checks as well as during preventative maintenance, many reported personnel errors have occurred including improper parts alignment, installation of overtorqued bolts, incorrect (or lack of) replacement of gaskets and seals, and the reversing of power lead connections.

All of the above represent various ways in which the human performance can and does adversely impact the performance of an electric motor. Since ultimately human input designs, builds, installs, tests, inspects, operates, and maintains these motors, human factors have a rather large and extensive impact on motor performance.

3.5 ENVIRONMENTAL EFFECTS

Most motor environments are relatively benign during normal nuclear power plant operation. Motors located in compartments outside of containment are affected primarily by the driven load. Heat from the motor as well as from recirculated liquid causes ambient temperature to rise which designers strive to limit to a maximum of 120°F, and during normal conditions radiation doses are frequently less than 10 Mrad which is within the endurance capability of most windings and lubricants. The majority of reactor system motors are not required to withstand a High-Energy-Line-Break (HELB) since the line that would fail in the vicinity of the motor is usually the same line associated with the driven load.

Certain system motors are required to operate under extreme conditions[22], such as Reactor Containment Fan Cooler (RCFC) motors which drive heat exchanger fans for heat removal from the containment of a PWR and also provide air circulation for cooling and filtering during and following a postulated Loss-Of-Coolant-Accident (LOCA). These motors must operate for up to one year in a steam environment which could include a concentrated chemical and radiation atmosphere in the case of a Design Basis Event (DBE). It is therefore essential that the motor housing be hermetically sealed to prohibit the admittance of moisture which would otherwise occur as motor and containment pressure equalized.

Motors that experience the most severe <u>normal</u> conditions are those that drive reactor recirculation pumps, (non-safety-related) containment fans and containment valve-operator motors. These motors can be subjected to temperatures upward of 135°F coupled with the higher radiation levels present inside the containment structure.

Modern windings are not particularly sensitive to high humidity, and older insulation systems seem to be relatively tolerant of moisture, if continuously operated or maintained always above the dew-points, until the attainment of a significant age (e.g., 20 years or more). Manufacturers and design engineers generally specify resistance heaters for motors that are expected to remain idle for long periods in high humidity.

3.6 SYNERGISTIC EFFECTS

The extent to which winding insulation materials are affected by synergistic (or, combined) effects of temperature, radiation, and other parameters is not fully understood. However, tests of magnet wire conducted by F. J. Campbell[23] of the U.S. Naval Research Laboratory indicate that some types of insulation may perform significantly better than expected when exposed to simultaneous heat and radiation conditions, as opposed to sequential or individual environmental exposures. Another study by Bustard, et. al. [24], on the effect of thermal and irradiation aging on polymers used for insulations and gaskets has revealed that the ordering of irradiation and thermal exposure was important in that irradiation followed by thermal exposure is more severe than the converse. Kadotani, et. al.[25], have recently published a study on combined thermal and electrical aging of coil insulation. The study has included laboratory tests of Class B mica epoxy insulation. In this study, aging stresses were limited to thermal and electrical loads. The lifetime of the insulation under normal voltage at normal temperature was estimated to be approximately 49 years. However, considering mechanical as well as environmental stressors, the service life prediction for such insulation has been conservatively limited to 15 years.

3.7 AGING MECHANISMS

Environmental parameters influencing aging mechanisms and therefore influence the degradation of insulation, lubrication, gaskets and seals, and other components made of organic materials are predominantly electrical, mechanical, chemical, thermal, environment, and radiational loads. In order to fully assess the effect of aging on degradation of motor components it is important that the behavior of the various organic or inorganic materials be characterized.

The extent of aging degradation for insulating materials is indexed by evaluating dielectric or mechanical properties: dielectric properties include dielectric strength, dielectric constant, dissipation factor, and volume/surface resistivity; mechanical strength is characterized by resistance to tensile or shear stress and the corresponding percentage of material elongation.

3.7.1 Electrical

The dielectric strength is a property of insulating material and is expressed in terms of the minimum electrical stress (in volts/mils) that will cause failure or "breakdown" under specified conditions. The electrical stress withstand characteristic[21] of most materials declines with increasing temperature, time, and thickness, as shown in Figure 3-4.

The breakdown strength of insulation varies with numerous factors (e.g., thickness, size and shape of electrodes, distribution of the electric stress field in the material, frequency of the applied voltage, rate and duration of voltage applied, temperature, moisture content, and possible chemical changes occurring while under stress). One of the resulting conditions from these factors, when linked with high voltage, is known as corona or ionization discharge. Corona effects occur when the voltage gradient on gas molecules in void spaces (in the insulation) exceeds a certain tolerance value which is dependent on the nature of the gas and its associated critical pressure and

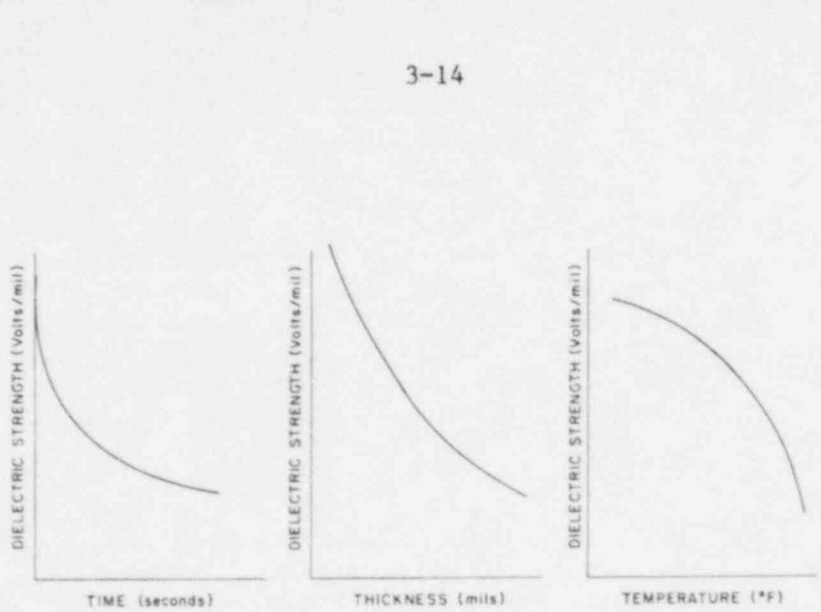

Figure 3-4: General Trend of Time, Thickness and Temperature Effects on Insulating Materials

temperature. The revealing symptoms of surface corona degradation often consists of red or white material deposits. Corona occurring on the outside surfaces of a motor insulation material does not promote damage as rapidly as internal corona. Figure 3-5 depicts the endurance with respect to time for failure under corona effects for several different kinds of insulating material, at room temperature, 50% relative humidity, and 360 hertz (frequency). It is evident from Figure 3-5 that mica is the more resistant and therefore the more suitable material for withstanding such discharges.

Dielectric constant is indicative of an insulation material's ability to pass dielectric flux: a material having a high dielectric constant will pass more dielectric flux than an insulation with a lower value under the same electrical condition. The value of this constant depends on the number of atoms or molecules per unit volume and the ability of each to be displaced in the direction of the applied voltage. Values of the dielectric constant range from unity for a vacuum to slightly greater than unity for gases at atmospheric pressure, 2 to 8 for common insulating materials, 35 for ethyl alcohol, 91 for pure water, and 1000 to 10,000 for titanate ceramics. Changes in these normal values indicate abnormal conditions such as the presence of moisture, short-circuited conductors or breaks in the insulating materials.

For a perfect dielectric capacitor, current leads the voltage by 90° and the imperfect dielectric has a current which leads the voltage by less than 90°. The difference between the perfect and imperfect phase angles (i.e., the angle between the voltage and current) is known as the loss angle whereas the tangent of this angle is known as the dissipation factor. Dissipation factor is a measurement of dielectric power losses which occur because insulating materials are not perfect in the dielectric sense, and because of the effects of hysteresis and conduction. Dielectric losses increase with temperature and

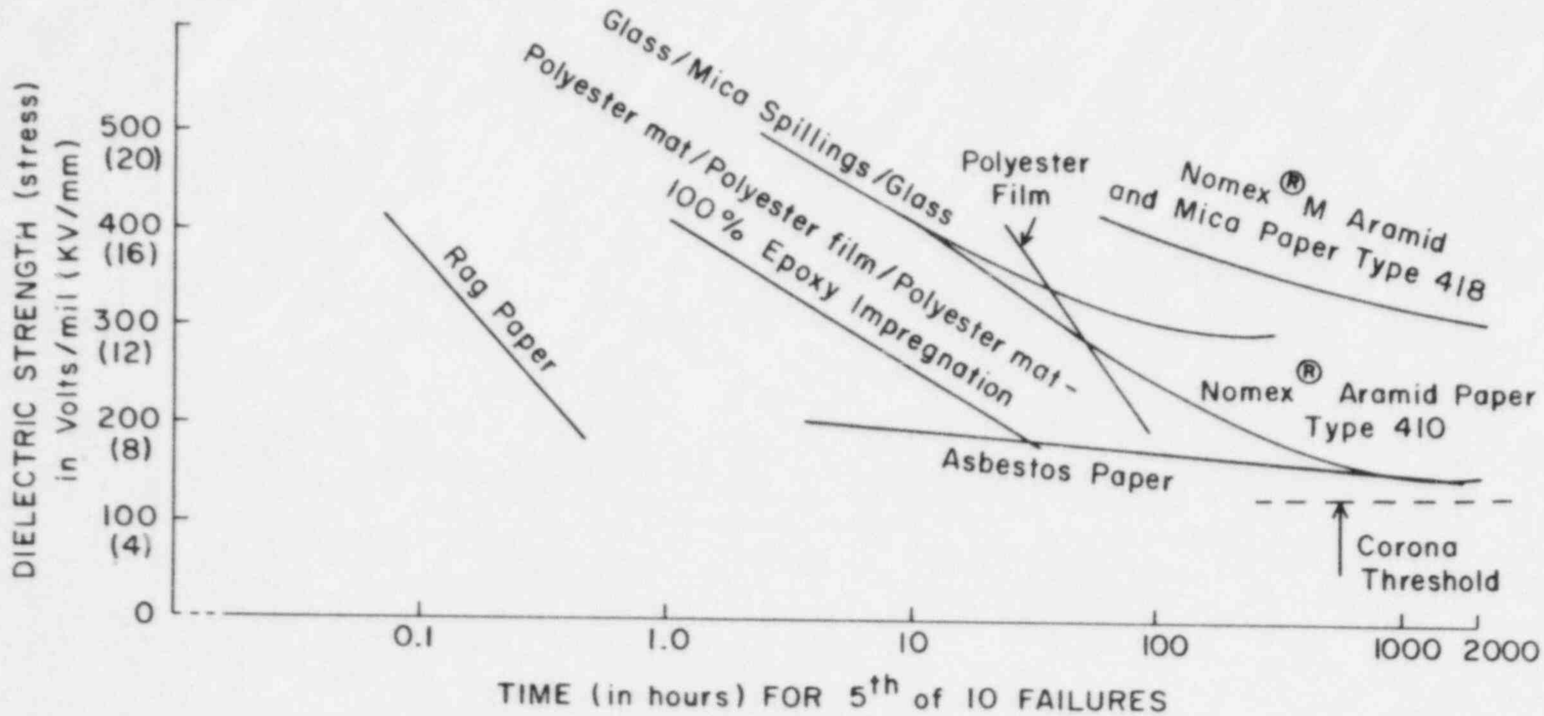

Figure 3-5: Voltage Endurance of Various Insulating Materials (Ref. 31-33) (Single layer of 10 mil material at room temperature, 50% R. H., and 360 Hz Frequency)

frequency, and are accelerated by the presence of moisture. In fact, the losses cause internal temperature rise which results in increased dielectric loss, thus creating a cummulative effect which can eventually lead to insulation breakdown.

The resistivity of an insulation material is expressed by volume, representing a bulk property (in ohm-meter units), and by surface resistivity (ohm/square meter). Surface resistivity characterizes leakage current across the insulator surface between electrodes having a potential difference. These properties are affected by surface or bulk moisture and are used to assess the condition of dampness in the insulating material. Both bulk and surface resistivities decrease with temperature.

3.7.2 Mechanical

The mechanical degradation[27] of an electric motor can be classified into four basic areas:

Major mechanical failures are typically bearing-related caused due to the lack of adequate lubrication, excessive radial and/or thrust loads, or a non-optimum bearing/lube system for the particular application. Lubrication converts solid friction of the two dry bodies in contact to fluid friction via a separating layer of liquid or semi-liquid medium. However, excessive lubricant can contribute to overheating and/or overpressure conditions. The life expectancy of a ball bearing is inversely proportional to the cube of the load and accordingly, a small increase in load can cause a significant decrease in bearing life. Other factors affecting bearing performance include misalignment of the rotor assembly, vibration, corrosion of the rollers or balls, and bearing currents. Misalignment of the rotor and stator can cause the (stator) lamination damage shown in Figure 3-6.

Another form of mechanical stress is related to the physical properties of the insulating material used in motor windings. Common insulation undergoes a significantly reduced tensile or yield strength and percentage of elongation with an increase in temperature and moisture content. Figures 3-7 and 3-8 indicate the trend for two types of insulating material. Additional reduction in strength and electrical integrity occurs with the presence of moisture, and therefore, simultaneous loss of both physical and dielectric strength typically causes irreversible damage.

Corrosion or fatigue of components made of steel or other metallics constitutes another form of mechanical aging. Severe environmental parameters can cause metal embrittlement and thus reduce the threshold strength inherent in the material. Leakage (moisture) or prolonged storage and idleness in an area of high humidity will cause corrosion, and common corrosion-related degradation is reported to affect mounting bolts, lead connections, conduit boxes, bearings, and housing enclosures.

One of the most critical mechanical loads which promotes the degradation process is vibration from internal or external sources (such as an earthquake). Vibration can cause loosening of rotor bars as well as laminations in the stator or rotor cores, chafing of insulations and also the fatigue of metallic components by imposing cyclic stresses. Figure 3-9 shows score marks on an end bracket of a motor caused by mechanically-induced bearing failure and the overall effects of vibration.

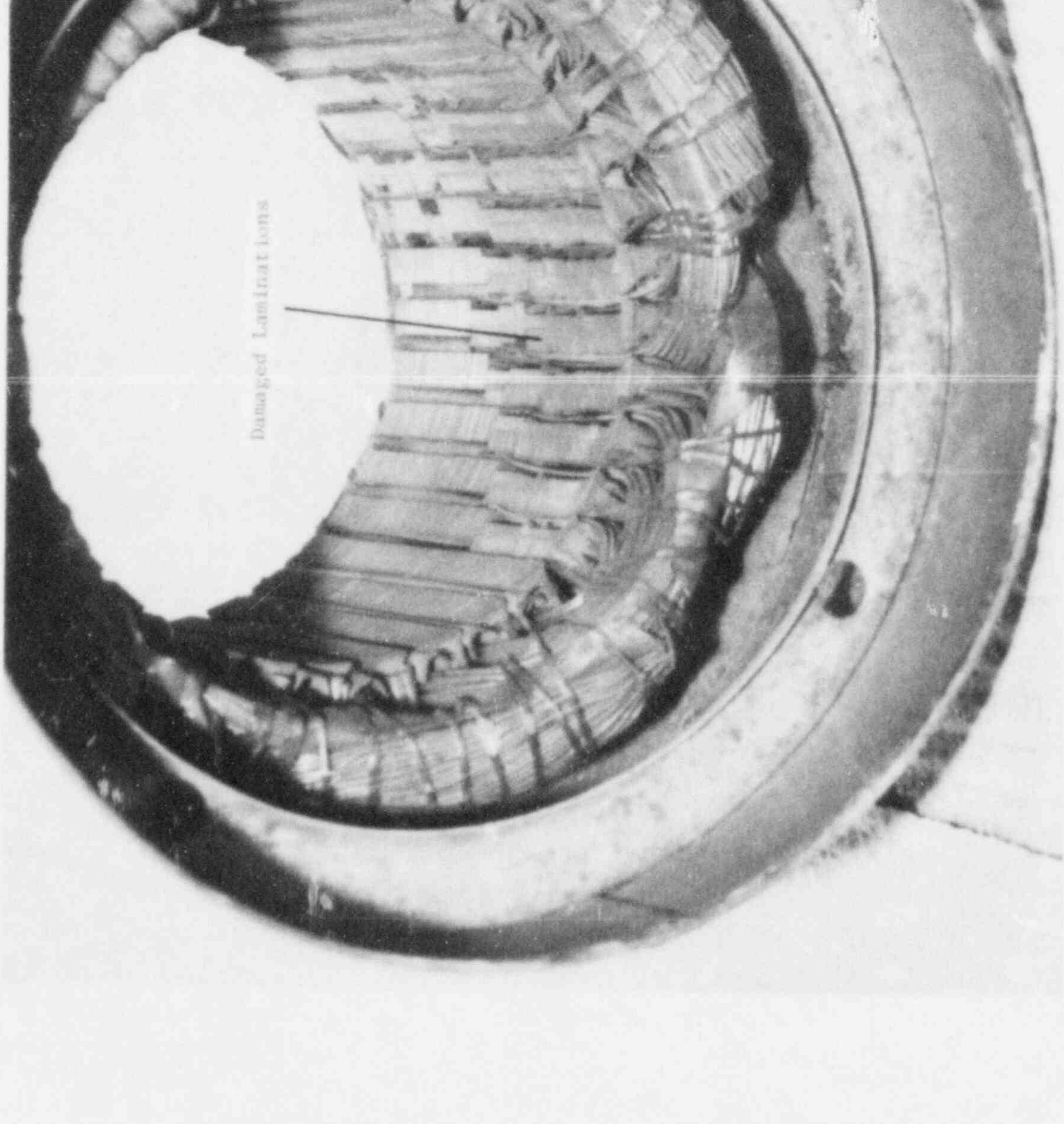

Figure 3-6: Stator Lamination Damage due to Rotor Interference

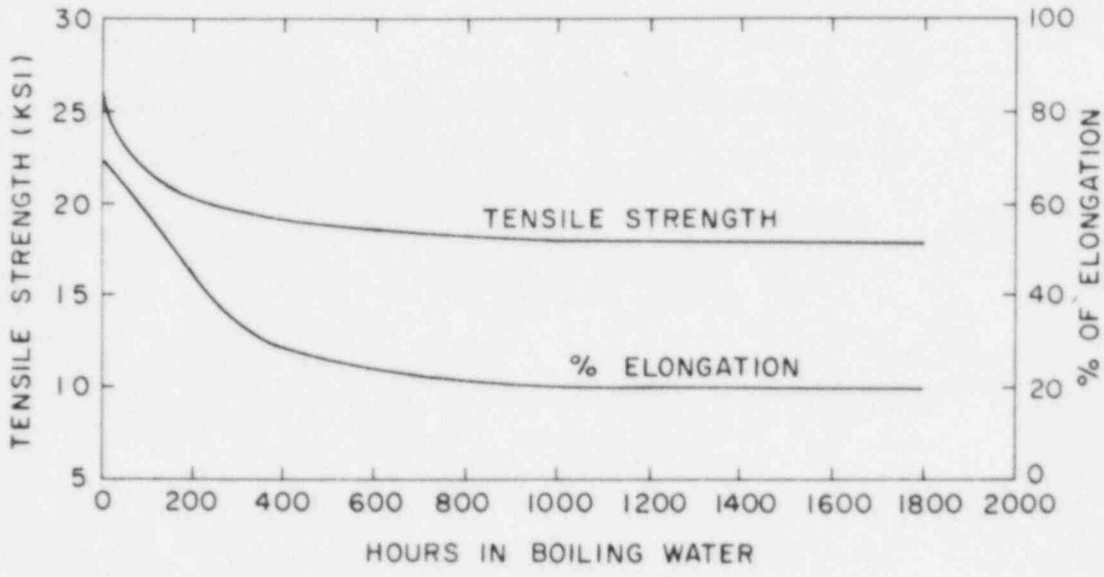

Figure 3-7: Tensile Strength and Ultimate Elongation of Kapton[R] Following Exposure to Water at 100°C (Ref. 29)

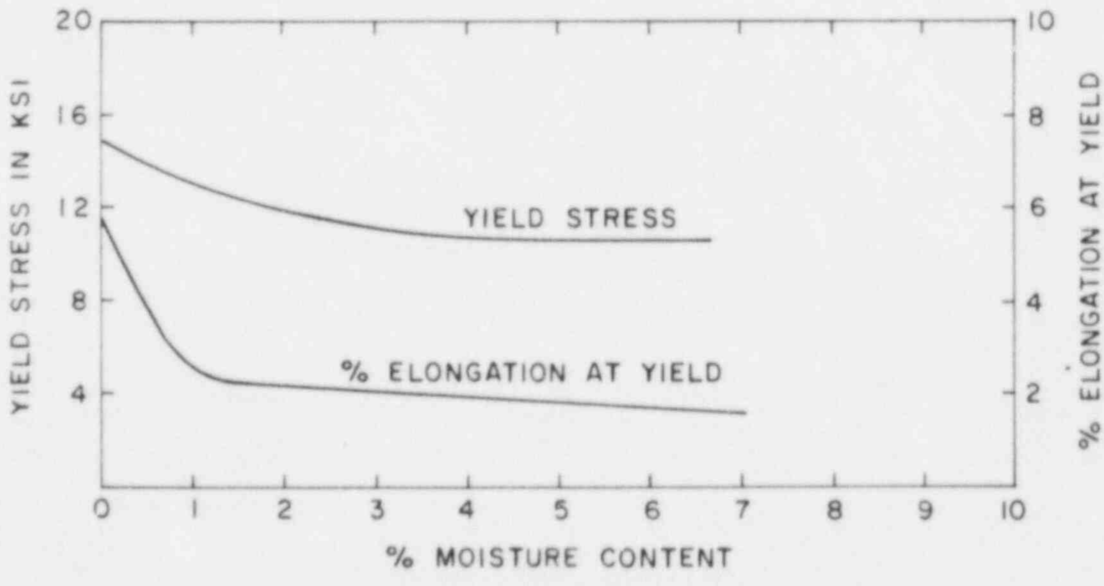

Figure 3-8: Effect of Moisture Pick Up on the Physical Properties of a Resin (Ref. 20)

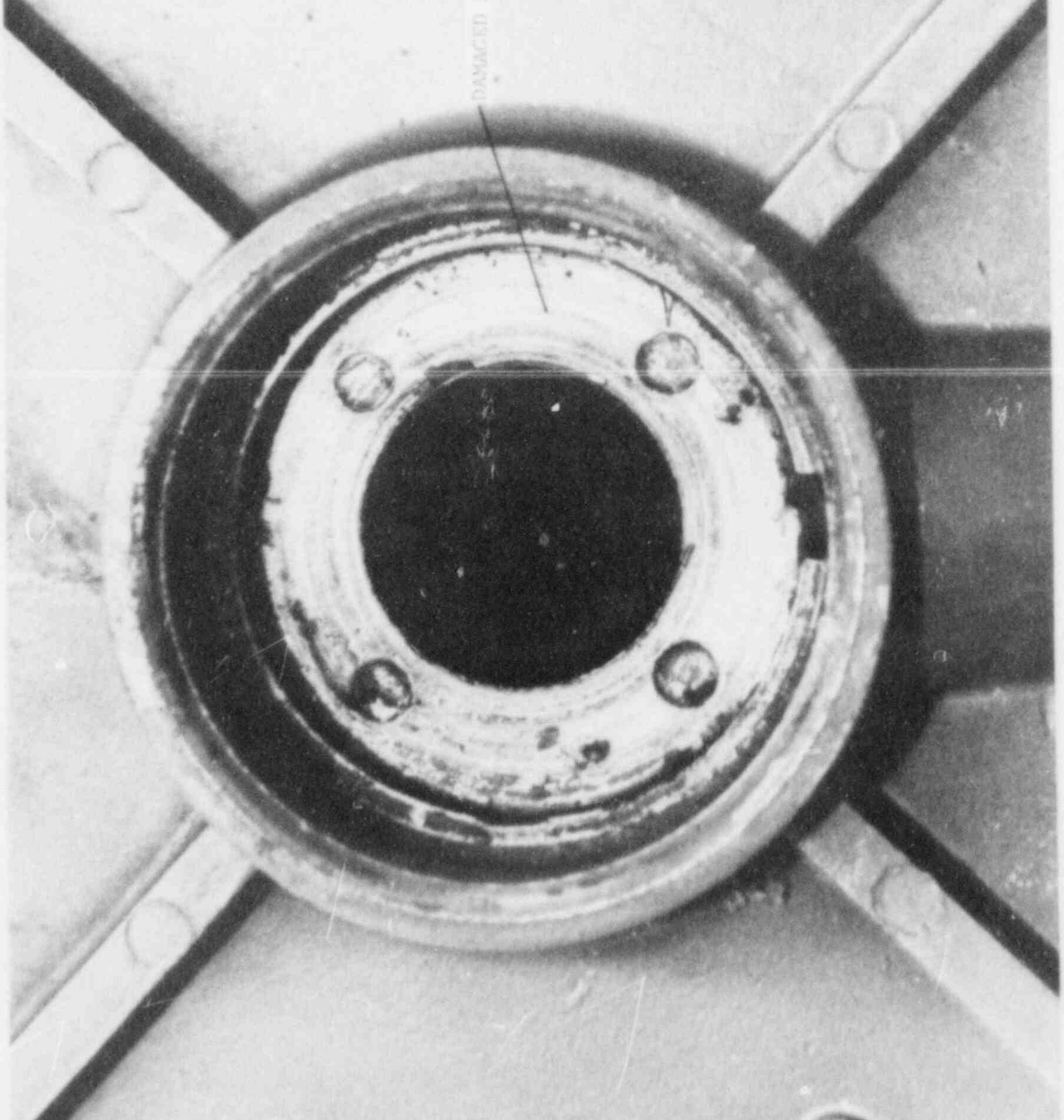

Figure 3-9: Scores on End Bracket due to Bearing Damage

3.7.3 Chemical

Under normal and particularly under abnormal environmental conditions, all motor components can undergo a chemically-induced deterioration process. Insulation degradation, lube oil decomposition (i.e., viscosity breakdown), and overall corrosion are the most significant forms which degrade motor performance with time.

With regard to motor insulation[28, 29], chemical properties are classified as resistance to external chemical effects and chemical changes to the material itself. For the first category, lubricating oil, varnishes used for impregnation, bonding and finishing, acids and alkalis resulting from electrical discharge or deposits of salts from the atmosphere as well as oxidation and hydrolysis from atmospheric conditions are included. The effects on insulating and adjacent motor materials can involve direct solvent action on rubber and also corrosion of metals. The material can experience oxidation, deterioration due to acidity, chemical instability of synthetic resins, self-polymerization of synthetic compounds, and vulcanization of rubber-sulphur mixtures.

The most common form of deterioration is slow oxidation which introduces acid groups into the polymeric insulation and thereby increases conductivity and thus the power factor of the insulation. Oxidation also divides polymer chains in resin insulation and consequently decreases tensile strength. Figures 3-10 and 3-11 represent the oxidative degradation of insulating materials when exposed to air. A second type of deterioration is the brittle hardening of insulation as a result of the loss of plasticizer and excessive oxygen cross-linking of polymer chains which occurs with plastic insulations, and a third type of deterioration is thermal or internally catalyzed depolymerization. This reaction is generally slower than oxidation although the process accelerates at higher temperatures as shown in Figure 3-12, and Table 3-5 provides age deterioration characteristics of an insulating material while under the influence of various chemical environments.

Chemical effects also are related to corona (ionization in the presence of voltage stresses) discharges in that oxygen molecules (O_2) in a gas space converts to ozone (O_3) and forms nitrous oxide when in the presence of water molecules. Attacks on organic material insulation and the corresponding degradation is usually revealed by the reddish or white deposits previously noted.

Lubricant deterioration and contamination are caused by the oxidation process which acidifies the medium. Evaporation or contamination of a lubricant increases viscosity to an undesirable level, and contamination with water will ultimately cause corrosion. These processes can affect the lubricity (the ability of the molecules to slide freely past one another) and the resulting change in viscosity can damage a bearing assembly by producing excessive pressure between support surfaces. Too low a viscosity may permit metallic contact in sleeve bearings which would destroy them.

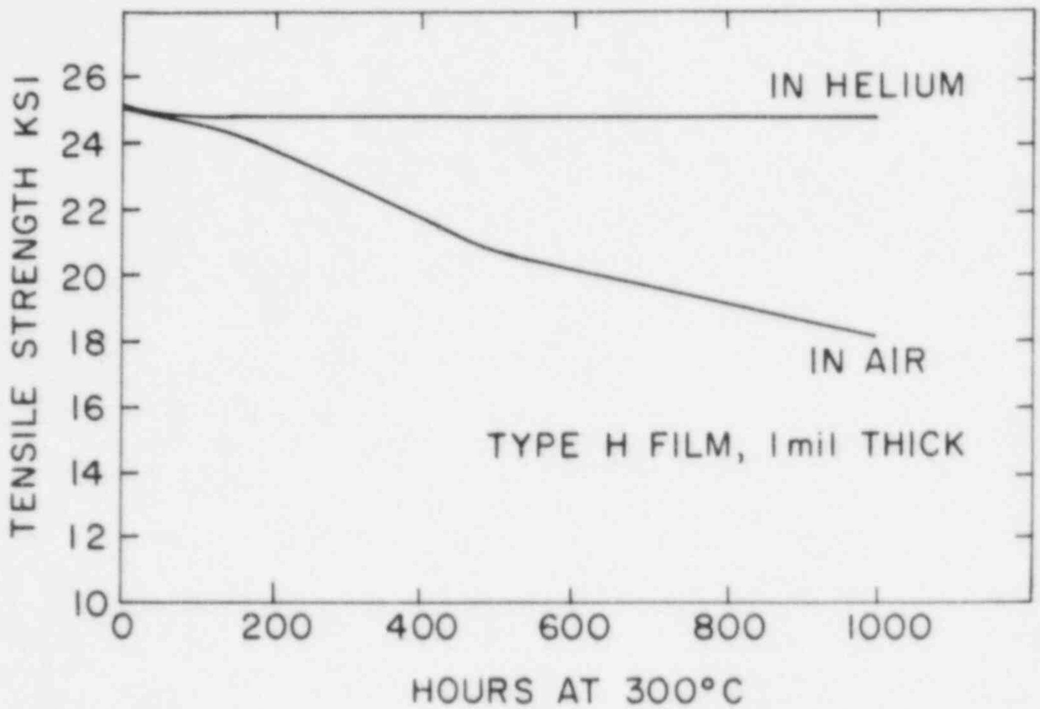

Figure 3-10: Tensile strength of Kapton^R subjected to oxidation degradation (Ref. 29)

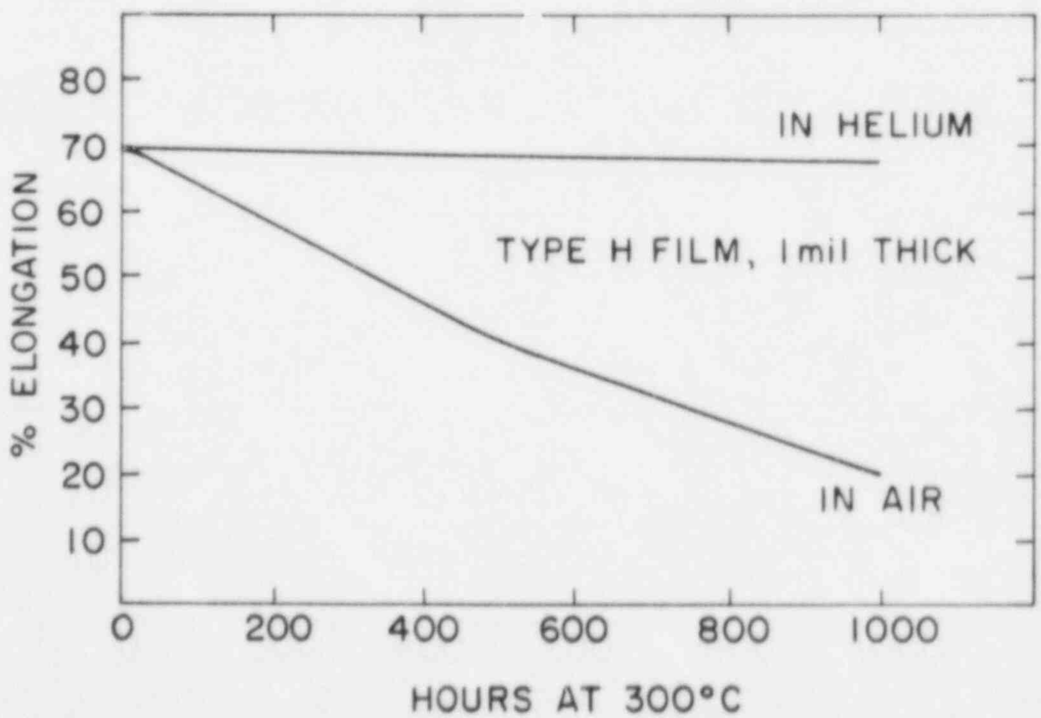

Figure 3-11: Ultimate Elongation of Kapton^R subjected to oxidation degradation (Ref. 29)

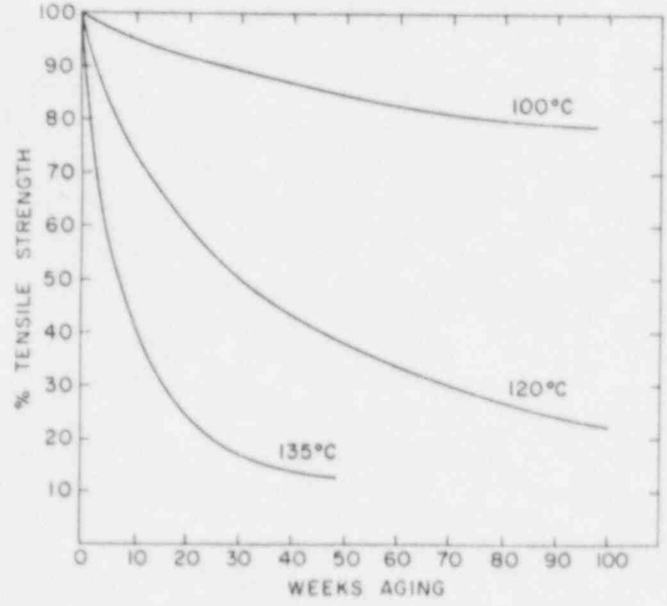

Figure 3-12: Tensile strength of Manila Paper in Oil in the Presence of Nitrogen (Ref. 28)

Table 3-5: Mechanical Strength of Kapton[R] Subjected to Chemical Aging [29]

PROPERTY	TYPICAL VALUES (1 mil) %Tensile Retained	%Elongation Retained	%Modulus Retained	TEST CONDITION/METHOD
RESISTANCE TO:				Days Immersed at Room Temperature
Benzene	100	82	100	365
Toluene	94	66	97	365
Methanol	100	73	140	365
Acetone	67	62	160	365
10% Sodium Hydroxide		Degrades		5
Glacial Acetic Acid	85	62	102	36 days @ (110°C)
p-Cresol	100	77	102	22 days @ (200°C)
Transformer Oil	100	100	100	180 days @ (150°C)
Water pH = 1	65	30	100	14 days @ (100°C)
pH = 4.2	65	30	100	14 days @ (100°C)
pH = 7.0	65	20	100	166 days @ (100°C)
pH = 8.9	65	20	100	14 days @ (100°C)
pH = 10.0	60	10	100	4 days @ (100°C)

R Registered trademark of DuPont Company

3.7.4 Thermal

Temperature is the most critical parameter[30-33] that can affect motor performance over the long term and also over a short duration of motor operation if at an excessive level. As with vibration, high temperature can be internally as well as externally generated. Manufacturers design a machine for specific temperature and humidity conditions with a certain margin of tolerance. Under normal operating conditions the motor performance should not be adversely affected by temperature; however, in the event of a Design Basis Accident (DBA) in which certain motors are required to withstand a combined (design basis) earthquake and conditions due to a loss of reactor coolant, a motor must be capable of enduring excessive temperature for an indefinite period including the post-accident.

Significant internal temperature-rise is usually generated within motor components due to mechanical or electrical (I^2R) stresses. Heat is also generated by leakage (or eddy) currents or by chemical depolymerization of the insulating system. In addition, mechanical stress can be generated by bearings which produce heat due to inadequate lubrication, shaft misalignment, and the like.

Deterioration of insulation with a polyester fibre strand material was observed by Mitsui, et al.[34], as a result of thermal cycling. Tests indicated that the dissipation factor changed significantly at 155°C and it was found that thermal cyclic degradation begins with a separation of the innermost insulation layer from the strand insulation and then propagates in the mode of (mica) delamination and eventually results in the formation of cracks.

Figures 3-13 thru 3-15 illustrate the electrical and mechanical strength versus temperature of some advanced insulating materials. Within the range of 200°C most values are observed to decline with an increase in temperature. All insulating materials lose strength to some degree at high temperatures and therefore characteristics at the designed operating temperature are important factors to be considered for a particular system application. Figure 3-13 also demonstrates that when thick grades of otherwise superior insulating materials are used, brittle conditions often occur (in certain dry environments) and disturb the balance of physical properties.

A "rule of thumb" known as the 10-degree-rule states that a 10°C increase in temperature will reduce the insulation life span by one-half. Accordingly Figure 3-16 illustrates the average age of an advanced insulating material, with respect to electrical and mechanical strength, in relation to the operating environmental temperature.

3.7.5 Humidity

The presence of humidity or actual water in the insulation[31-33] of a motor can expedite the degradation process thereby reducing electrical life and dielectric strength. Both dissipation factor and dielectric constant change dramatically when an insulating material is exposed to humid air and volume resistivity also declines at high relative humidity. As shown in Figure 3-8, the mechanical strength of an insulating material declines with the percentage moisture content. Chemically, water serves to break the binding of insulation materials since in many cases water is used as a plasticizer. Thus

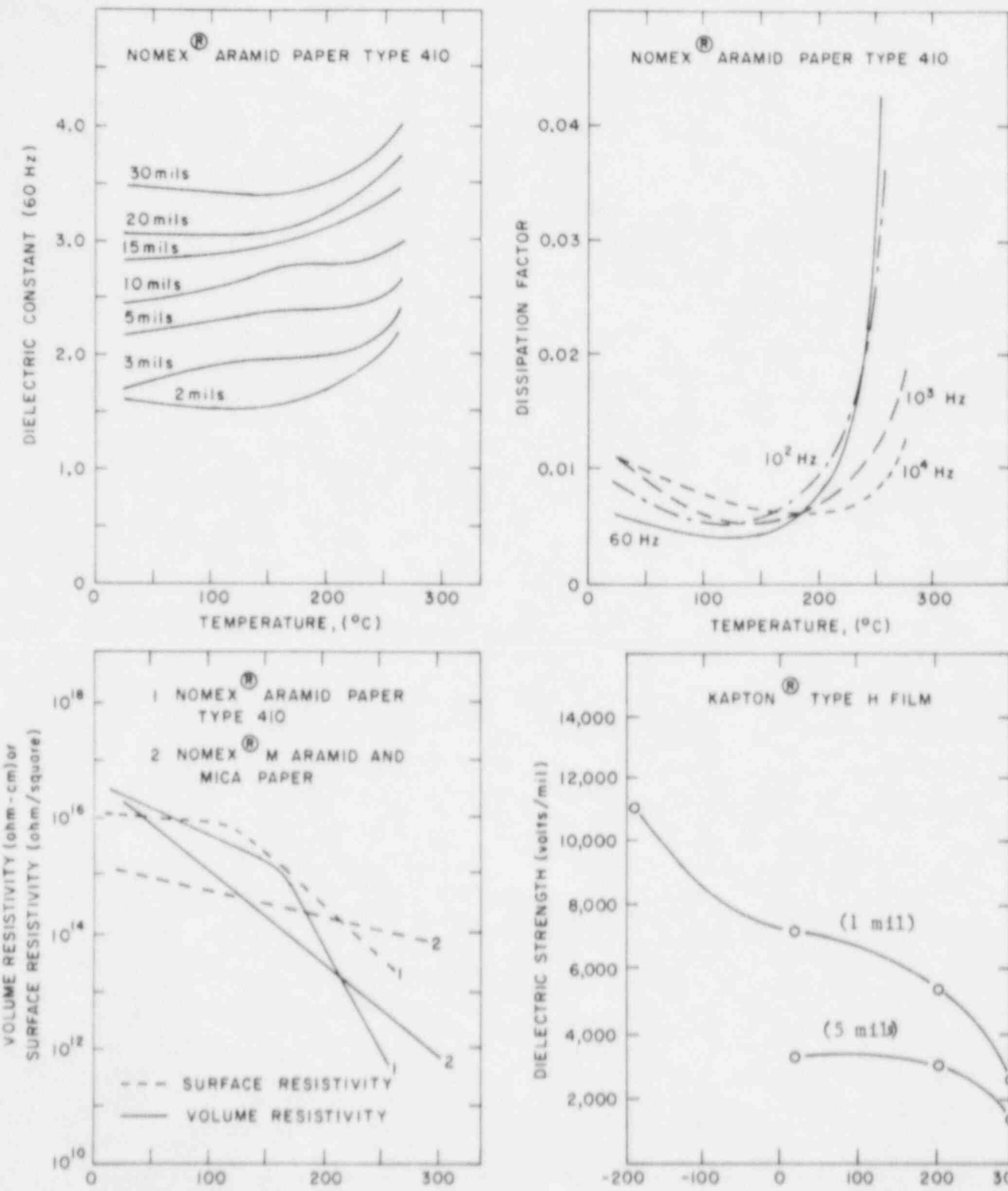

Figure 3-13: Electrical Properties of Insulation with respect to Environmental Temperature (Ref. 29, 31-33)

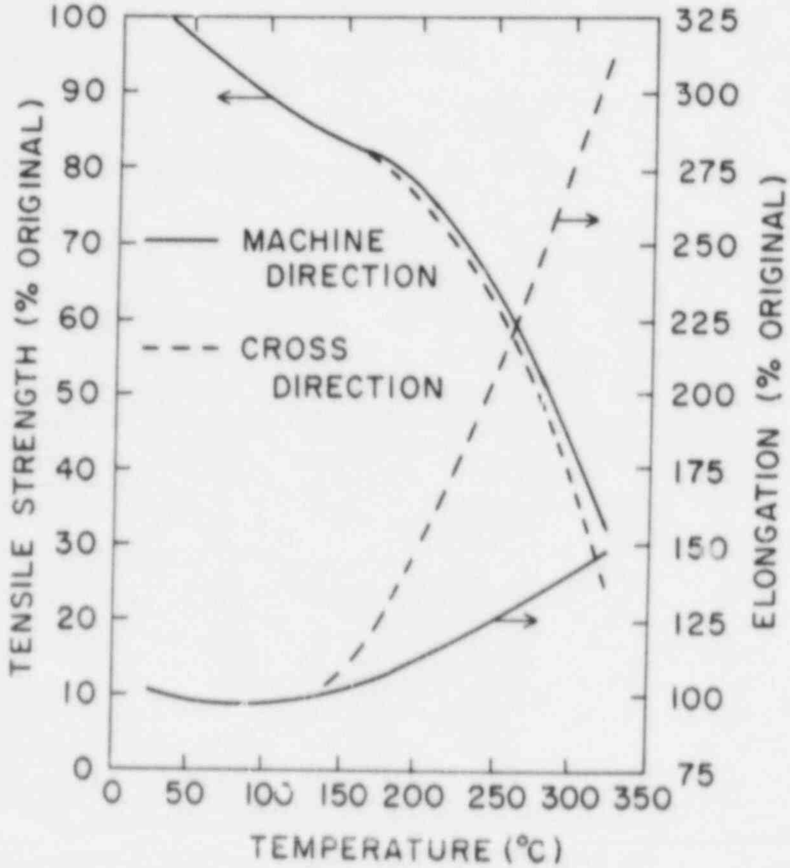

Figure 3-14: Mechanical Strength versus Temperature for Nomex[R] Aramid Paper Type 410 (10 mil) (Ref. 31)

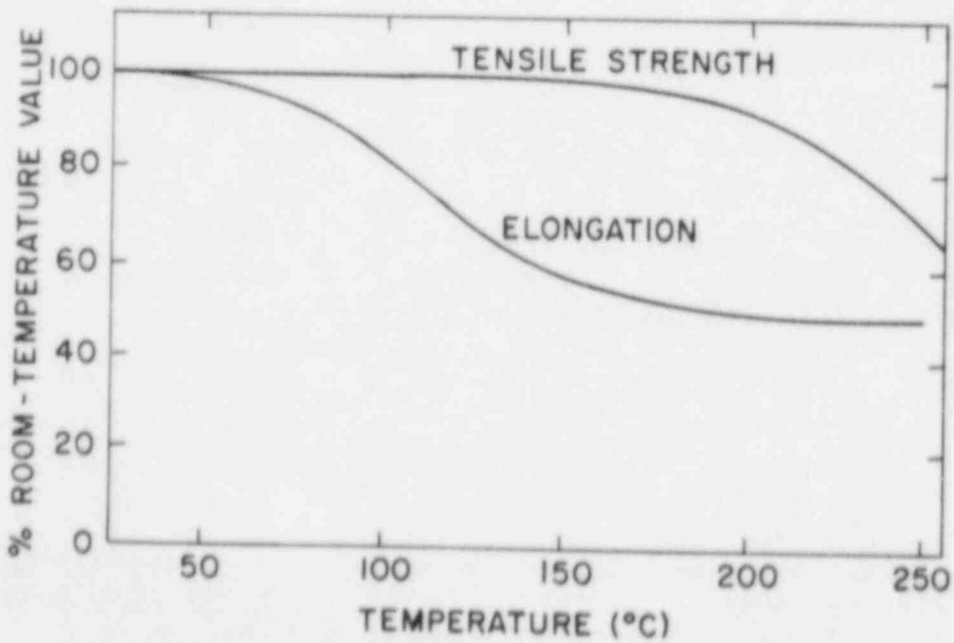

Figure 3-15: Mechanical Strength versus Temperature for Nomex[R] M Aramid and Mica Paper Type 418 (5 mil) (Ref. 33)

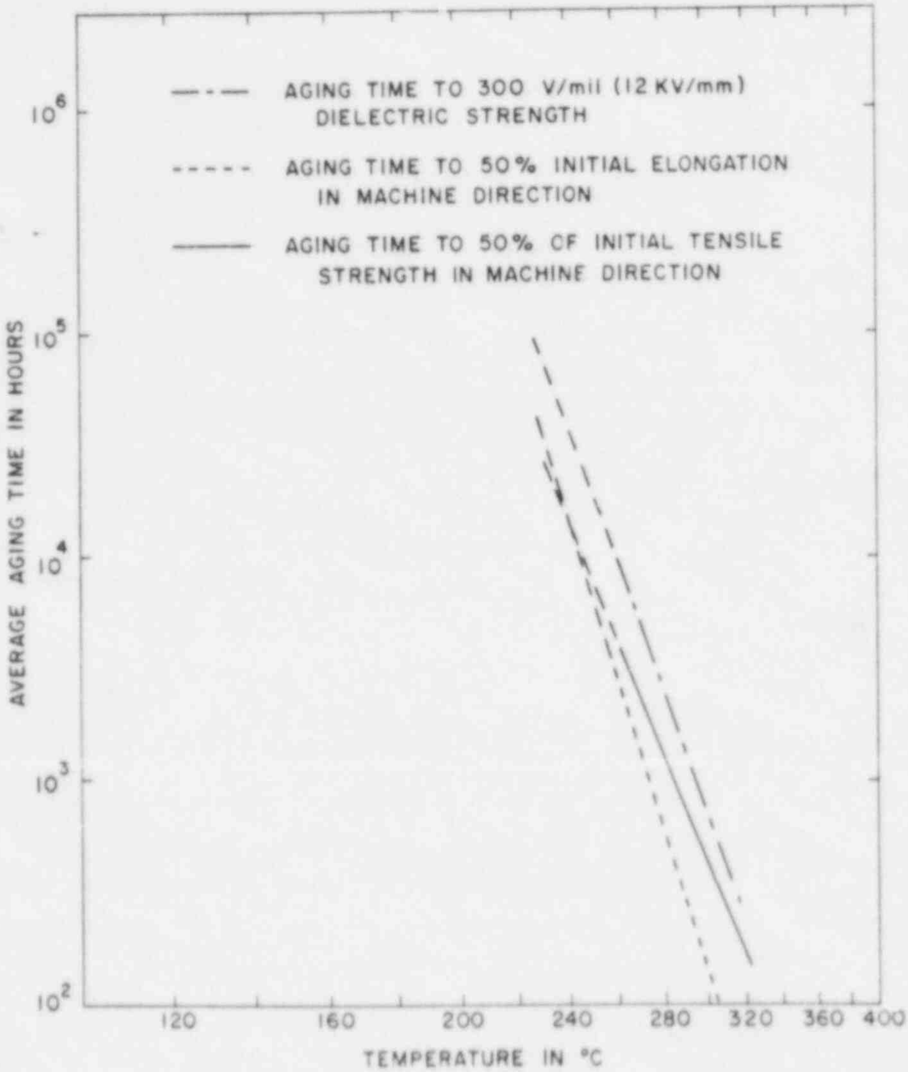

Figure 3-16: Useful life versus temperature for Nomex[R] Aramid Paper Type 410 (10 mil) (Ref. 31)

humidity becomes one of the greatest deterioration agents with time. Many newly developed insulating materials utilize water only as a mild plasticizer and consequently there is little effect on mechanical and tear strength even at 95% relative humidity. In fact, most modern insulating materials have vastly improved electrical and mechanical properties and low water absorption characteristics. Table 3-6 depicts the electrical properties of some common insulating materials with respect to relative humidity.

Table 3-6: Effect of Relative Humidity on Insulation Electrical Properties [29, 31]

Insulation Material	Relative Humidity (%)	Dielectric Strength (V/mil)	Dielectric Constant (60Hz)	Dissipation Factor (60 Hz)
Kapton[R] (1 mil)	0	7800	3.0	.0018
	30	7300	3.3	.0021
	50	7000	3.5	.0025
	80	6500	3.7	.0037
	100	6200	3.9	.0047
Nomex[R] (Type 410) (10 mil)	0	920	2.5	.0059
	50	880	2.7	.0061
	95	840	3.2	.011

[R] Kapton and Nomex are registered trademarks of DuPont Company

3.7.6 Radiation

Nuclear power plant motors exposed to radiation can be adversely affected. However, radiation can also have a beneficial effect by causing synthetic polymers to crosslink. Irradiation of polyethylene improves resistance to heat and mechanical failure, the polymerization of plastics, and curing of resin and varnish films. Table 3-7 further illustrates the variations of electrical and mechanical properties of a typical insulating material when exposed to radiation.

In general, however, organic insulation deteriorates[56] both mechanically and electrically as a result of irradiation since chemical changes rearrange the molecular structure of the material. Mechanical strength is affected more than electrical strength as shown in Table 3-7, and the probable life dose for typical insulating material is given in Table 3-8.

Radiation damage to insulating material is typically revealed by discoloration, cracking, disintegration, and the transformation of suppleness to hardening and embrittlement.

Table 3-7: Radiation Resistance for NOMEX[R] Aramid Paper Type 410 [31]
[10-mil paper exposed to 2 MeV electrons (beta rays)]

DOSE megarads	RETAINED TENSILE STRENGTH % MD	% XD	RETAINED ELONGATION % MD	% XD	DIELECTRIC STRENGTH 1/4 in. diam. electrode V/mil	60 Hz DK*	DF**	1 kHz DK	DF	10 kHz DK	DF
0	100	100	100	100	870	3.1	0.0083	3.0	0.0132	2.9	0.0183
100	96	100	89	92	855	3.0	0.0135	3.0	0.0161	2.9	0.0205
200	100	99	92	91	845	2.9	0.0104	2.9	0.0147	2.9	0.0198
400	100	99	96	88	845	3.0	0.0120	3.0	0.0156	2.9	0.0199
800	94	97	76	82	850	2.9	0.0089	2.9	0.0134	2.8	0.0185
1600	87	86	60	47	860	3.1	0.0137	3.1	0.0156	3.0	0.0195
3200	81	81	36	27	885	2.3	0.0071	2.3	0.0107	2.2	0.0148
6400	65	69	18	16	790	2.5	0.0095	2.5	0.0132	2.4	0.0174

*DK - Dielectric Constant
**DF - Dissipation Factor
R - Registered Trademark of DuPont Company

Table 3-8: Radiation Resistance of Organic Insulating Materials[56]

Materials	Upper dose limit in Gy = 100 rad	
Acrylic scintillator	$10^2 - 10^4$	*
Butyl rubber	5×10^4	*
Electronics components (active)	$10^2 - 10^3$	*
Optical fibre	$10 - 10^2$	*
Perfluoro ethylene-propylene (FEP)	5×10^4	*
Phenolic resin, unfilled	10^4	*
Polyacryl (Plexiglas)	10^5	*
Polyamide (Nylon)	1×10^5	*
Polyester resin, unfilled	5×10^4	*
Silicone oil	5×10^5	*
Silicone rubber	5×10^5	*
Teflon (PTFE)	10^3	*
Viton	$1\text{-}2 \times 10^5$	*
Araldite D (epoxy resin, cured at ambient temperature)	$1\text{-}2 \times 10^6$	
Chlorosulfonated PE (Hypalon, CSP)	$1\text{-}2 \times 10^6$	
Cross-linked PE (XLPE)	$1\text{-}2 \times 10^6$	
Ethylene-acrylate rubber (EAR)	$1\text{-}2 \times 10^6$	
Ethylene-propylene rubber (EPR)	$1\text{-}2 \times 10^6$	
Ethylene vinyl acetate (EVA)	$1\text{-}2 \times 10^6$	
Flamtrol (polyolefin)	$1\text{-}2 \times 10^6$	
Halar (CTFE)	$1\text{-}2 \times 10^6$	
Hytrel (PETP copolymer)	$1\text{-}2 \times 10^6$	
Lupolen (PE)	$1\text{-}2 \times 10^6$	
Polychloroprene (Neoprene)	$1\text{-}2 \times 10^6$	
Polyolefin	$1\text{-}2 \times 10^6$	
Polyvinyl chloride (PVC)	$1\text{-}2 \times 10^6$	

Materials	Upper dose limit in Gy = 100 rad
Araldite B (epoxy resin)	$1\text{-}2 \times 10^7$
Araldite F (epoxy resin)	$1\text{-}2 \times 10^7$
Epikote (epoxy resin)	$1\text{-}2 \times 10^7$
Epoxy Novolac	$1\text{-}2 \times 10^7$
Epoxy resin, aromatic hardener	$1\text{-}2 \times 10^7$
Glass-fibre reinforced EPR-hoses	$1\text{-}2 \times 10^7$
Mineral oil	$1\text{-}2 \times 10^7$
Paints based on epoxy or polyurethane resins	$1\text{-}2 \times 10^7$
Polyimide resin	$1\text{-}2 \times 10^7$
Special radiation resistant lubricants	$1\text{-}2 \times 10^7$
Special radiation resistant motors	$1\text{-}2 \times 10^7$
Cerium-doped glass	1×10^8
Ryton (PPS)	1×10^8
Inorganic filled resins: - Epoxy, aromatic hardener	1×10^8
- Phenolic	1×10^8
- Polyester	1×10^8
- Polyimide	1×10^8
- Polyurethane	1×10^8
- Silicone	1×10^8
Aluminium oxide	$> 10^8$
Magnesium oxide	$> 10^8$
Magnetic materials	$> 10^8$
Metals	$> 10^8$
Mica	$> 10^8$
Glass fibre	$> 10^8$
Quartz	$> 10^8$

*) Use of these materials in radiation areas is not recommended or to be used with precautions.

3.8 AGING-SEISMIC CORRELATION

Most motor manufacturers maintain that winding starting forces are equivalent to or in excess of predicted seismic forces. However, a potential source for seismic failure is inadequate end-bell-to-frame-support on older (large) motors which has led to the addition of dowel pins between the frame and end bells for withstanding the shear forces expected during seismic events.

As indicated, the aging-related degradation of materials is primarily influenced by mechanical, electrical and chemical loads. The potential seismic damage to motor components on the other hand is primarily mechanical and inertia-related. Since inertial failures are always associated with the size of the mass and the vibration acceleration, many components of a motor can be excluded from seismic consideration. However, one can not exclude damage caused by external seismically-provoked conditions, such as dislodged objects falling on the motor, although this can be avoided by suitable installation design.

Since aging-related degradation is complex in nature, the correlation of aging with seismic effects is difficult to qualify and quantify. Nutech[12] has suggested a method based on the mechanical failure of weak link motor components in consideration of the environmental, service wear, and cyclic mechanisms. For certain small induction motors (approximately 10hp) seismic effects should be minimal providing motor dielectric, rotational, and mechanical integrity has been maintained.

4.0 DATA EVALUATION AND ASSESSMENTS

LER, IPRDS, and NPRDS data provide the most complete information available to date on actual nuclear power plant motor failures and therefore provide the primary basis for the assessment of common failure modes, mechanisms, causes, and the associated frequency. Other sources of information utilized include NPE, EEI, and EPRI reports as well as actual experience relayed by motor maintenance and design specialists. A thorough analysis of operating experience necessarily requires a review of incipient, partially degraded, and catastrophic losses of motor integrity which then serve to identify those critical parameters that provide functional performance indications.

4.1 LER REVIEW

The LER motor failures compiled for the period 1974-1983 detail any degraded safety condition involving a motorized system or specific equipment item. While pumps and valves are predominantly reported, fans and miscellaneous motor-driven components are included as well. Most of the failure event information outlines a condition pertaining directly to the stator, rotor, bearings, or accessories although certain reports were the converse dealing with non-applicable conditions and therefore were omitted. In some instances applicable external effects were cited as the cause of failure and these events were classified accordingly. (Motor boundaries were defined in Section 1.3.)

4.1.1 Failure Data Assessment

Figure 4-1 depicts motor failures within the driver boundary for General Electric (GE), Westinghouse (West.), Babcock & Wilcox (B&W), Combustion Engineering (CE), and other NSSS vendors, proportioned with regard to reactor years. As shown by the legend the application equipment includes pumps, valves, and miscellaneous motor-driven items. Similarly Figure 4-2 illustrates the LER motor failure relationships that occurred due to external events or the driven equipment. Figures 4-1 and 4-2 indicate that BWR systems experience a higher valve motor failure rate than PWR systems.

Table 4-1 expands the within-boundary information provided by Figure 4-1 by relating the architect/engineer (A/E) to the NSSS supplier, and Table 4-2 allocates the total failures to specific plants and the corresponding utility company. Section A of Table 4-3 addresses outside-motor-boundary failures by linking pump, valve, and miscellaneous motors to MCC, pump, valve, and externally-imposed causes, and Table 4-4 a, b, c, & d detail the various external factors that contributed to the motor failures.

Table 4-5 provides the number of motor failures related to reactor status at the time of detection. Note that the majority of failures occurred when the reactor was in an operational mode.

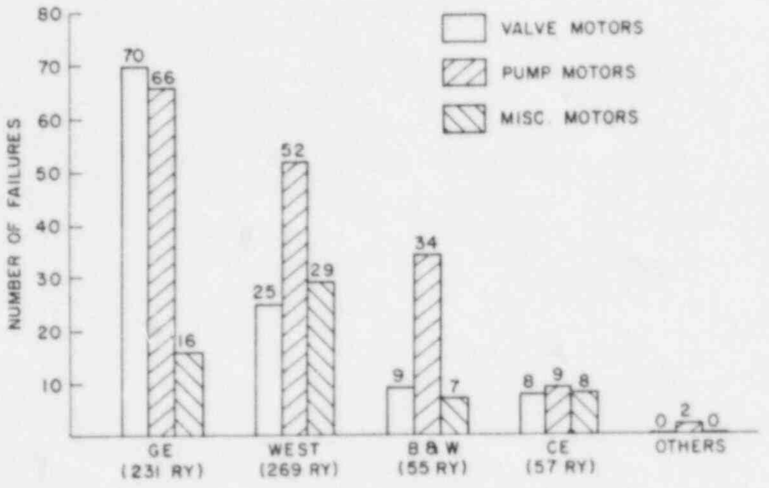

Figure 4-1: Within-Motor-Boundary Failures (LER DATA: 1974-1983)

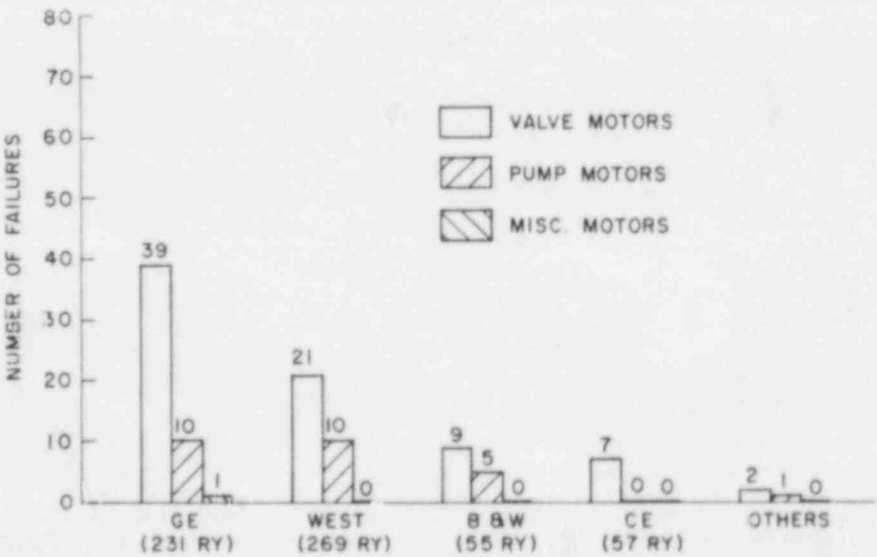

Figure 4-2: Outside-Motor-Boundary Failures (LER DATA: 1974-1983)

Table 4-1: NSSS/AE (Within Boundary) Motor Failures
(LER DATA: 1974-1983)

	GE(25)*	WEST.(27)	B&W(9)	CE(8)	Total
AEP (2)*	--	3	--	--	3
Bechtel (22)	36	8	17	19	80
Burns & Roe (3)	12	--	5	--	17
Duke (3)	--	9	20	--	29
Ebasco (4)	8	7	--	2	17
Gibbs & Hill (1)	--	--	--	3	3
Gilbert/Common. (3)	1	3	8	--	12
PSE&G (1)	--	9	--	--	9
Pioneer (3)	--	6	--	--	6
Niagara Mohawk (1)	4	--	--	--	4
Sargent & Lundy (7)	29	13	--	--	42
SSI (2)**	25	--	--	--	25
Stone & Webster (9)	10	36	--	1	47
TVA (4)	21	4	--	--	25
UE&C (4)	6	8	--	--	14
Totals	152	106	50	25	333

*( ) indicates the total reactor units built by the company

** in collaboration with Bechtel

Table 4-2: Utility/Plant Within-Motor-Boundary Failures (>5)
(LER Data: 1974-1983)

Utility	Plants	Failures	Reactor Years
Arkansas P&L	Arkansas 1&2	10	14
Boston Edison	Pilgrim 1	9	10
Carolina P&L	Brunswick 1&2	9	15
	Robinson 2	8	10
Commonwealth Edison	Dresden 1,2&3	17	25
	Lasalle 1	2	1
	Quad Cities 1&2	8	20
	Zion 1&2	4	20
Duke Power	McGuire 1	9	2
	Oconee 1,2&3	23	29
Georgia Power	Hatch 1&2	26	14
Metropolitan Edison	Three Mile Is 1&2	10	10
Nebraska Public Power	Cooper Station	7	9
Pacific Gas & Elec.	Humboldt Bay	5	3
Philadelphia Electric	Peach Bottom 2&3	11	19
PASNY/Niagara Mohawk	Fitzpatrick	10	8
Public Svc. Elec & Gas	Salem 1&2	12	9
TVA	Browns Ferry 1,2&3	21	26
	Sequoyah 1	6	5
Toledo Edison	Davis Besse 1	10	6
Virginia Electric & Power	North Anna 1&2	8	8
	Surry 1&2	17	20

Table 4-3: Outside Motor Boundary Failures
(LER Data: 1974-1983)

(A)	Pump Motors	Valve Motors	Misc. Motors
MCC Related	14	11	1
Valve Related	-	37	0
Pump Related	10	-	0
Miscellaneous	2	30	0

(IPRDS Data: 1974-1981)

(B)	Plant 1 Pump Motors	Plant 1 Valve* Motors	Plant 2 Pump Motors	Plant 3 Units (Pump Motors) 1	Plant 3 Units (Pump Motors) 2	Plant 3 Units (Pump Motors) 3	Plant 4 Pump Motors	Plant 4 Valve Motors
MCC Related	100	29	28	23	8	7	35	15
Valve Related**	-	107	-	-	-	-	-	34
Pump Related**	49	-	47	41	23	28	86	-
Miscellaneous	-	-	1	8	2	2	-	-

*Packing related failures (consisting of 50% of the total) are not included.
**Includes the control system part of the respective component design.

Table 4-4(a): Typical Outside-Motor-Boundary Failure Causes

TYPICAL MOTOR CONTROL CENTER (MCC) FAILURE CAUSES

- Sticking interlock in MCC components
- Faulty MCC components
- Faulty MCC starter control mechanism
- Overload relay/breaker trip
- Fuse blown
- Loose connection
- Low power supply voltage
- Breaker linkage misalignment/repair

Table 4-4(b): Typical Outside-Motor-Boundary Failure Causes

TYPICAL VALVE FAILURE CAUSES

- Wear of timing gear teeth
- Jammed valve/stuck plunger
- Solenoid valve malfunction
- Tight packing/valve seating
- Design deficiencies
- Corrosion of valve stem/disc
- Torque switch failure or wrong adjustments
- Excessive grease in operator
- Lodging of valve wedge between valve seats
- Valve bolts failed
- Limit switch out of adjustment
- Loss of seals and gaskets
- Back-seating
- Lights/position indicator

Table 4-4(c): Typical Outside-Motor-Boundary Failure Causes

TYPICAL PUMP FAILURE CAUSES

- Degraded gaskets
- Wear of pumps cause excessive vibrations
- Steam/water leak into valves
- Seized/degraded bearings
- Jammed impeller on housing
- Float/level failures
- Control switch failures/adjustments

Table 4-4(d): Typical Outside-Motor-Boundary Failure Causes

TYPICAL MISCELLANEOUS FAILURE CAUSES

- Inadvertently bumping the breaker trip switch
- Administrative deficiency
- Blown fuse
- Motor voltage ratings are low
- Wrong grade limit switches/torque switches
- Undersized overload heater installations
- Flood damage
- Fans, turbines, compressors, chart indicators, etc.
- Supporting structures

Table 4-5: Motor Failures/Reactor Operating Status
(LER Data: 1974-1983)

	Valve Motors	Pump Motors	Misc. Motors
81-100% power	39	68	31
21-80% power	11	28	7
0-20% power	35	34	14
Test	12	12	0
Refueling Outage	5	11	2
Unknowns	10	10	6

Basic conclusions drawn from the LER sort which relates to safety systems alone are as follows:

- For PWR Systems, pump-motor failures within the boundary significantly exceed valve-motor failures.
- For BWR Systems, pump-and valve-motor within the boundary failures are nearly equal.
- The number of failures attributable to effects within-the-boundary are significantly greater than those outside-the-motor-boundary.

4.1.2 Correlation With Utility Maintenance Programs

After completing the review of motor operating experience using the LER system, it appeared that the motor failures tended to occur much more frequently at certain plants and certain utilities. Since the EPRI study[1] also found that motor failures were dependent on the generating station or utility, it was decided to investigate the hypothesis that the number of motor failures were related to the quality of the maintenance program at a given utility. Ranking the quality of the maintenance program at particular utilities and sites is somewhat subjective and sufficient data is lacking. The NRC however, has performed a Systematic Assessment of Licensee Performance (SALP) of each utility annually since 1980. The SALP is an integrated NRC staff effort utilized to collect available observations and to evaluate licensee performance based on those observations, with the objective of improving the NRC regulatory program and licensee performance, and is described in detail in the NRC Manual, Chapter 0516. SALP evaluates licensee performance in a number of functional areas, one of which is maintenance. Each area is assigned a numerical value from 1 to 3. Although the judgement as to what merits a 1, 2 or 3 has varied over the years, generally the ratings are based on a scale as follows:

1 - Above Average Performance
2 - Average Performance
3 - Below Average Performance

To test the hypothesis that failure rates depend on utility maintenance programs, failure data for utilities with multiple sites and corresponding NRC SALP maintenance ratings were reviewed in detail. Both reviews tended to support the conclusion that the motor failure rates did depend on utility maintenance programs.

First of all, for utilities with multiple sites, generally if one site had a high failure rate for motors and a below average SALP rating, then the other sites operated by that utility also did. Conversely, if one site had low failure rates and above average SALP ratings, then the other sites run by that utility also did. This is illustrated in the table below:

Utility	Site Avg. SALP Maint. Rating	Site # Motor Failures Per Reactor Year
Co. A	1.25	0.00
	1.75	0.10
Co. B	1.30	0.00
	2.00	0.10
Co. C	1.70	0.29
	2.00	0.10
Co. D	1.70	0.20
	2.00	1.00
Co. E	2.00	1.50
	2.00	0.95
Co. F	2.00	0.20
	2.00	0.40
	2.30	0.68
Co. G	2.00	0.80
	2.30	0.81
Co. H	2.30	0.80
	2.70	0.60

Furthermore, when the number of motor failures for these utilities with multiple sites was compared with SALP maintenance ratings, a similar trend appeared. It can be seen from Figure 4-3 that as SALP maintenance ratings improve, the number of motor failures decreases toward zero.

A similar study was made to determine the correlation between SALP maintenance ratings and number of motor failures for all plants in the country. The SALP maintenance ratings from 1980 to 1983 were obtained and averaged and were compared to the number of motor failures per reactor year at each site. A statistical regression was obtained as shown in Figure 4-4. As given above, it was noted that as the SALP ratings improve the number of failures tends toward zero.

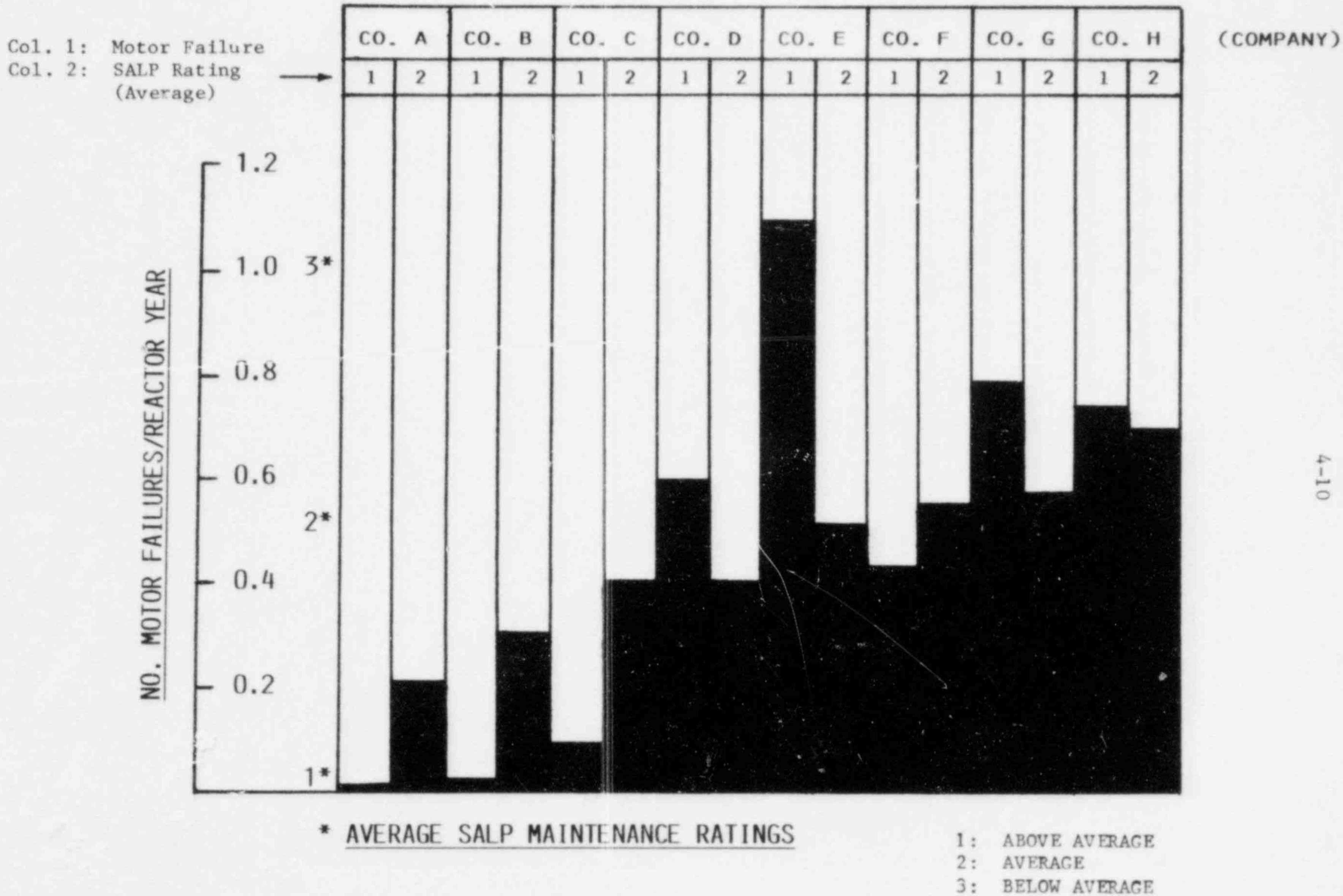

Figure 4-3: Motor Failures and SALP Maintenance ratings for eight (8) Utility companies with multiple plant sites (LER DATA: 1974-1983)

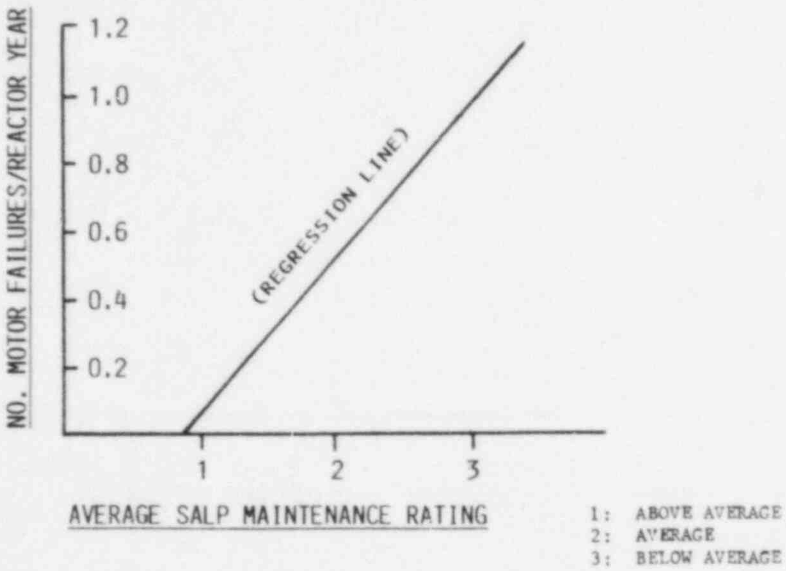

Figure 4-4: Motor Failure versus SALP Maintenance ratings (LER DATA: 1974-1983)

A qualitative review of the LER descriptions also shows a number of cases which seem to imply poor maintenance practices, e.g. repetitive motor cooler leaks, electrical termination failures, and motor bearing failures.

In drawing conclusions from the above data, one must be careful due to a number of limitations, namely:

1. The quality of the LER data base is not the highest (i.e., insufficient data, inaccurate failure categorization, incomplete failure reporting).
2. The SALP ratings are somewhat subjective.
3. The time periods involved for the LER review and SALP review are not identical.
4. The statistical correlation obtained, while good, does have a fair amount of scatter.

4.2 IPRDS REVIEW

IPRDS* data for the period 1974-1981 delineates motor-driven pump and valve failures for four nuclear power plants. Figures 4-5 and 4-6 indicate the relative proportions of the failures caused due to boundary internal and external effects. From these illustrations, it is evident that the motor

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* Note that LER and IPRDS are different data bases and some observations appear to be in disagreement with each other. Where significant, those observations are discussed in Chapter 6.

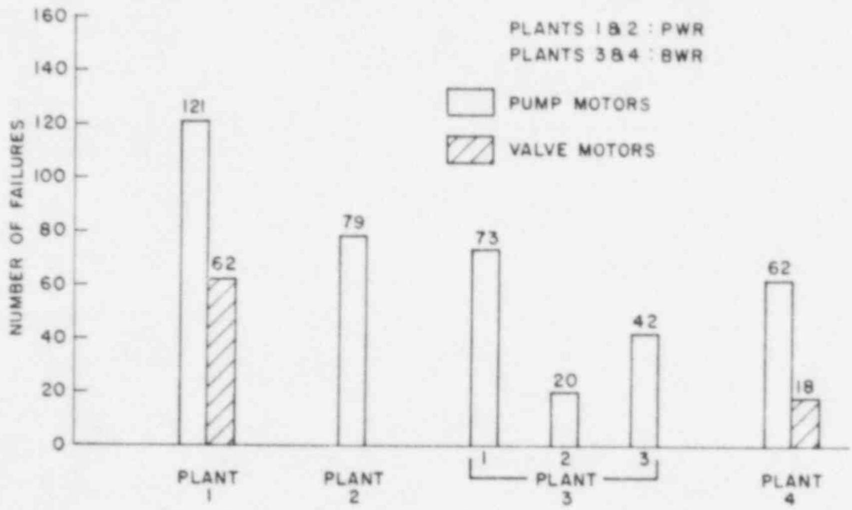

Figure 4-5: Within-Motor-Boundary Failures (IPRDS DATA: 1974-1981)

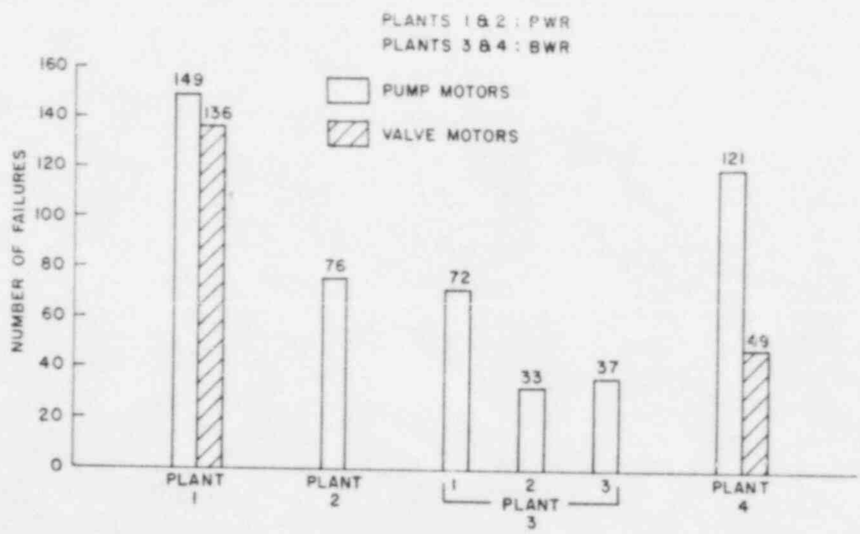

Figure 4-6: Outside-Motor-Boundary Failures (IPRDS DATA: 1974-1981)

failures are almost equally caused by internal malfunction of the motor components as well as by external effects (e.g., caused by the MCC). An itemization of failure causes induced by external effects obtained from the IPRDS data is given in Table 4-3 (B). The failures presented in Table 4-3 do not include motor degradation occurrences imposed by pump or valve seals and packing leaks although it was observed that nearly 50% of the IPRDS reported motor failures were caused by these and other moisture-related effects. As shown by Figures 4-5 and 4-6, valve motors are more susceptible to failure than pump motors to a significant degree.

Table 4-6 indicates that valve motors sized for operation on 6" lines and under are more likely to fail than others although the actual value of the data is questionable.* Furthermore, Table 4-7 provides evidence that suggests that small pump motors may be more prone to failure than large pump motors. Table 4-8 (A) outlines (pump) degradation or failure modes for the IPRDS plants in broad categories while Table 4-8 (B) addresses similar information for Plant 1 and plant 4 valve motors. Note that "failure to start" is an all encompassing description provided for numerous motor malfunctions without additional detail as to the actual failure cause or mechanism. Figure 4-7 classifies failures by catastrophic, degraded, and incipient severity levels. With the exception of those for Plant 4, motor failures were catastrophic which resulted in an absolute loss of required system function and operational readiness. As expected, a number of the reported failures occurred when the reactor was at power as shown in Figure 4-8.

Summarized observation from the IPRDS data review, which includes both safety and non-safety systems, indicate the following:

- Pump-motor failures are often control system and pump seal-related; whereas valve-motor failures are typically caused by valve leakage and mechanical malfunction.
- Continuous pump operation is less extreme duty for a motor than intermittent or infrequent running. (Reference Fig. 3-3)
- Vibration and moisture in-leakage are prime contributors and causes for pump and valve motor failure.
- Pump and valve motors are about equally likely to fail due to internal component degradation as well as due to external effects imposed by the MCC or application equipment.
- Small pump and valve motors apparently experience a large number of failures (however, the total population of these motors is unknown).
- Most pump and valve (reported) motor failures are catastrophic.
- Although a large number of the failures reported were independent of reactor status, most failures were detected while the reactor was in operation.

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* It is suspected that the data for Plant 4 is incomplete, and for the IPRDS sort made available for this study, no valve failure data in relation to pipe size were provided for Plants 2 & 3. In any instance where IPRDS data for Plants 1, 2, 3, or 4 are not listed in a table, it can be assumed that the information either was unavailable or is non-existent.

Table 4-6: Motor Failures/Valve Sizes
(IPRDS Data: 1974-1981)

	Plant 1	Plant 4
2" & under	30	2
3" to 6"	20	3
8" to 12"	2	12
14" & over	10	1

Table 4-7: Motor Failures/Pump Horsepower Ratings
(IPRDS Data: 1974-1981)

Pump Horsepower	Plant 1	Plant 2	Plant 4
1 - 9.99	51	27	9
10 - 100	33	30	2
>100	35	22	12
Unknown	2	-	39

Table 4-8: IPRDS Failure Modes (1974-1981)

(A) Pump Motors	Plant 1	Plant 2	Plant 3			Plant 4
Unit(s)	1	1	1	2	3	1
Fails to start	34	1	6	1	11	5
Fails while running	22	25	28	8	12	22
Low output	8	6	28	4	8	9
Vibration	20	7	9	4	7	11
Leak	10	7	-	1	-	4
Other (trips, bearing failure, wet winding, indicating light, & alignment)	27	33	2	2	5	11

(B) Valve Motors	Plant 1	Plant 4
Unit	1	1
Fails to operate	30	-
Spurious operation	2	-
Pluggage	-	-
Leaks through	1	5
Fails to reclose	1	-
Improper operation	10	7
External leakage	14	6
Faulty indication	2	-
Chattering	2	-

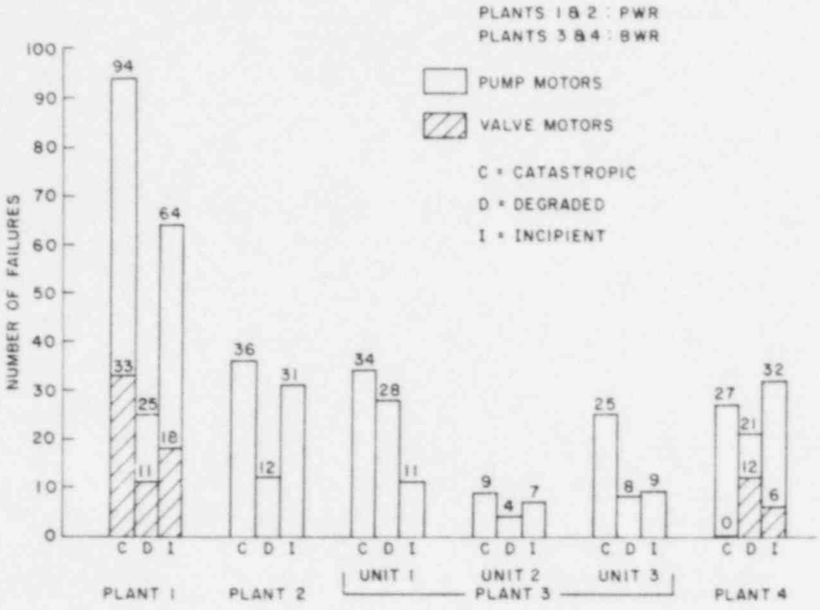


Figure 4-7: Motor Failure Severity (IPRDS DATA: 1974-1981)

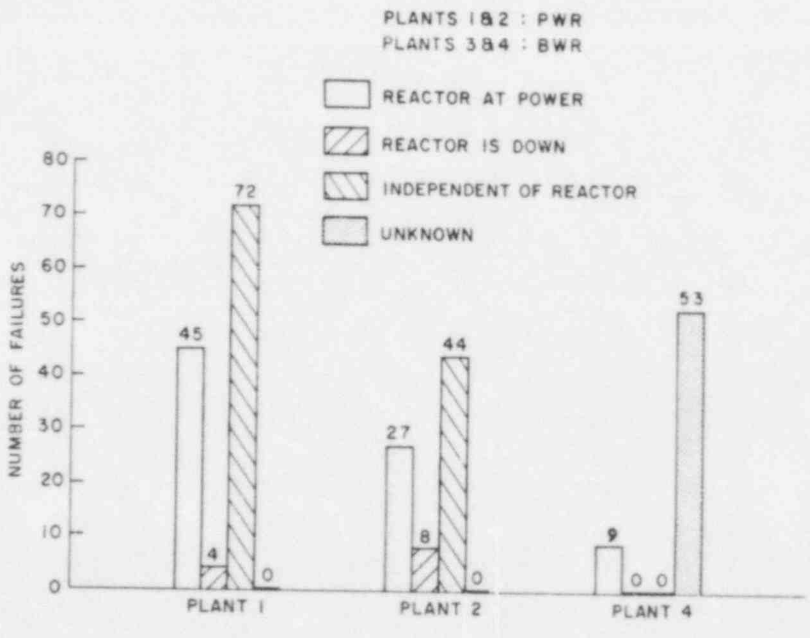


Figure 4-8: Pump Motor Failures and Reactor Status (IPRDS DATA: 1974-1981)

4.3 BALANCE OF DATA REVIEW

Other data sources were surveyed in order to further assess typical motor failure modes, mechanisms, and causes. While NPRDS information required cataloging and organization, the balance of the information utilized was available directly from reports and studies already presented in useable form.

Figure 4-9 provides the reactor status of the various plants included in the 1974-1982 NPRDS data base at the time of motor failure. Figure 4-10 indicates the manner in which failures were detected. As shown by the chart, most failures are discovered at the time of a severely degraded condition or following catastrophic malfunction while others are uncovered during surveillance, inspection, and testing. Table 4-9 itemizes the failures by motor voltage ratings (ranging from 300-4999V ac) and provides a complete listing of failure modes from NPRDS data for squirrel cage polyphase induction motors. As with the IPRDS failure information, "failure to start" is the only description provided for many of the motor malfunctions. NPE data presented in Table 4-10 also includes a significant number of failures (356) without any mode, mechanism, or cause detail for BWR and PWR plant but does delineate typical sub-component failure statistics (which encompass stators, rotors, bearings, and accessories). Note that in Figure 4-10, some failures are included in more than one detection category.

Failures for 100 hp and larger motors compiled by EPRI[1] are given in Table 4-11, and the various modes are weighted as percentages of the total number of failures. Stator (insulation) grounding is indicated as the highest percentage cause of the failures; but as with the other data sources utilized, unspecified causes which are therefore unknown comprise a major portion of the total (35.9%). Also, bearing-related problems are shown to have a significant impact on motor reliability contributing 24.1% to the total failures. Table 4-12, developed from the EPRI survey for generating units placed in service between 1969 and 1979, also classifies bearing-related and stator-related failures as the predominant types for 100 hp and larger motors. Data for motors rated at not less than 250 hp and the associated failure information is included in the 1982 EEI Trouble Report Summary[3] and is outlined in Table 4-13. Of the 66 failures reported, the majority occurred on 5000V ac, squirrel cage, drip-proof (indoor) motors. Design and workmanship (i.e., human factors) were the primary cause of these failures. Additionally these failures occurred while the motors were in operation, and were primarily driving pumps and fans. The EPRI study further addresses failures in terms of human factors as shown in Table 4-14. Although design flaws are indicated as the predominant contributors to the failures, it must be realized that the unspecified failure category can include a portion of any or all of the other categories such as design, workmanship, misoperation, misapplication. Basic conclusions from the balance-of-data review include the following:

- Motor failures predominantly occur while the system is in operation.
- 79% of the failures are detected either by operational abnormality or during surveillance testing or by routine surveillance.
- Stator grounding and bearing-related problems contribute significantly to motor failures.

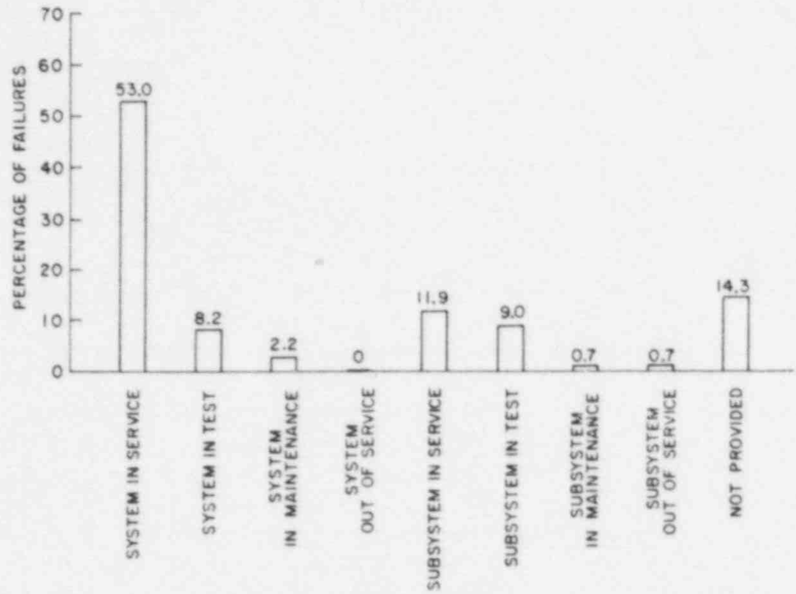


Figure 4-9: Plant System Status at the Time of Motor Failure (NPRDS DATA: 7/74-12/82)

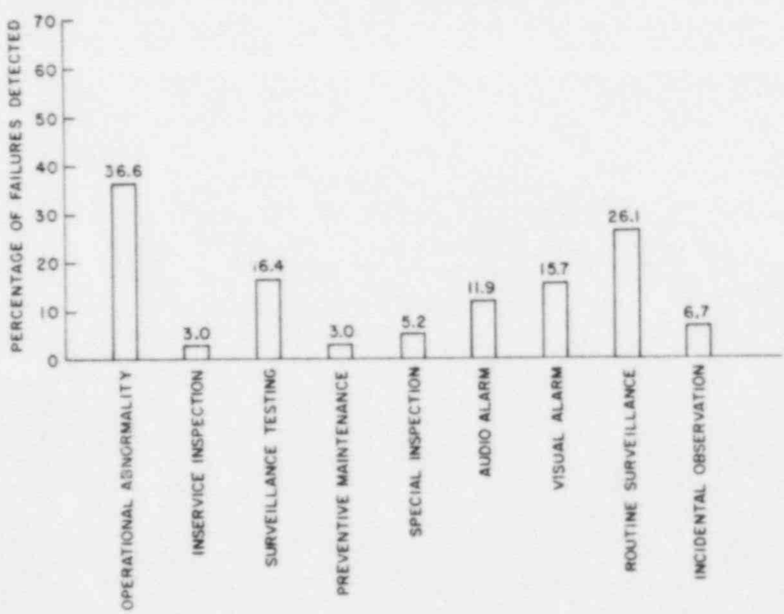


Figure 4-10: Motor Failure Detection Methods (NPRDS DATA: 7/74-12/82)

Table 4-9:
NPRDS Motor Failures for the Period 7/74-12/82[9]
(Squirrel Cage Polyphase Induction Motors)

FAILURE MODES	300-499 VAC No. Failures	300-499 VAC No. Units*	2000-2599 VAC No. Failures	2000-2599 VAC No. Units	3500-4999 VAC No. Failures	3500-4999 VAC No. Units
Leakage					5	4
Crack	1	1				
Physical Distortion	5	2	5	1	4	4
Physical Displacement					1	1
Collapse	1	1				
Fracture/Break	1	1				
Won't Start/Move	20	7			2	2
Won't Stop	1	1			1	1
Won't Close	1	1				
Won't Open	2	1				
Out of Limits					3	2
Out of Adjustment	1	1			1	1
False Response	1	1			1	1
Won't Operate Per Demand	1	1				
Overheating	1	1	2	1	3	2
Vibration	1	1				
Noise					1	1
Contamination	1	1				
Short					1	1
Short to Ground	1	1				
Other	1	1			3	2
Total	40	11	7	1	26	12

* Units represent reactor units

Table 4-10: Nuclear Power Experience (NPE) Failure Data[10]

Components	Number or Failures BWR	PWR
Air Deflector	1	0
Bearings	16	48
Brushes	6	0
End Bells	4	2
Fan	4	4
Insulation	17	8
Lube	3	10
Overload	15	14
Starter	5	25
Vibration	5	5
Windings	29	32
Failures (General)	58	45
Total	163	193

Table 4-11: Failure Modes for Motors 100 HP and Larger (EPRI Study, Reference[1])

	Percent of Total
Stator Frame	0.8
Insulation-GND	18.5
Insulation-Turn	3.7
Coil Connection	0.6
Loose Blocking	1.8
Line Cable	0.8
Stator Slot Wedges	1.3
Shaft	1.5
Bar Failure	3.5
Loose Iron	1.0
Balance Weights	0.6
Ball Bearing	4.9
Roller Bearing	2.3
Sleeve Bearing	9.7
Oil Leakage	4.1
Bearing Seal	2.3
Oil System	1.4
Thrust Bearing (V)	4.7
Thrust Bearing (H)	0.2
Accessories	0.5
All Others	35.9
	100.00

Table 4-12: EPRI Survey - 100 HP and Larger Motor Failures[1]
(Generating Units Went into Service 1969-1979)

Bearing Related	41%
Stator Related	37%
Rotor Related	10%
Accessories	12%

Table 4-13: EEI Trouble Report Summary[3]
(For Motor Sizes 250HP and Larger)

	No. of Failures Out of 66 Reported
Squirrel Cage	59
5000 V	59
Drip-proof Enclosures	49
Indoor	56
Pump Motors	34
Fan Motors	18
Design (Manufacture)	36
Workmanship (Manuf. & Instal.)	29
Found While in Operation	53
Manufacturing Defects	13
Operational Failures	53

Table 4-14: Failure Causes (EPRI Study, Reference[1])

	Percent of Total
Design	19.5
Workmanship	13.3
Misoperation	10.2
Misapplication	6.8
Not Specified	50.2
	100.00

4.4 FAILURE MODES/MECHANISMS/CAUSES AND FREQUENCY

Table 4-15 is a culmination of the review and analysis of operating experiences, data banks, applicable reports, motor design and materials of construction, and consideration of the existing stresses. The table classifies the failure modes, causes and mechanisms for various motor components. It also indicates whether the component is susceptible to aging, whether it has an aging seismic correlation, and identifies the failure category. The probability of occurrence was determined subjectively based on expert opinion. Terms used to organize and classify the information presented in the table are defined below:

- **FAILURE MODES** indicate the basic manner in which the motor failed to start on demand or ceased to continuously operate.
- **FAILURE MECHANISMS** detail the materials and parts of the motor affected by degradation thereby causing the occurrence of the malfunction.
- **FAILURE CAUSES** explain the actual malfunction by describing the manner in which motor materials and parts jam, crack, separate, shrink, burn, (etc.) and therefore create the failure mechanism.
- **AGING** and **AGING-SEISMIC CORRELATION** categories indicate whether the failure mode, mechanism, and cause are directly attributable or potentially susceptible to time-related effects and externally-induced vibrational effects, respectively.
- **FAILURE CATEGORY** classifies the underlying or root cause of the motor malfunction.
- **PROBABILITY OF OCCURRENCE** (subjectively) indicates the likelihood of the corresponding failure to occur based on the characteristics of the failure cause, and is assigned either a high, medium, or low probability.

It should be noted that the information presented in Table 4-15 is generic and thus applies to motors of various sizes and ratings in many environmental and industrial settings. The most significant failure modes are viewed as those having the highest probability of occurrence and the greatest potential impact on motor dielectric, rotational, and mechanical integrity.

As previously noted, most data base reported motor failures are prompted by catastrophic losses of functional integrity as opposed to a minor condition of degraded performance. From the various modes, mechanisms, and causes it can be observed that the adverse effects causing component wear and material deterioration are very much time-related and rarely initiate immediate motor failure. The occurrence of various failure modes is dictated by conditions ranging from human factors-related events to environmental effects. Several basic contributors to motor failure can be determined from the data review based on intermittent versus continuous operation and reactor load status conditions. Although time provides an index for anticipating motor degradation it is apparent that other factors, such as the number of motor starts, is highly significant.

Table 4-15: Motor Failure Modes/Causes/Mechanisms

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
STATOR-CORE (Consists of insulated laminations & locked bars)	Loose Laminations	Loosening of stator laminations stackings (made with notches lined up to make slots for receiving the winding) or locking bars which are processed into notches spaced around the periphery.	Improper assembly of laminations or mounting of locked bars. External dynamic forces caused by vibration or misalignment.	No	No	Workmanship	Low
	Lamination overheat (poor electrical efficiency)	Shrinkage of Lamination Insulation (Coating of alkaphos on both sides & baked)	Thermal degradation & torsional forces during cyclic loads & motor operations.	Yes	No	Wear	Low
	Loose Stator Assembly	Failure of locking devices of the stator punching assembly into the frame or casing. (pressed or tack welded)	Material shrinkage or large rotational/vibrational forces.	No	No	Workmanship	Low
- WINDINGS (consist of copper conductor, slot liner for ground insulation, turn/phase insulation, slot insulation and end rings)	Loose windings	Wedges came out of the slot, blockings came out of the windings or coil ties came loose.	Thermal degradations, vibrations causing embrittlement & reduction in strength.	Yes	Yes	Wear	Medium
	Stator Insulations (turn to turn, phase to phase, phase to ground)	Winding short or overheating leading to burning of stator.	Thermal & radiation degradation of insulation, water/steam leak into the motor coil, or loss of integrity of insulation by cracking.	Yes	Yes	Wear (or degradation)	High

* Susceptibility to aging and aging-seismic correlation are based upon a general consensus on a certain failure mode for any type and size of a motor. Note that for certain classes of motors (such as small induction motors) these statements may not be applicable.

Table 4-15: Motor Failure Modes/Causes/Mechanisms (Cont'd.)

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
STATOR-WINDINGS (Cont'd.)	Stator Insulation (Cont'd.)	Stator Winding Overheating (Cont'd.)	Excess current in winding due to larger loads or too frequent starts.	No	No	Misoperation	Low
			Faulty nylon wrap around each last phase to absorb the resins during impregnation leading to passage for entering water/steam into the coil.	No	No	Workmanship	Low
	Ending or lead cable	Coil connections to end rings and the line cable loose.	Thermal degradation or improper ties during manufacturer.	Yes	No	Workmanship/ Wear	Medium
ROTOR-CORE (Consist of insulated laminations)	Lamination over heat	Insufficient air cooling	Due to rotational centrifugal forces, faulty design of cores in the air ducts and their spacing fingers.	NO	No	Workmanship Maintenance	Low
		Insulation damage (less critical from the dielectric standpoint since voltage generated per-inch of stack length is inversely proportional to speed).	Thermal, Radiaton, & Humidity could cause insulation shrinkage.	Yes	No	Wear	Low
- CAGE (Consists of windings, commutator for DC motor, squirrel cage bars and fingers)	Armature winding & insulation	Winding short or overheating of rotor Coils leading to burnt motor	Thermal/Radiation degradation of insulations. Water/steam leak to short coils.	Yes	Yes	Wear Maintenance	Medium
			Excess current due to too many starts, or cage winding failure due to jogging & poor brazing.	Yes	No	Wear Misoperation Workmanship	Low

Table 4-15: Motor Failure Modes/Causes/Mechanisms (Cont'd.)

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
ROTOR-CAGE (Cont'd.)	Commutator Contact	Loose brush connection to the commutator coil for DC motor, synchrous & wound rotor motors.	Normal wear out of carbon brushed or relaxed spring load in the brush holder mechanisms.	Yes	Yes	Wear	Medium
		Lack of cleaning dirt, foreign particles or oil deposits.	Dirt/moisture on the commutator & their oxidation effects.	Yes	No	Maintenance	Medium
- SHAFT (includes coupling & balance weights)	Misalignment	Pulsating pressure on the bearing supporting the rotor shaft	Misalignment between motor and load shafts would impose heavy pressure followed by a relaxing of the pressure.	No	No	Maintenance	Medium
	Vibration	Unbalanced rotors	Loss of balance weights	No	No	Maintenance	Low
		Broken couplings between the load and motor shaft.	Excessive wear or misalignment at the coupling.	No	No	Maintenance	Low
			Frame distortion or shift in the rotor's center of gravity.	NO	No	Maintenance	Low
	Coupling Keys	Sheared Keys	Large mechanical torque on the coupling due to jammed pump. Also defective motor bearing or loss of grease.	No	No	Misapplication	Low
BEARINGS (Sleeve, Ball or Roller)	Seized bearings	Lack of proper lubrication	No oil/lube in the bearing, deteriorated and contaminated lubricant, leak of oil, moisture/	Yes	No	Maintenance	High

Table 4-15: Motor Failure Modes/Causes/Mechanisms (Cont'd.)

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
BEARINGS (cont'd.)			water in the lube, or incorrect lubricant viscosity.				
		Corrosion of bearing (especially sleeve bearings)	Exposure to air & water for a long period in case of intermittently used motors.	Yes	No	Misapplication Maintenance	Low
		Damaged oil sling ring and bearing housing	Brass powder in bearing housing and in oil reservoir from worn out bearing oil sling ring.	No	No	Maintenance	Low
		Flooding of bearing housing	Pump seal leak, cooling system leak, pit flooding could jam the bearing.	No	No	Maintenance	Medium
	Overheated bearings	Improper lubrication or bearing insulation damage.	Loss of coolant or lubricant, damage in the bearing insulation which enhance the circulation of bearing current. Excess lubricant would be churned by the bearing generating high temperature and pressure.	Yes	No	Maintenance	High
		Improper design of type of bearing for the loading. Excessive axial shaft movements.	Thrust on bearing could be larger than the design value/poor alignment of shaft	No	No	Misapplication	Low
		Cooling pump & accessories	Insufficient cooling of bearings.	No	No	Maintenance	Low

Table 4-15: Motor Failure Modes/Causes/Mechanisms (Cont'd.)

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
BEARINGS (Cont'd.)	Bearing Vibrations	Lack of lubrication or misalignment	dried or leaked lubrication from the housing or rotor-stator interference causing scoring on the stator surfaces.	No	No	Wear	Low
	Bearings/ Housing Fracture	Cracking of the bearings, housing and end plates	Lack of lubrication, vibration of motor asembly, electrical pitting, machine chips or foreign objects inside the bearing which could wear indentations in races where the balls/rollers are touching.	Yes	No	Maintenance	Medium
			Excessive vibration/ flawed material on the bearing housing design without the copper ring around the bearing.	No	No	Maintenance	Low
ACCESSORIES - MOUNTING	Bolts, Flanges, or Housing Failures	Sheared bolts, cracked flanges or housing	Large mechanical external forces, vibrations due to improper installation. Corrosion of bolts due to atmospheric conditions.	Yes	Yes	Maintenance	Medium
- CASING or FRAME	Casing cracked	Excessive Vibration or bearing failure	Improper installation, flaw in material, fatigue.	No	No	Workmanship	Low
	Overheated frame	Heat generated inside the motor due to normal operating	Improper ventilation system design or clogged up vents.	No	No	Maintenance	Low

Table 4-15: Motor Failure Modes/Causes/Mechanisms (Cont'd.)

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
CASING or FRAMES (Cont'd.)	Dowel pins between frames and end bells failed	Sheared dowel pins	Undersized pins or large vibrational forces can cause shear failure	Yes	Yes	Workmanship Misapplication	Low
ACCESSORIES - BRAKE COILS (MOV'S)	Burning of motor windings	Jamming of brake coil excited electrically	Overload the motor drawing large currents into the windings.	No	No	Misoperation	Low
- AIR FILTERS & SCREENS	Overheating motor	Clogging the vents or air path	Improper ventilation of motor by a concentration of contaminants environments.	No	No	Maintenance	Low
- CONDUIT BOX	Leak	Leads exposed to the outside environment (temp., press. & humidity)	Improper seals of the coverplate/vibration/ flimsey mounting screws.	Yes	No	Maintenance	Low
	Poor electrical lead contact	Lack of cleaning dirt, foreign objects or oil deposits preventing proper connection.	Swelling of motor leads caused by residual oil, dirt/moisture and their oxidation effects.	Yes	No	Maintenance	Medium
	Broken or loose leads	Inadvertently bumping or pulling leads out of the box, improper installation	Human error or negligance.	No	Yes	Maintenance	Low
- SEALS & GASKETS	Leakage	Cracking or shrinking of Material	Heat, vibration, and radiation causing material embrittlement and depolymerization.	Yes	Yes	Maintenance	Medium

Table 4-15: Motor Failure Modes/Causes/Mechanisms (Cont'd.)

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
SPECIFIC ** PROBLEMS	Overcurrent in windings	Unknown	Use of oversized test instrument.	No	No	Maintenance	Low
	"Locked rotor" current	Unknown	Wrong or loose adjustment in the valve torque switch settings.	No	No	Maintenance	Low
			Broken valve gear mechanism or teeth	No	No	Wear	Low
	Burned or dead motor	Unknown	Excess of design duty cycle or valve seating to prevent leak in the stem area or shaft brushing froze.	No	No	Misoperation	Medium
	Disengaged motor	Unknown	Broken electrical connections in starting motor	No	No	Maintenance	Low
			Fuse Blown in MCC	No	No	Maintenance	Low
		Unknown	Solenoid valve hung up allowing for disengagement	No	No	Maintenance	Low

** Specific problems found in data base without any specific mode, cause or mechanism and also no specific motor component was identified.

Table 4-15: Motor Failure Modes/Causes/Mechanisms (Cont'd.)

Motor Component	Failure Modes	Failure Causes	Failure Mechanisms	Aging*	Aging-Seismic* Correlation	Failure Category	Probability of Occurrence
SPECIFIC PROBLEMS (Cont'd.)	Unknown	Low torque for the drive	Low winding resistance, damaged winding load, open circuit through overload heaters.	No	No	Manufacturers	Low
		Water/oil in the motor (flooding)	External source, ruptured oil resevoir diaphragm valve packings leak, environment.	No	No	Maintenance	Medium
	Inoperable motors	Damaged phase windings	Attributed to previous operation of the 3 phase motors in a single phase mode.	No	No	Misoperation	Low

4.5 PERFORMANCE OR FUNCTIONAL INDICATORS

During the operation of motors various parameters such as temperature, vibration, current, and voltage can be monitored and utilized to assess motor integrity. The performance or functional indicators serve to characterize the behavior of any electric motor. When normal values for these parameters are observed to adversely change, degradation, potentially leading to ultimate failure, may be occurring. Appropriate parameter performance can be linked to failure modes, mechanisms, and causes that are representative for all types of motors.

For the sucessful operation of a motor, three integrities, dielectric, rotational, and mechanical, need to be properly maintained. In each case the dominant failure mechanisms and associated motor components are identified based upon the operating experience data base and qualitative analyses of designs and materials. Typical aging related hazards which have influenced the perormance readiness of motors in various plant settings are then established. At this point of the study, both normal and accident stressor are considered. The failure effects caused by the plant stressors on the motor components are evaluated to select the functional indicators which can be used to monitor the integrity of the motor. These parameters will be further studied in the next phase of the NPAR study to identify the most significant ones and specifically how to monitor them.

Dielectric integrity (provided by the motor insulation system) is sensitive to performance hazards such as the environment, vibration, excess current, high voltage gradients, improper ventilation, and inadvertent spray of water/steam. The operating environment includes the temperature, humidity, radiation, chemicals, and contaminants of the exposed atmosphere. Motors inside of containment can be exposed to a harsher environment under accident conditions. Deterioration or loss of dielectric integrity can result in shorted and burned windings, overheating leading to burned out windings, excessive eddy current losses, corona or ionization of insulating materials causing insulation breakdown, and corrosion or contamination of contact points leading to poor electrial connections. These effects degrade motor performance and could lead to failure. Dielectric integrity is unique in that deterioration or loss of this property is usually underterminable by visual inspection and requires fairly sophisticated testing measures to reveal it. Operating parameters such as winding temperature, vibration signature, current signature, voltage gradient or corona effects, insulation resistance, power factor/loss factor, and polarization index for measuring insulation dryness are the functional indicators for dielectric integrity. Standards and guides used to measure these quantities are discussed in the next section. A more comprehensive selection of these parameters will be done in the second phase of this study.

Unlike the dielectric integrity, rotational integrity is a more physically apparent property of electric motors and therefore, it is more straight forward to assess and maintain. With the exception of the insulating system in the rotor assembly, the bearings and the lubricating systems are responsible for most dominant failures. Some large motor bearing housings contain an independant cooling system for dissipating heat from the bearing frictional energy. The primary failure stressors are excessive/insufficient lubrication, vibration, and improper cooling of bearings. Other hazards include spray or

leaking of water/steam in the bearing assembly, bearing insulation damage causing overheating, and other mechanical problems resulting from frozen bushing, contaminant deposits, excessive axial movement, and misalignment of rotor assembly. These hazards affect the bearing performance in terms of overheating, cracking, scoring, brinelling, corrosion, noise, jamming, shifting of rotor center of gravity, and tripping of accessories. The bearing assembly can be maintained in good condition by monitoring parameters such as lubrication condition, vibration signature, bearing or oil temperatures, bearing current losses, alignment of rotor assembly, clearances and speed-torque characteristics of the motor. Many of the bearing related failures can be avoided by an adequate bearing maintenance program. Operating experience has indicated that pump motors are more susceptible to such failures than motors in other types of applications.

Motor failures other than those mentioned above are categorized as mechanical failures and are attributable to all motor sub-components. Typical mechanical hazards include unwanted machine vibrations causing bolts, pins and welding failures, contamination and corrosion of certain metallic parts, seals and gasket degradations, improper adjustments and settings due to human errors, faulty components such as heaters, misapplication and misoperations, and commutator brush wear. These stressors can impair the mechanical ability of motors causing distortions and failures, poor connections, leaking oil or water from the lubricating or cooling systems, overloading and overheating components, and making the equipment potentially dangerous to accidental dynamic loads such as earthquakes. Based on this, the following functional indicators which can be monitored during the motor operating life, are: vibration signature, environmental conditions, corrosion, cracks, leaks and wear.

It should be reiterated that functional or performance indicators are primarily of interest for ensuring motor dielectric, rotational, and mechanical integrity. Detriments to these integrities can be induced by improper design, misapplication, insufficient maintenance, incorrect operation, and any other action that detracts from the ability of the motor to perform the required driving function.

5. DISCUSSION OF CURRENT METHODS, TECHNOLOGY, AND REQUIREMENTS

This section discusses in a general fashion those areas which will be examined in greater details in phase II of the NPAR study. Electric motor reliability is continuously being improved by advances in design, manufacturing standards, research, condition monitoring, and diagnostic testing. Chronic failure modes have been identified from the numerous types of motor malfunctions that have occurred; however, those failure mechanisms and causes related to aging are in many cases not fully understood. Various codes, standards, and guidelines have been developed for standardizing and enhancing motor design and testing for particular applications and also for environmentally qualifying motorized systems and associated equipment. The concept of aging versus service wear is not clearly distinguished in existing failure-related documentation and reports and the evaluation and determination of motor component fragility limits is not fully addressed in existing seismic-related guidelines. Thus, current methods, technology, and requirements should be expanded and improved to include all potential failure-related aspects of nuclear power plant electric motor operation.

This section seeks to review and preliminarily discuss existing motor designs and specifications including relevant standards, guides, and codes as well as manufacturer recommendations for ensuring reliability, and also inspection, surveillance, monitoring, and testing practices currently in use. The benefit and value of NRC experience, expert knowledge, and on-going research within the context of these areas is addressed as well.

5.1 DESIGN & SPECIFICATIONS

The design and application strategy for an electric motor drive requires consideration of both the functional objective and the operational environment. Included in these considerations must be an allowance for abnormal circumstances as needed to sustain excessive duty cycle and possible accident effects. In essence then, engineering criteria based on functional and operational requirements serve as the guidelines for motor design development.

General design and performance requirements typically addressed by the motor manufacturer include the following[35]:

- output horsepower required at each operating condition
- synchronous speed and number of windings (where applicable)
- normal voltage (including tolerance)
- minimum starting and running voltage
- phase and rotational direction
- frequency (including tolerance)
- load inertia
- driven equipment speed/torque (curve) - minimum & normal voltage
- maximum allowable time for load acceleration, or open/close, (etc.)
- temperature rise and method of measurement
- service factor
- insulation life/temperature class
- thrust requirements
- locked rotor current limit (in amperes or percent of rated current)
- type of motor

- type of enclosure required
- size of terminal and auxiliary enclosures
- interior and exterior finish (coating) requirements
- bearings: type, vent; drain plug, detectors, lubricant, (etc.)
- maximum reverse speed/torque curve (where applicable)
- surge protection
- current transformers
- space heaters
- winding temperature detectors
- type of ventilation and cooling (e.g., convection air; air-to-water heat exchanger)
- duty cycle
- vibration monitoring

The horsepower and corresponding voltage rating for a motor is dictated primarily by the application equipment load and the overall system configuration. MOVs are readily outfitted with an appropriately-sized motor based on the necessary opening and closing torque and time values, whereas pump and fan motors are rated for output between the minimum and maximum required flow at ambient as well as operating temperatures. Miscellaneous equipment (i.e., other than pumps, valves, and fans) are similarly motorized by addressing specific functional requirement parameters. Accident conditions are considered where applicable.

As an example, consider large motor design specifications for a Reactor Coolant Pump (RCP)[36]. The horsepower required by the RCP incorporates 125% load capacity as needed for start-up when the transfer fluid is cold. In effect then, proper rating selection requires that cold loop horsepower not exceed 125% of motor capability and that the hot loop horsepower not exceed 100% of motor capability. It is imperative that calculated torque ratings for the motor be adjusted to the same basis between the hot and cold conditions since the motor must always be capable of accelerating against the maximum torque load realized by the RCP. High reliability is of the utmost concern for this vital primary system motorized component and allowance must be made for extended periods between maintenance while the motor is subjected to considerable radiation (e.g., 33 x 10^6 Roentgens over the expected 40-year plant life), a typical ambient temperature of 50°C, 100% relative humidity, and even more extreme combined conditions which can include chemical spray in the event of a LOCA.

Similar considerations can be applicable for an MOV which typically utilizes a high-torque, high-slip, intermittent duty motor[37]. Valve actuator motors are commonly rated by torque as opposed to horsepower, and most specifications (e.g., National Electric Code [NEC], Section 430-7) require that motor rating be based on locked rotor torque. Manufacturers usually accomadate operating requirements by recommending 40% duty motors which serve to ensure that temperature limits will not be exceeded (i.e., predicted full-load torque will only be 40% of rated torque).

Since the selection of proper insulation for withstanding motor heating is a major concern, this area of design and specification is perhaps the most crucial for avoiding premature failure. System or component malfunction and persistent intermittent motor operation causes excessive current draw which

often results in high temperature excursions. The adverse effects of even normal levels of heating can promote the aging process; therefore, provisions are needed in the form of electrical protection to avoid under and overvoltages and excessive current during normal as well as abnormal operating and accident conditions and also to maintain adequate ventilation and cooling. Designers strive to minimize thermal loads by effectively dissipating heat via modes of conduction and convection. Small motors are typically ventilated and cooled by a non-airtight enclosure that may incorporate fins, whereas larger motors often require a more deliberate cooling medium system such as that provided by a heat exchanger. (Note that, from a seismic analysis point of view, the use of a tube bank apparatus complicates the motor model by introducing the likelihood for an additional source of induced vibration, and also tube leakage as well as other detrimental conditions potentially leading to motor failure can be imposed.) Certain relatively small motors that could normally be air-cooled are designed with heat exchangers due to rigorous duty and hermetic sealing requirements. Whether the cooling mechanism is specified for combating external effects or is based solely on the most effective means for counteracting heating loads, motor insulation class and the maximum allowable temperature-rise (reference Table 2-3) must be fully complemented in the design process to ensure that thermal loads can be continuously dissipated.

Starting current and torque represent the highest expected normal operating stressors for a motor of any size while locked rotor (stall) torques, insulation breakdown, as well as other eccentric duty cycle conditions must be anticipated. The actual running state of a motor usually does not impose excessive stressors. Therefore, failure is often the result of degradation caused by the environment and/or prior misoperation. While valve motors are poised for direct functioning in a strictly defined manner, pump motors must be designed for various configurations and operating conditions including overspeed protection against reverse rotations. As a case in point, an RCP motor (previously discussed) typically has the built-in capability to withstand rotation up to 25% overspeed in the forward and reverse directions as well as an accidental reversed-phase condition.

A variety of bearing types and associated lubrication systems exist for specification which are based on motor size, operating environment, and the overall required performance function. Common MOV bearings provided for maintaining rotational integrity generally do not require lubrication, whereas, large fan and pump motors are often equipped with self-contained systems having (motor-driven) lube oil pumps and oil-to-water heat exchangers supplied by plant service water.

Rotor and frame balance is essential for minimizing wear and thereby inhibiting catastrophic failure due to excessive vibration. Consequently manufacturers and designers seek to eliminate machine imbalance, lack of lubrication conditions, and the corresponding bearing degradation which can include spalling, abrasion, surface fatigue, fretting, brinelling, pitting, fluting, smearing, scoring, debris denting, fracture, and hot working[38]. The National Electrical Manufacturers Association (NEMA) has developed exhaustive criteria for motor dynamic balancing, bearing specification, and motor mounting, and these guidelines serve as the basic design standard for virtually all U.S. manufacturers.

Clearly the objective of the electric motor is to immediately and reliably provide rotational displacement of the driven equipment upon demand. Achievement of this function often requires an array of supporting components in addition to the stator, rotor, and bearings, and the quantity and extent of which is essentially dictated by the size of the motor. Therefore, accessories which include all supporting components (within the defined boundary) are essential to the basic motor for achievement of the driving action. Motor designs and specifications are less developed for these items than for other motor components, although NEMA, IEEE, ASME, and others address this equipment on a generic level. Accessories range from oil quantity and temperature indicators to heat exchangers, flywheels, space heaters, quick-disconnects, and terminal boxes, capacitors, and power (cable) leads. Despite the fact that many of these supplementary devices appear to be of minor importance to actual motor operation, it should be realized that degradation caused by aging and service wear or ultimate destruction caused by a seismic event could potentially result in total motor failure due to the loss of an accessory.

Engineering criteria as well as user operating requirements pertaining to duty cycle, maintenance, and system function must be considered in the design process for electric motors and particularly for those used in nuclear power plants. Adherence to state-of-the-art guidelines ensures standardized manufacturing and should also promote long-term motor reliability.

5.2 STANDARDS, GUIDES, AND CODES

Contemporary motor manufacturing technology and service methods are derivatives of the vast number of standards, guides, and codes established by NEMA, IEEE, ASME, ANSI, AFBMA, and others (note Appendix A). These documents have been developed for the purpose of providing standard methodology to the motor designer and operator. The recommendations and technical format of most of the guidelines have proven to be suitably generic for adaptation to nuclear power plant application. Those standards, guides, and codes intended mainly for accessory-type equipment must be interpreted in a safety-related motor context in order to adequately comply with environmental qualification and other regulatory requirements such as [ASME] N-stamp criteria for a vital motor heat exchanger piping system. The purpose of the review of existing guidelines is to establish the adequacy and suitability of the information in regard to maintaining operating reactor safety.

NEMA standards "define a (motor) product, process, or procedure with reference to one or more of the following: nomenclature, composition, construction, dimensions, tolerances, (personnel) safety, operating characteristics, performance, (manufacturing process) quality, rating, testing, and the service for which (the motor) was designed." This reference source has been compiled for the purpose of guiding designers with the proper selection and application of motors and the information is revised periodically as required for accommodating user needs and advances in technology. Those NEMA standards applicable to electric motors address design, operating performance, and testing methods suitably for machines in any industrial setting and are appropriate for many nuclear power plant motorized system considerations. The testing guidelines offered by NEMA standards are basically inclined towards assessing motor dielectric integrity.

Certain IEEE standards (Appendix A) are rigorously inclined towards motor testing in general (e.g., IEEE-112, 113, 114, 115) as well as for evaluating dielectric integrity (e.g., IEEE-429, 433, 434), and for otherwise maintaining machine reliability (e.g., IEEE-56). The IEEE objective is distinct from NEMA in that testing and integrity evaluation is essentially focused on in-service motor operation versus design stage considerations. Selected IEEE standards are specific to nuclear power plant requirements including equipment qualification (e.g., IEEE-323, 334, 344).

AFBMA guidelines provide information suitable for nuclear power plant motor bearing design aspects (and to some extent, for motor operational aspects) and obviously are germane to rotational integrity considerations (e.g., ANSI/AFBMA 11-1978). As with NEMA and other related standards, the AFBMA information is pertinent to assessing and ensuring motor reliability even though no particular focus is directed toward the conditions and requirements unique to nuclear power plants. However, motor failure due to bearing-related causes induced by cyclic fatigue, inadequate lubrication, and numerous other conditions can be evaluated and circumvented based on these standards. During the design stage, calculation of rating life (based on the guidance of AFBMA for the various bearing types) serves to predict the expected functional life of the bearing assembly which implies the expected service life of the motor. While the objectives and purpose of the AFBMA standards for bearings parallel those for other motor components, the unpredictable (i.e., human-factor-related) and esoteric (i.e., aging and/or seismic-related) variables known to contribute to and sometimes cause motor failure are again not specifically addressed.

Table 5-1 organizes the various IEEE, ANSI, and AFBMA standards by categories of applicability, and Table 5-2 links specific motor types with certain corresponding IEEE standards. In addition to NEMA, IEEE, ANSI, and AFBMA, another source of pertinent engineering and testing information for the motor manufacturer and licensee is ASME Boiler and Pressure Vessel Code, Section XI which delineates nuclear power plant in-service inspection and testing procedures primarily for pumps and valves.

Current BWR and PWR Technical Specifications (Tech Specs) incorporate mandatory provisions for in-service inspection and testing activities that are primarily in accordance with ASME Section XI. Of relevance for assessing motor degradation is the requirement for on-going testing of safety-related pumps and valves. ASME Section XI pertains to the conduct of physical diagnostics while the motorized apparatus is either in the standby or running mode versus disassembled and de-energized. Due to the nature of these conditions, the terms of ASME Section XI are applicable mainly for assessing rotational and mechanical integrities since dielectric properties are effectively indeterminable while the motor is in service.

Surveillance, testing, and inspection requirements for ASME Code Class 1, 2, and 3 components are mandated by 10 CFR 50.55(a). Tech Specs dictate operational limits, and by incorporation of ASME Section XI provisions, the frequency for in-service inspection. While the purpose of the procedures is to verify equipment operability, the detection of motor degradation can become a coincidental by-product of the evaluation process. (Further consideration of the applicability of ASME Section XI to the detection of motor aging is given

Table 5-1: ANSI/IEEE/AFBMA Standards Classifications-Specific or Relative to Electric Motors

Standard	Temperature	Insulation	Speed	Sound	General	Bearings
IEEE	1	56	121	85	58	
	98	62	251		66	
	101	68			112A	
		95			113	
		117			114	
		118			115	
		275			116	
		286			119	
		304			120	
		429			252	
		432			288	
		434			290	
		522			303	
					323	
					329	
					334	
					344	
					421	
					649	
ANSI/IEEE		43			4	
		99			67	
		433			86	
					100	
					112	
					492	
					C50.10	
					C50.13	
					C50.14	
					C50.41	
ANSI/AFBMA						9
						11
						13

Table 5-2: Selected IEEE Standards and Corresponding Motor Types

IEEE Standard	Induction	Synchronous	Direct-Current
56	X	X	
58	X		
66			X
85	X	X	X
86	X	X	
95	X	X	
112A	X		
113			X
114	X		
115		X	
121	X	X	X
252	X		
288	X		
304			X
329		X	
421		X	

in Section 5.4.). It is worthwhile to note that, within the context of Tech Spec requirements, a possibility exists for imposing excessive duty cycle-related stressors on a motor. For example, consider the typical (PWR) required provision for maintaining a boration flow path from the safety injection tank to the main coolant system via the charging pumps whenever the plant is operating in Mode 1. If for any reason difficulty is experienced in establishing or maintaining this flow path, the operator may elect to exceed the normal capability of an equipment item such as an MOV. Once the boration flow path limiting condition for operation has been satisfied, and if the MOV has apparently not been adversely affected, it is possible that subsequent routine valve stroking and maintenance will not detect any resulting loss of motor dielectric integrity that could have occurred. In effect then, the operational strength and reliability of the MOV may have been altered by this service wear condition to the extent that stator insulation aging will be accelerated.

5.3 MANUFACTURER RECOMMENDATIONS

The design, production, operation, and service of any electric motor requires thorough consideration of all required functional aspects for ensuring dependability. With the development of the environmental and seismic qualification requirements for safety-related Class 1E components, the motor manufacturer has been required to address and document more performance and reliability parameters than ever before.

Of particular concern to the motor designer/manufacturer is the driven equipment required function, the corresponding duty cycle, and the specific installed plant location including whether the motor will be located inside or outside of containment. On the basis of the aforementioned as well as on the applicable requirements of NEMA, IEEE, ANSI, ASME, and AFBMA, production specifications are developed for the type of drive hardware (e.g., direct, belt, hydraulic coupling) and for the materials and tolerances for the maximum predicted starting voltage and torque. Additional considerations are given for phase, frequency, maximum allowable (or minimum required) time to accelerate the load, predicted temperature rise, and methods for critical value measurement and continuous monitoring. Therefore, the information and data typically supplied to the motor user mainly in the form of recommendations and warranty requirements usually include the following[36]:

- full-load and locked rotor current limits
- efficiency, power factor, torque, %-slip (where applicable), power output (load)
- acceleration time at 100%-voltage from zero speed to full speed with standard load (square-law speed/torque curve and standard inertia)
- stator winding connections
- open-circuit and short-circuit time constants
- transient reactance
- thermal limit curve (current vs. time)
- cooling water flow requirement (where applicable)
- allowable operating time without cooling water flow (where applicable)
- oil or grease properties and specification
- maximum allowable mounting displacement from true vertical or horizontal

- torque required to turn rotor with oil lift system operating (where applicable)
- power loss to air or cooling water
- ventilating air CFM requirements, where applicable (flow and maximum ambient temperature)
- list of instruments and controls with power requirements, range, action, and set-point accuracy
- total kinetic energy of rotating parts
- description and recommended frequency for conduct of tests
- list of recommended renewal parts
- required maintenance schedule frequency

Manufacturers of large motors which are intended for continuous duty highly recommend the use of stator electrical protection. Therefore most pump and fan motors employ either overload relays, inherent protectors, or thermostatic protection. Since NEC (Section 430-33) does not require that intermittent duty motors have specific overload protection, the decision to protect an MOV motor and the corresponding selection of the protector type is often left to the discretion of the specifying engineer or manufacturer[37]. The objective of motor overload protection is to limit the temperature of the winding to maximum safe levels for all expected conditions of operation[39]. Removing a motor from service prior to reaching the maximum safe operating temperature unnecessarily limits output and thereby interrupts plant operations, while failing to remove a motor from service once maximum safe operating temperature is reached or exceeded is to risk destroying the windings. Depending on the type of duty and particular system function requirements, motor manufacturers endorse the use of either built-in (stator) temperature detectors or remote (outside the defined boundary) current-sensitive protection devices. For example consider polyphase induction motors ranging in size from 1-200 horsepower manufactured with mesh or randomwound stator coils and a die-cast aluminum rotor. These machines are most effectively protected from all conditions of overheating and overloading by directly sensing the temperature of the main winding in the stator. It is usually better to incorporate internal temperature detectors rather than use remote relay since the different ambient (surrounding) motor and device temperatures prevent a true representation of motor internal temperature. It is important to note that internal temperature-sensitive devices only protect the motor windings and not any of the (outside-of-the-boundary) system circuitry and therefore manufacturers stress the importance of design compatibility with the motor starter, branch circuit protectors, and manual disconnecting devices (e.g., "quick disconnects").

Numerous types of motor protection devices exist for detecting over current resulting from an overload, a stalled rotor, and phase failure (etc.), including the thermostat and thermistor types. While these elements are adaptable to nearly all motors, the use of such motor protection is typically reserved for smaller-sized, continuous duty machines. The temperature-sensing thermostat consists of two dissimilar metals having different rates of thermal expansion. The metals are rolled together and then cut into strips or discs for locating within the motor. When operating temperature increases, the metal on one side expands at a faster rate than the other causing the rolled strip or disc to bend. This action serves to open the controlling electrical circuit thereby tripping the motor since the thermostatic device is calibrated

to operate when stator temperature approaches the degree harmful to the insulation. A modified version of the temperature-sensing thermostat is manufactured for small (e.g., 1-5 HP) motors and is more directly protective of overcurrent conditions in addition to sensing actual heat. By incorporating a small resistance heater made of several wire turns connected in series with the motor winding, the bimetal is heated by the heater as well as by the winding and this condition trips the motor.

A thermistor type protection device also utilizes thermal sensing and resistance principles to safeguard a motor. A totally encapsulated ceramic disc having no moving contacts maintains essentially constant resistance up to a predetermined critical temperature. When the temperature limit is reached or exceeded, the resistance changes very rapidly and the thermistor acts to cause a relay to trip the motor or to at least provide warning annunciation to the operator.

A survey of motor manufacturers and service facilities has revealed that approximately 60% of all machine failures are due to high winding temperature excursions and the resulting insulation damage which could have been prevented by the use of adequate thermal overload protection. It is noteworthy to realize that the detrimental service wear and advanced aging effects caused by overcurrent/overheating can be induced or contributed to by system-level parameters, component-level parameters, application and operation errors, as well as by environmental conditions including synergisms.

Manufacturer recommendations for motor specification, duty cycle, operation, maintenance, testing, and monitoring cover virtually every aspect of preventing or retarding performance and reliability decline. However, the basic guidelines offered by designers and producers of electric motors mainly consist of adhering to the specified requirement and warranty operating limits, maintaining the environment to conform with original and predicted conditions (to the extent possible), utilization of thermal overload protection, and the implementation of on-going maintenance and parts renewal.

5.4 INSPECTION, SURVEILLANCE, AND MONITORING

The procedures of ASME Section XI that form an integral part of NRC-required Tech Specs provide for in-service vital component operability diagnostics. Of particular applicability to motor performance considerations are the rules governing in-service inspection of pumps (Subsection IWP) and valves (Subsection IWV). The basic objective of the ASME Section XI guidelines is to format procedures for documented component inspection, surveillance, monitoring, and testing, which includes verifications somewhat pertinent to motor condition assessment. For pump components, ASME Section XI stipulates performance diagnostic methods by observing flow rate and differential pressure at various motor output levels with regard to previously established reference values. In the event of deviation from the reference values, corrective action ranging from instrument calibration checks to (pump) bearing replacement, and equipment overhaul is required. Failure to achieve the specified acceptance criteria naturally implies that whatever action is needed to restore operability must be accomplished, which may include motor service or replacement. Rigorous guidelines for measurement methods are another aspect of ASME Section XI which details required instrument ranges, instrument calibration, instrument and transmitter location, as well as bearing temperature and

vibration amplitude detection. A similar and equally thorough approach is taken for motorized valves in order to verify operational readiness on a continuing basis. Valves must be exercised on a periodic basis to the full position of required flow or closure and the inspection process is to be conducted based on the valve category (e.g., A or B), and the necessary plant operating status. Of particular significance in terms of the motorized feature of the valves is the required response time for effecting the flow path or flow blockage. As with the pump component, any failure to perform in accordance with pre-established reference values requires timely corrective action which again may include motor repair or replacement.

A published report, national standard, Regulatory Guide, or manufacturer's service manual exists for inspecting, surveying, and monitoring virtually every important facet of an electric motor. While the intent of this documentation is not to identify aging per se, it is plausible that through testing and critical parameter trending the age-related incipient stage of motor degradation can be determined. However, the high cost of extensively monitoring and inspecting a motor on a frequent basis often results in a lack of complete surveillance and testing, and as a result, age-related common cause failures continue to occur. Currently there are no NRC guidelines or requirements for licensees to implement monitoring, testing, and inspection programs specifically for electric motors.

In addition to straightforward reference value check procedures such as visual inspection of brushes, brush supports and commutators in case of a dc motor, sophisticated analytical and empirically-derived methods exist for assessing motor condition via inspection, surveillance, and monitoring results. For example, a correlation between certain non-destructive level measurements and the motor residual breakdown voltage can be developed to ascertain insulation strength[40]. Again utilizing advanced methods and measured performance values, time-related and service wear induced phenomena such as leakage current can be assessed[42].

NUTECH Engineers[42] has developed an approach to nuclear power plant equipment inspection, surveillance, and monitoring that is readily adaptable to electric motors. Condition monitoring, defined as "the use of quantitative indicators in surveillance procedures to monitor the "health" of equipment," relies on measuring key parameter values by cost-effective means to identify the onset of critical "weak links" that have occurred with time. But, as pointed out in the NUTECH report, monitoring results are not always independently conclusive and absolute in terms of diagnosing the (motor) performance condition, and therefore supplementary testing is sometimes required (e.g., especially for those property assessments related to dielectric integrity).

Common practice by licensees for inspection, surveillance, and monitoring of motors is viewed as an apparent trade-off of priorities which is mainly due to the overwhelming number of routine operating and maintenance requirements that have been imposed in recent years. Further complicating the equipment diagnostic process is the number of large and small electric motors employed in a typical PWR or BWR and the resulting manpower and equipment needed to adequately assess the operability status for each. Aside from Tech Spec and associated ASME Section XI requirements, plant monitoring and maintenance practices are predominantly adapted from the recommendations and warranty

terms of the motor manufacturer and from prior plant (both nuclear and non-nuclear) utilities. In conjunction with motor manufacturers, and especially for large, high-cost machines, post-failure examinations for determining the actual cause of the catastrophic loss of performance integrity are sometimes conducted. These efforts serve the two-fold purpose of improving the list of critical parameters vital to effective continuous (condition) monitoring which can improve motor on-going maintenance as well as subsequent manufacturing. Aside from environmental qualification, Tech Spec, and other regulatory requirements, it is clear that cost has a significant impact on the extent and degree of motor inspection, surveillance, monitoring, and testing that is performed at a typical nuclear power plant. As a case in point, a relatively small MOV of minor safety consequence simply does not warrant a full-scale, continuous motor diagnostic program and as a result numerous equipment failures occur (note the MOV-proportioned failures delineated in Sections 4.1, 4.2, and 4.3). Current methods, technology, and requirements focused on motor inspection, surveillance, and monitoring are presently inclined towards improving motor reliability.

5.5 NRC EXPERIENCE, EXPERT KNOWLEDGE, AND ON-GOING RESEARCH

In the course of conducting audits, inspections, and through evaluation of required data submittals, the NRC has compiled motor failure data and analysis reports that have helped formulate the basis for existing design, manufacturing, quality assurance, quality control, maintenance, operating, and testing requirements. LER reports, I&E inspection findings, NRR accomplishments, nuclear vendor 10 CFR Part 21 and Part 50 audits, TMI lessons-learned, and various other activities and events have structured the conduct of operating and maintaining a commercial reactor plant in the United States.

Within the context of safety-related components manufacturing, the NRC has imposed strict requirements for reporting deviations from those quality standards which are deemed necessary for ensuring motor reliability. NUREG-0040 (entitled Licensee Control and Vendor Inspection Status Report) frequently reveals deficiencies on the part of manufacturers that could, conceivably, have serious safety implications. As an example, a motor producer was cited for insufficient adherence to a process quality specification for stator insulation, even though the omission was inadvertent. On another occasion, a manufacturer was noted for several deviations since "gauges used for the measurement of product (electric motor) quality were found to be uncontrolled, out of calibration, in use without (internal) authorization, and not identified properly." Therefore, despite comprehensive standards, guides, and codes and the institution of advanced inspection, surveillance, and monitoring practices as well as manufacturing methods, the service wear versus aging question acquires new meaning when considering the fact that an electric motor may be at an operational and environmental endurance disadvantage even when new. Deficient manufacturing practices such as the aforementioned from NRC experience clearly escalate the importance of in-plant condition monitoring and the application of periodic yet frequent maintenance.

Scheduled as well as unannounced inspections of licensees and vendors by the NRC and utility-initiated notifications (such as those relayed by the LER) are part of the continuing effort to circumvent material hysteresis and personnel-induced equipment degradation that can result in unsafe reactor operation when undetected and/or not corrected. Reports by I&E and notifications

by plant staffs confirm that essential in-service inspections and other requirements pertinent to ensuring motor and other safety-related component reliability are occasionally violated.

Sugarman[42] agrees that adherence to design specifications and continuous inspection, surveillance, and condition monitoring functions are essential for vital components such as electric motors. Potentially at least, an aging-seismic correlation is thought to exist for certain motor components (e.g., for the stator winding including the slot lines, wire insulation, phase insulation, separator, and slot cap, and also for the stator core lamination insulation and terminal leads). It should be noted that equipment qualification methods, technology, and requirements must not only cater to accident conditions but to post-accident conditions as well (Carfagno[43]). While not defined as a qualification process, condition monitoring is viewed as a means to quantify the natural aging phenomenon. Although SQUG has essentially ascertained that seismic events will not impair nuclear plant operating safety based on fossil plant evaluations of pumps and motorized valves, it is still important to periodically index the aging rate of vital components since aging and aging-seismic correlation have not been quantified.

Numerous research efforts have been implemented to guide and organize the understanding of aging, aging-seismic correlation, environmental qualification requirements, and the post-accident effect of synergisms on vital components. Oak Ridge National Laboratory (ORNL) is currently conducting an aging assessment study for the ultimate purpose of improving and ensuring MOV operational readiness. In addition, comprehensive evaluations of the equipment degradation effects of the TMI-2 incident[44] are on-going, and that portion related to electric motors indicates that abnormal performance modes resulted from system-level parameters, aging, pre-event service wear, and human factors. All of the studies and research programs tend to promote the basis for motor endurance life predictions that will enable diagnostic and maintenance practices to be enhanced.

5.6 TESTING

Electric motor testing is most commonly performed either for the purpose of periodic condition diagnostics or for failure mode analysis once a catastrophic loss of dielectric, rotational, or mechanical integrity occurs. Numerous IEEE, ASME, ANSI, and AFBMA standards, guides, and codes exist for conducting the latter type of test while comprehensive guidelines for on-going aging and service wear assessment are more limited.

Special tests are of course conducted as needed for research, material evaluations, warranty claims, and the like. The aging-seismic correlation motor test conducted at BNL[15] represents an example of a special test performed to enhance the research basis of the aging assessment program. While it is realized that the assessment of two aged motors is not necessarily representative of the entire nuclear power plant motor population, it is significant that despite 12 years of age and service wear, both machines were able to maintain satisfactory performance levels at the prolonged input of (approximately) 24 g's of acceleration. The conduct and requirements of a special test are often not applicable for operating reactor in-situ evaluations and as stressed by Nailen[45], tests must be practical, i.e., readily performed, non-destructive, and the results adjustable to a realistic basis.

Common motor tests currently used by manufacturers, service facilities, and licensees include those outlined below which are accompanied by supporting descriptions of applicability, advantages, disadvantages, and other considerations.

- **POWER FACTOR (INSULATION) TEST** - Effective for incipient stage diagnostics by the detection of insulation degradation resulting in increased value of power factor: short-duration test for ac machines while dc machines require extended time; itemizes dielectric watts loss and charging current; permits determination of capacitance, ac resistance, and the presence of ionization (corona). Power factor increase (tip-up) as non-destructive voltage as applied indicates insulation breakdown; power factor upward trends can be utilized for scheduling motor rewinding. Motor must be removed from service.

- **OVERVOLTAGE TEST** - Effective for assuring insulation minimum strength: applicable for ac as well as dc machines; overvoltage is applied nondestructively to determine the level at which leakage current is excessive; small, easily portable equipment required for dc tests, but larger required for ac test due to higher charging current requirements.

- **VIBRATION AND TEMPERATURE (BEARING) TESTS** - Effective for diagnosing end of bearing useful life and/or need for lubrication: dynamic balance assessed by measuring peak-to-peak amplitudes for various machine speeds (completely non-destructive); temperature indicators reveal wiping and the need for addition or replacement of lubricant.

- **INSULATION RESISTANCE (MEGGER) TESTS** - Effective for assessing insulation strength, cleanliness, and dryness: Resistance capability evaluated by the application of a potential, tests can be performed on the entire winding or on individual phases (if possible); data is particularly useful for long-term assessment of insulation condition.

- **POLARIZATION INDEX** - Effective for assessing winding dryness and fitness for overpotential tests. This is defined as the ratio of the 10 min resistance value to the 1 min resistance value. This is also used as indicative of the slope of the dielectric absorption characteristic of the insulations.

In addition to the testing procedures, normal operating parameters such as voltage, current, and vibrational amplitude trend values are often maintained for on-going performance assessment. Motor current is indicative since progressive increases in the value of this quantity can reveal overload conditions caused by bearing friction, coil failures, insulation voids, and loss of load assymetry. While sophisticated power factor, overvoltage, and power factor tip-up tests are necessary for identifying the actual cause of motor performance decline, condition monitoring trending represents a cost-effective means for detecting the onset of dielectric, rotational, and mechanical integrity decline (i.e., the incipient stage of motor failure).

The results of the BNL test may serve to establish higher limits for motor endurance. From the evaluation it is at least conceivable that seismic forces will not adversely affect a motor that has been periodically tested and appropriately maintained. Recent studies by EPRI conducted at Wyle Laboratory support the BNL findings in that 4 small motors (2-3 hp) tested under no-load conditions were not adversely affected by simulated seismic excitation. Clearly a drawback of on-line testing methods and technology is the inability to assess motor seismic integrity. Since no one test or will absolutely determine the ability of a motor to continuously and reliably perform, it is evident that as many evaluations as possible (with cost-effective considerations) should be instituted on a frequent basis for assessing bearing, lubricant, and insulation condition.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The evaluation of operational failure data utilized for determining common failure modes, mechanisms, and causes has revealed those functional indicators critical to motor dielectric, rotational, and mechanical integrity. Subjective assessments derived from the review of motor design, construction, and materials in conjunction with the failure and test data base have been utilized to address the concept of aging degradation and the corresponding effects on motor components. In addition, standards, guides, and codes currently relied upon for ensuring reliable motor performance have been reviewed.

Figure 6-1 illustrates the interrelationship of the program elements required to achieve the interim conclusions of Part I and to complete the study in Parts II and III.

6.1 CONCLUSIONS

The evaluation of operating experience and aging-seismic susceptibility has disclosed certain electric motor failure trends and tendencies which permit conclusive deductions to be made in regard to reliability and performance. Alternatively, some aspects of the motor failures noted from the data base are viewed as isolated yet significant occurrences of functional integrity losses that can only be classified as general observations due to the lack of adequate information noted throughout the report.

6.1.1 Performance Indicators

The identification of chronic failure mechanisms has disclosed those performance or functional indicators that provide the operational status of a motor. Figures 6-2, 6-3, and 6-4 depict the association of performance hazards and their effects, functional indicators, and primary motor components to dielectric, rotational, and mechanical integrities, respectively.

Electric motor dielectric hazard effects are given in Figure 6-2. The stator windings, and possibly the rotor windings depending on motor type, serve as the primary insulating system area of the machine. Conditions of degraded electrical and mechanical strength resulting in shorted windings, physical loosening of subcomponents, overheating, corona effects, and short circuits have been linked to extreme environmental conditions, excessive vibrations, and the introduction of water or steam. From this cause and effect relationship, critical parameters such as winding resistance and temperature, voltage gradient, vibration amplitude, current, and power factor are noted as essential for diagnosing motor dielectric integrity.

Figure 6-3 provides rotor assembly common failure mechanisms and corresponding performance indicators for the bearing and lubrication system required for motor rotational integrity. Bearing overheating and corrosion resulting in cracking, scoring, brinelling, splitting, and seizing are noted to be induced by excessive or under lubrication, the introduction of water or steam, vibration, the loss of (bearing) electrical insulation, inadequate cooling, misalignment, and the presence of dirt or other foreign particles. These symptomatic effects are detected by vibrational checks, lubrication analysis, temperature monitoring, eddy current checks, speed tests, and physical clearance measurements and alignment checks.

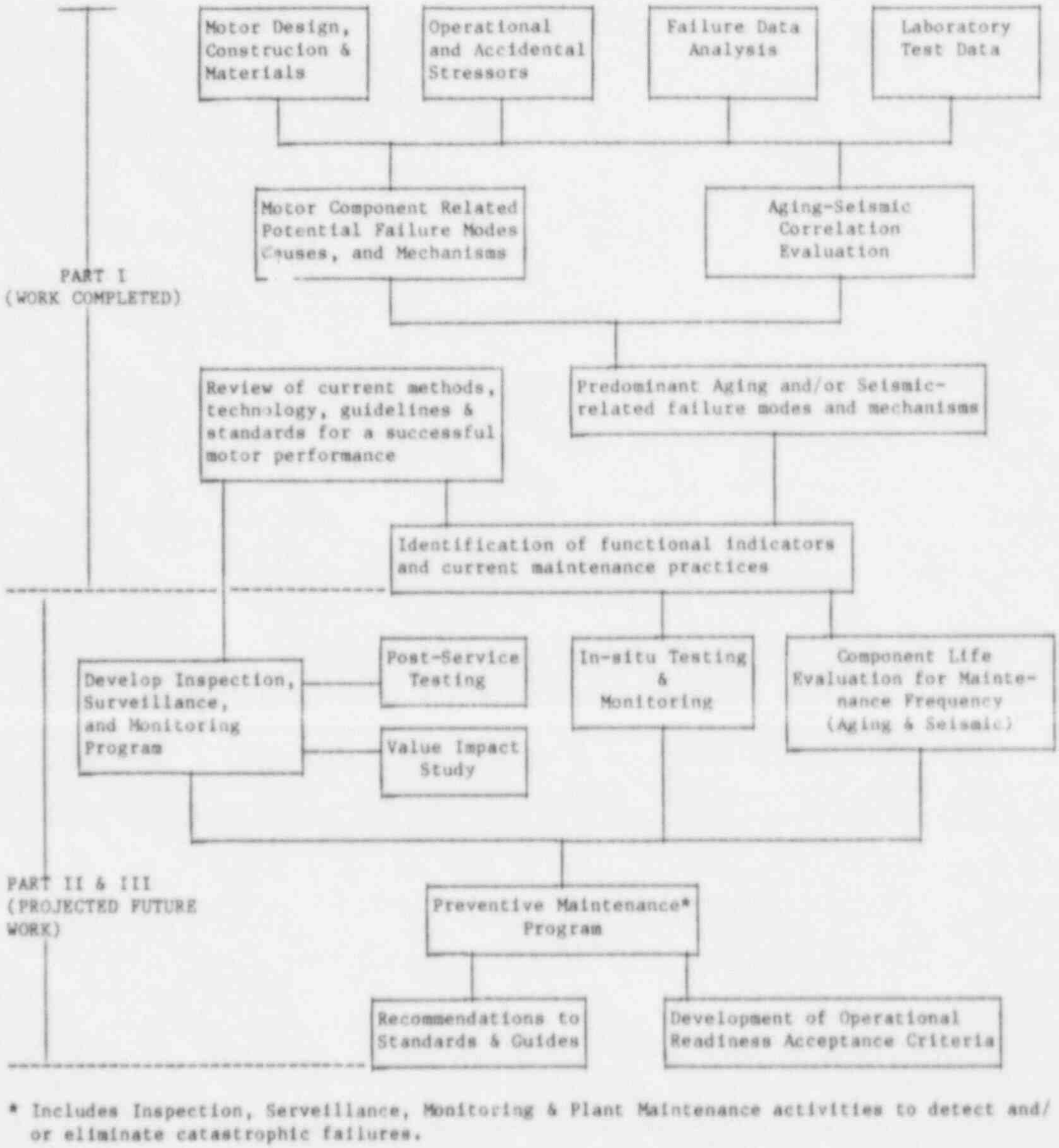
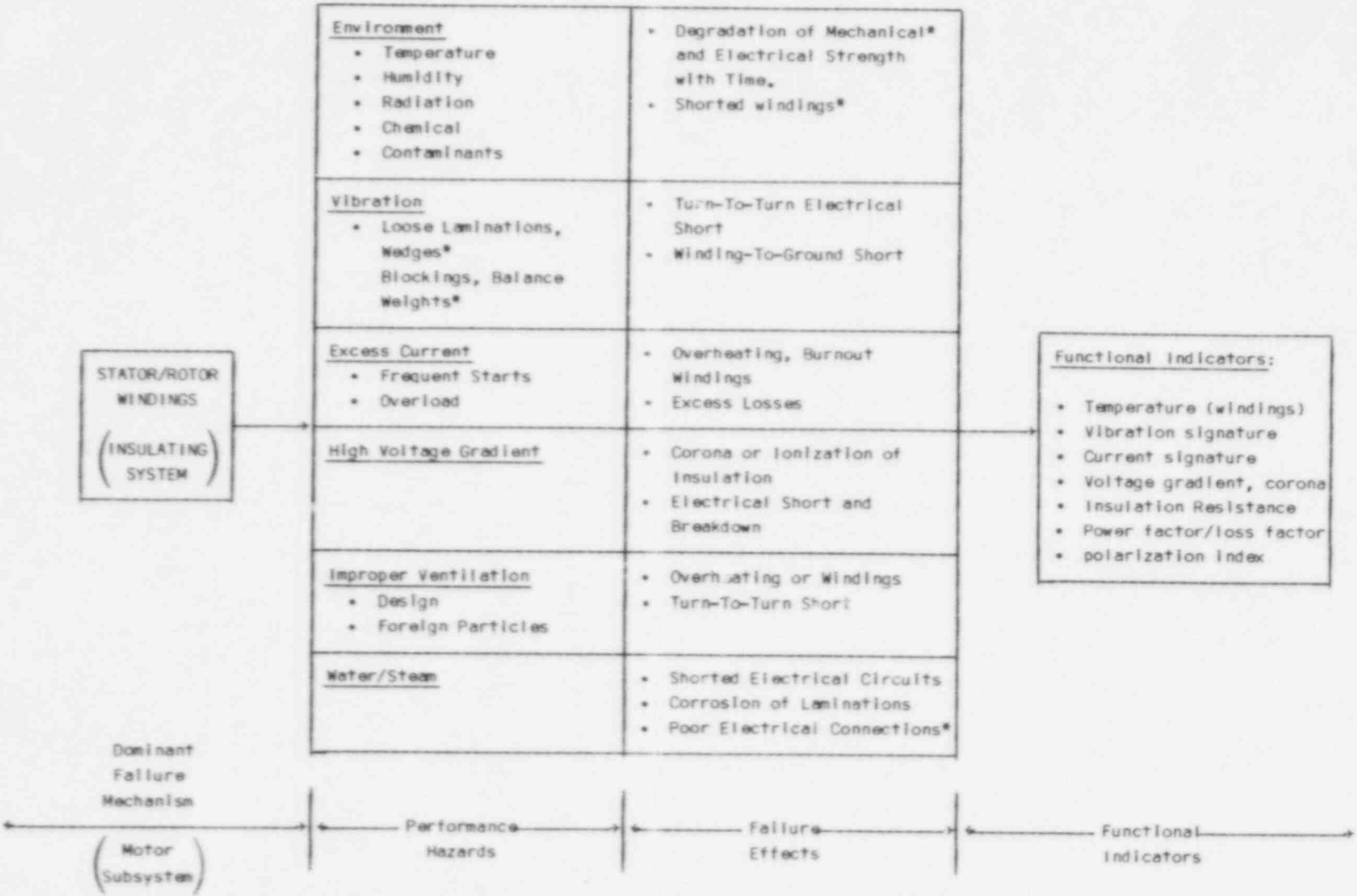


Figure 6-1: Electric Motor Aging Research Flowchart



* Aging Susceptibility per Table 4-15

Figure 6-2: Functional Indicators for Dielectric Integrity

BEARINGS
&
LUBRICATION

(ROTOR ASSEMBLY)

Performance Hazards	Failure Effects
Excessive or Under Lubrication • Damage Oil Sling Ring • Seal or Gasket Leakage	• Overheating • Cracking, Scoring, Brinelling, or Splitting of bearings
Water/Steam	• Corrosion
Vibration • Misalignment	• Noise* • Cracking
Bearing Insulation Damage	• Bearing Current Leading to Overheating
Improper Cooling • Seal or Gasket Leakage	• Overheating
Mechanical Problems • Oil/Foreign Particle Deposits • Rotor-Stator Interference • Excessive Axial Movement • Too Much Clearance Between Bearing and Shaft • Frozen Bushing	• Jamming/Freezing of Balls* • Stator Lamination Damage • Tripping of Accessories • Shifting of Rotor C.G.

Functional Indicators:

- Lubrication
  - Lubricity
  - Viscosity
- Vibration signature
- Temperature (Bearing, oil)
- Eddy current losses
- Alignment
- Clearances
- Speed (torque)

Dominant Failure Mechanism (Motor Subsystem) ← → | ← Performance Hazards → | ← Failure Effects → | ← Functional Indicators →

* Aging Susceptibility per Table 4-15

Figure 6-3: Functional Indicators for Rotational Integrity

MISCELLANEOUS FAILURES (ALL COMPONENTS) →

Performance Hazards	Failure Effects
Vibration • Bolts • Welding/Brazing • Dowel pins	• Loose or Damaged Leads* • Weld Failure • Loss of Balance Weight • Bending or Distortion of Shaft • Shear of dowel pins
Environmental Contamination/Corrosion of Leads	• Improper Electrical Contacts
Damaged Seals & Gaskets	• Oil or Water Leaks*
Wrong Adjustments and Settings	• Overloading, Overheating
Faulty Heaters	• Too Much Moisture
Misapplication/Misoperation • Valve Seating • Phase Error • Frequent Starting	• Overloading, Overheating
Commutator Brushes (wear)	• Poor Connections*

→ Functional Indicators:

- Vibration signature
- Environmental conditions
- Corrosion
- Cracks
- Leaks (seals & gaskets)
- Wear

Dominant Failure Mechanism (Motor Subsystem)	Performance Hazards	Failure Effects	Functional Indicators

* Aging Susceptibility per Table 4-15

Figure 6-4: Functional Indicators for Mechanical Integrity

Miscellaneous mechanical hazards for all motor components including accessories are outlined by Figure 6-4. Effects ranging from faulty heaters permitting conditions of excessive humidity to human error resulting in material overstress are noted to occur. Visual and instrumented machine inspections coupled with proper operation and maintenance applied over a periodic basis represent the most practical methods for ensuring motor mechanical integrity. Other indicators that can be monitored are vibration amplitude, environmental conditions, evidence of corrosion or cracks, seal and gasket leaks, and component wear.

6.1.2 Failure Data Evaluations

Conclusions and general observations derived from the Part I research are categorized and listed below. The classification of the findings is associated with design and manufacturing, application and operation, or maintenance depending on the nature of the determined motor condition.

Design & Manufacturing

- Induction motors represent approximately 90% of the total population as shown by Figure 2-5 and are characteristically more durable than most other motor types.

- Stator failures occur primarily as a result of insulation breakdown as given in Table 2-4.

Application & Operation

- From the total NPRDS failure population represented, small (0-99.9 hp), medium (100 - 1000 hp), and large (> 1000 hp) motors as shown by Figure 2-6 have the following probability of failure:

	SMALL	MEDIUM	LARGE
Population	47%	23%	9%
Failure	3%	8%	9%

NOTE: The remaining 21% of the population represents fractional size motors.

- From examination of IPRDS data which represents many motor applications it has been noted that BWR and PWR plants have similar motor failure rates.

- Intermittent or alternating motor operation results in a greater absolute number of failures than continuous on-line operation as shown by Figure 3-3 from IPRDS data.

- Motor driven mechanical equipment (e.g., pumps and valves) in general contribute to a greater number of failures than the MCC and associated outside-of-the-boundary electrical control system as noted from IPRDS data and as shown by Figures 4-5 and 4-6; however, from LER data, the converse is true for safety-related system motors.

- Service water, radioactive waste, residual heat removal, high-pressure coolant injection, condensate, and circulating water systems exhibit a noticeably higher number of failures than other plant systems as given by Tables 3-1 and 3-2.

- Motor bearings fail more frequently while driving pumps as compared to other application equipment such as valves and fans, as shown in Figures 3-1 and 3-2.

Maintenance

- Most reported failures are catastrophic as noted from IPRDS data and as shown in Figure 4-7.

- Prominent and chronic causes of motor failure include moisture absorption into windings, excessive heat, and bearing-related degradation due to lack of lubrication, as given by Table 4-15.

General

- As noted from SALP maintenance ratings and LER data, plants with below average maintenance ratings experience more motor failures than plants rated average or above average.

- In consideration of utilities having multiple plant sites, typically if one site exhibits a high motor failure rate, the other site(s) follow the trend.

- Most motor failures have been detected while the reactor was in operation.

- Common types of motor failure or malfunction detection are the result of operational abnormality, routine surveillance, or surveillance testing.

- Dc motors have a higher failure probability than ac motors, and the dc motor failure is often the result of worn or otherwise degraded commutators.

- Excessive duty cycle (i.e., frequent starts) is a common cause of motor failure.

6.1.3 Aging-Seismic Correlation

In order for a motor component to independently undergo severe inertial loading as a result of seismic effects, the part or substructure must have significant mass in order that the input acceleration produces other than a negligible amount of force. However, as an assembled unit, individual component masses are combined which can have susceptibility to earthquake-induced excitations. Within the context of age-related degradation, it is plausible to conclude that certain component material "weak links" will fail subject to unsuitable levels of cyclic frequency response. Accordingly, the following basic motor items are considered to potentially have an aging-seismic correlation: winding laminations, insulating systems, commutators, terminal leads,

gaskets and seals, and bearings. These were extracted from the findings presented in Table 4-15 which were compiled from assessments made during the evaluation of failure data and review of design and materials of construction and it is to be noted that an aging-seismic (specific) data base does not exist.

In essence then, it is conceivable that an electric motor has the potential to fail in the event of an earthquake, and particularly when the equipment is in an aged state. However, recent EPRI seismic evaluation tests performed by Wyle Laboratories on small motors and BNL tests on two naturally aged 10 hp induction motors provided no evidence of seismically induced performance decline. SQUG pilot program findings also indicated no apparent operational abnormality in motors that have experienced real earthquake excitations, although the actual aged condition of the equipment was not assessed.

Based on the above, it appears that for certain small induction motors (approximately 10hp) seismic effects should be minimal providing motor dielectric, rotational, and mechanical integrities have been adequately maintained.

6.2 FUTURE WORK

As continuation of the work performed to date, and in accordance with the NPAR program strategy, the future work planned is shown in Figure 6-1. Three separate investigations will be conducted for the final goal of developing a cost effective preventive maintenance program and operational readiness acceptance criteria. An in-situ testing and monitoring program will be performed on the functional indicators identified in the Part I study. Finally, after reviewing advanced in-service inspection, surveillance, and monitoring techniques, preventative maintenance program recommendations will be developed for investigating the effects of aging. Additional efforts focused towards the further understanding of aging-seismic correlation relationships, particularly for large motors, will also be made.

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APPENDIX A

INDUSTRY STANDARDS ON MOTORS

IEEE STANDARD	TITLE
1-1969	General Principles for Temperature Limits in the Rating of Electric Equipment
56-1977	Guide for Insulation Maintenance for Large AC Rotating Machinery (10,000 kVA and Larger)
58-1977	Induction Motor Letter Symbols
62-1978	Guide for Field Testing Power Apparatus Insulation
66-1969	Short Circuit Characteristics of DC Machinery
68-1975	Recommended Practice for Measurement of Power-Factor Tip-up of Rotating Machinery Stator Coil Insulation
85-1973	Airborne Sound Measurements on Rotating Electric Machinery
95-1977	Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage
98-1972	Guide for the preparation of Test Procedures for the thermal evaluation and establishment of Temperature Indexes of Solid Electrical Insulating Materials.
101-1972(R1980)	Guide for the Statistical Analysis of Thermal Test Data
112A-1964	Test Procedure for Polyphase Induction Motors and Generators
113-1973	Test Code for Direct-Current Machines
114-1969	Single Phase Induction Motor Tests (ANSI C50.21-1972)
115-1983	Test Procedure for Synchronous Machines
116-1975	Test Code for Carbon Brushes
117-1974	Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery
118-1978	Standard Test Code for Resistance Measurement

IEEE STANDARD	TITLE
119-1974	Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus
120-1955(R1972)	Master Test Code for Electrical Measurements in Power Circuits
121-1959	Guide for Measurement of Rotary Speed
251-1963	(Reaff 1972) Test Procedures for DC Tachometer Generators
252-1977	Test Procedures for Polyphase Induction Motors with Liquid in the Magnetic Gap
275-1966	(Reaff 1972) Test Procedure for Evaluation of Systems of Insulating Materials for AC Electric Machinery Employing Form-Wound Preinsulated Stator Coils
286-1975	Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation
288-1969	Guide for Induction Motor Protection (ANSI C37.92-1972)
290-1977	Recommended Test Procedure for Electric Couplings
303-1969	Auxiliary Devices for Motors in Class 1 - Groups A, B, C, and D, Division 2 Locations
304-1977	Test Procedure for Evaluation and Classification of Insulation Systems for DC Machines
323-1974	Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Station
329-1971	Synchronous Motor Protection Guide (ANSI C37.94-1972)
334-1974	Type Test of Continuous Duty Class 1E Motors for Nuclear Power Generating Stations
344-1975	Recommended Practices fro Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations
421-1972	Criteria and Definitions for Excitation Control Systems for Synchronous Machines
429-1972	Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Stator Coils (ANSI C50.26-1972)

IEEE STANDARD	TITLE
432-1976	Guide for Insulation Maintenance for Rotating Electrical Machinery
434-1973	Guide for Functional Evaluation of Insulation Systems for Large High-Voltage Machines
522-1977	Guide for Testing Turn-To-Turn Insulation on Form-Wound Stator Coils for Alternating Current Rotating Electric Machines

ANSI/IEEE STANDARD	TITLE
4-1978	IEEE Standard Techniques for High-Voltage Testing
43-1974(R 1979)	IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery
67-1972(R 1980)	IEEE Guide for Operation and Maintenance of Turbine Generators
86-1975	IEEE Standard Definitions of Basic Per-Unit Quantities for Alternating-Current Rotating Machines
99-1980	IEEE Recommended Practices for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electrical Equipment
100-1977	IEEE Standard Dictionary of Electrical and Electronics Terms
112-1978	IEEE Standard Test Procedure for Polyphase Induction Motors and Generators
433-1974(R 1979)	IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency
492-1974(R 1981)	IEEE Guide for Operation and Maintenance of Hydro-Generators

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

ANSI STANDARD	TITLE
C50.10-1977	American National Standard General Requirements for Synchronous Machines
C50.13-1977	American National Standard Requirements for Cylindrical-Rotor Synchronous Generators
C50.14-1977	American National Standard Requirements for Combustion Gas Turbine Driven Cylindrical Rotor Synchronous Generators
C50.41-1982	American National Standard for Polyphase Induction Motors for Power Generating Stations

ANSI/NEMA STANDARD	TITLE
MG1-1978(R1982)	Motors and Generators

U.S. NRC REGULATORY GUIDE	TITLE
1.89	Qualification of Class 1E Equipment for Nuclear Power Plants
ASME-Section XI	Rules for Inservice Inspection of Nuclear Power Plant Components

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13. ABSTRACT (200 words or less)

This report provides an aging assessment of electric motors and was conducted under the auspices of the NRC Nuclear Plant Aging Research Program (NPAR). The objectives of this program are to identify concerns related to the aging and service wear of equipment operating in nuclear power plants, to assess their possible impact on plant safety, to identify effective inspection surveillance and monitoring methods and to recommend suitable maintenance practices for mitigating aging related concerns and diminish the rate of degradation due to aging and service wear.

Motor design and materials of construction are reviewed to identify agesensitive components. Operational and accidental stressors are determined, and their effect on promoting aging degradation is assessed. Failure modes, mechanisms, and causes have been reviewed from operating experiences and existing data banks. The study has also included consideration for the seismic correlation of age-degraded motor components.

The aforementioned reviews and assessments were assimilated to characterize the dielectric, rotational, and mechanical hazards on motor performance and operational readiness. The functional indicators which can be monitored to assess motor component deterioration due to aging or other accidental stressors are identified. Conforming with the NPAR strategy as outlined in the program plan, the study also includes a preliminary discussion of current standards and guides, maintenance programs, and research activities pertaining to nuclear power plant safety-related electric motors.

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