Guidelines for the Qualification of Insulation Systems for Use in Rewinding Nuclear Safety-Related Harsh Environmental Motors

Technical Report

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GUIDELINES FOR THE QUALIFICATION OF INSULATION SYSTEMS FOR USE IN REWINDING NUCLEAR SAFETY-RELATED HARSH ENVIRONMENT MOTORS

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Prepared By
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R E P O R T   S U M M A R Y

Guidelines for the Qualification of Insulation Systems for Use in Rewinding Nuclear Safety-Related Harsh Environment Motors

This document provides guidance on the selection, procurement, acceptance, and dedication of the insulating materials used during the rewinding of environmentally qualified (EQ) motors located in plant harsh environment areas. This guideline is the third in a series of documents published by EPRI to facilitate the repair of safety-related motors.

INTEREST CATEGORIES

Engineering and technical support
Nuclear plant operations and maintenance
Maintenance practices

KEYWORDS

Procurement
Qualification
Repair and Replacement
Motors
Rewinding

BACKGROUND As existing nuclear power plants mature, there remains a need to provide high quality repair services for safety-related motors. Many motor manufacturers have not maintained their nuclear quality assurance programs and are unwilling to re-establish these programs for infrequent purchases. This problem is further compounded when motors must be qualified for harsh accident environments in accordance with NRC regulation 10 CFR 50.49 and other related NRC guidance documents. These motors are generally termed harsh environment qualified or environmentally qualified (EQ) motors.

OBJECTIVE To provide guidance on the selection, procurement, acceptance, and dedication of the insulating materials used during the rewinding of EQ motors located in plant harsh environments.

APPROACH A Task Group comprised of utility electrical motor engineers, equipment qualification engineers, and representatives from several motor rewind/repair shops was formed to develop this guideline. The group met five times over a twelve-month period to define the scope of the report and review various drafts assembled by a task contractor.

Determination of the scope for this guideline was facilitated by the use of questionnaires but the scope was ultimately established by the Task Group. The questionnaires were issued to utilities and to a variety of organizations that had been involved in the qualification of motors for harsh environments.

RESULTS This guideline includes both form- and random-wound coil constructions. Form-wound coils are assumed to be fabricated using a vacuum pressure impregnation (VPI) process and solventless resins. Random-wound coils may be designed for either VPI or the more common “dip & bake” insulating system treatments. The guideline primarily focuses on stator windings; however, the general technical guidance can be applied to armatures and DC field windings for similar applications.

The guideline provides:

- General information regarding environmental qualification of rewinds
- Information supporting the qualification of selected rewinds through the use of analysis and partial testing
- Technical information on several rewind systems currently qualified by type testing

EPRI PERSPECTIVE This report and two earlier published reports (listed below) provide utilities and commercial repair shops with the information necessary to repair/rewind motors for nuclear power plant applications.

- EPRI NP-6407, *Guidelines for the Repair of Nuclear Power Plant Safety-Related Motors*
- EPRI TR-103585, *Guidelines for the Selection and Acceptance of Nuclear Safety-Related Motor Insulation Systems*

PROJECT

RP3186-15

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ABSTRACT

As existing nuclear power plants mature, the need to provide high quality, safety-related, replacement electric motors in a wide range of sizes increases also. Many motor manufacturers have not maintained their nuclear quality assurance programs and are unwilling to re-establish these programs for infrequent purchases. This problem is further compounded when motors must be qualified for harsh accident environments in accordance with NRC regulation 10 CFR 50.49 and other related NRC guidance documents. These motors are generally termed harsh environment qualified or environmentally qualified (EQ) motors.

This document provides guidance on the selection, procurement, acceptance, and dedication of the insulating materials used during the rewinding of EQ motors located in plant harsh environment areas. This guideline is the third in a series of documents published by EPRI to facilitate the repair of safety-related motors.

This guideline includes both form- and random-wound coil constructions. Form-wound coils are assumed to be fabricated using the vacuum pressure impregnation (VPI) process and solventless resins. Random-wound coils may be designed for either VPI or the more common “dip & bake” insulating system treatments. The guide primarily focuses on stator windings; however, the general technical guidance can be applied to armatures and DC field windings for similar applications as well.

UTILITY ACKNOWLEDGMENTS

The following individuals were ongoing members of Plant Support Engineering's Harsh Environment Motor Insulation Task Group. As such, they made significant contributions to the development of this guide by attending the majority of the task group meetings, reviewing and commenting on various drafts, and writing portions of the document.

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1.0

INTRODUCTION, PURPOSE, AND SCOPE

1.1 Introduction and Purpose

This guideline is the third in a series of documents published by EPRI to facilitate the repair of safety-related motors. As existing nuclear power plants mature, there remains a need to provide high quality, safety-related, replacement electric motors in a wide range of sizes. Many motor manufacturers have not maintained their nuclear quality assurance programs and are unwilling to re-establish these programs for infrequent purchases. This problem is further compounded when motors must be qualified for harsh accident environments in accordance with NRC regulation 10 CFR 50.49 and other related NRC guidance documents. These motors are generally termed harsh environment qualified or environmentally qualified (EQ) motors.

Typical costs for a new EQ random-wound motor qualified for LOCA conditions range from $5,000 to $100,000 with delivery times on the order of three to six months. Costs for an EQ form-wound motor qualified for inside containment LOCA or outside containment HELB conditions can vary widely based on size. Costs are around $250,000 with 6- to 12- month delivery times. For certain designs, delivery times could be greater than three years.

One approach to this dilemma is to use quality motor rewinding and repair methods to refurbish existing environmentally qualified power plant motors. Although most utilities have motor repair facilities in their service areas that can provide quality services, these facilities might lack the detailed QA programs necessary to qualify them as safety-related suppliers. A related concern involves the acceptability of commercially procured materials used in the rewinding and repair processes. For environmentally qualified motors, the problem is further complicated by the need to establish 10 CFR 50.49 qualification for the repaired motor, generally through type testing of a representative motor, and to fabricate or rewind motors so that the EQ type testing applies to the repaired motor.

EPRI, in response to the concern about proper QA programs for utility repair facilities, issued NP-6407, *Guidelines for the Repair of Nuclear Power Plant Safety-Related Motors* [1]. That document provides utilities and commercial motor repair shops with the information necessary to establish procedures, controls, and methods to document the motor repair process. Regarding the second concern, acceptability of commercially procured repair materials, EPRI recently issued TR-103585, *Guidelines for the Selection, Procurement, and Acceptance of Nuclear Safety-Related Mild Environment Motor Insulation for Rewinds* [2], to provide guidance on the selection, procurement, acceptance, and dedication of the insulating materials used during the rewinding of motors located in plant mild environment areas.

This guide is specifically focused on safety-related motors requiring qualification for harsh accident environments. Currently, both high cost and long-lead times characterize utility efforts to repair/replace these motors. Consequently, the guideline focuses on methods for motor rewind qualification.

1.2 Scope

Determination of the proper scope for this effort was facilitated by the use of questionnaires but the scope was ultimately established by the Task Group. The questionnaires were issued to utilities and to a variety of organizations that had been involved in the qualification of motors for harsh environments.

This guideline includes both form- and random-wound coil constructions. Form-wound coils are assumed to be fabricated the using the vacuum pressure impregnation (VPI) process and solventless resins. Random-wound coils may be designed for either VPI or the more common “dip & bake” insulating system treatments. The guide primarily focuses on stator windings; however, the general technical guidance can be applied to armatures and DC field windings for similar applications as well.

Only safety-related motors operating at 7 kV and below are considered in this guide. Consequently, the special slot area conductive and coil end semiconductive materials applied to the coil surface and used in higher voltage coil designs to minimize corona effects are not addressed. The 7 kV voltage limitation was selected based on the general assumption that special conductive materials are not necessarily needed at this and lower voltages to address corona effects.[1]

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1 The issue of corona protection is discussed further in EPRI TR-103585 [2]. That task group unanimously agreed that corona concerns were minimized for all 1 kV to 7 kV safety-related motor rewind insulating systems, if the systems are designed and fabricated to be *essentially void-free* using a VPI solventless resin system. Many in that task group felt an essentially void-free construction was sufficient to preclude corona effects; however, others, based in part on the continued use of special conductive materials by the major motor manufacturers, believed these materials should be strongly considered at the higher voltages (e.g, 6.6 kV motors).

The guideline was initially intended to provide:

1) General information for environmental qualification of rewinds
2) Information supporting the qualification of selected rewinds through the use of analysis and partial testing
3) Technical information on several rewind systems currently qualified by type testing to LOCA, HELB, and radiation-only conditions

This guideline addresses all these objectives; however, only a limited number of qualified systems are contained in this document.

Currently, the NRC prefers the use of type testing as a qualification basis for all harsh EQ applications. The guideline presents technical information supporting the use of analysis and partial tests as a qualification basis for motors in radiation-only harsh areas and totally-enclosed motors in low-pressure outside containment HELB conditions. Although the NRC has not reviewed the recommendations for the use of analysis and partial tests for qualification, the methodologies do comply with the requirements of the EQ rule 10 CFR 50.49, other related NRC EQ guidance documents, and industry consensus IEEE standards on EQ. Based on the approach used to develop this document, utilities are encouraged to apply these methods to both radiation-only harsh and low-pressure outside containment HELB conditions.

In an effort to make available to EPRI members information on motor insulating systems qualified by type tests to current EQ requirements, solicitations were made to utilities, manufacturers, and others who might have developed and qualified such harsh environment insulating systems. In response Tennessee Valley Authority (TVA) provided environmental qualification test reports for two insulation systems (form-wound and random-wound). These systems can be used by member utilities and rewind shops to qualify rewinds to LOCA, HELB, and radiation-only harsh conditions based on type testing. These two EQ reports have been published as a supplement to this report. To obtain copies, please call the EPRI Plant Support Engineering offices at (704) 547-6036. The information on the systems described in this guideline, combined with detailed qualification, material specification, and winding fabrication data (available upon request from EPRI), should permit the qualification of selected rewinds for harsh applications. In an effort to expand the scope of qualified systems, EPRI is currently developing and qualifying additional form- and random-wound rewind systems, which will be made available to member utilities.

Section 2.0 presents various terms and definitions used throughout this document. These terms supplement those presented in EPRI TR-103585 [2]. Section 3.1 provides general information on motor and winding types that is relevant to harsh environment qualification. Subsequent portions of Section 3.0 present information on conditions occurring during harsh accident environments and their possible effects on motor insulating systems. It also suggests a grouping of environmental conditions (LOCA, low-pressure HELB, and radiation-only) that is used in subsequent guideline sections.

Section 4.0 describes the guideline methodology and presents general technical information relevant to the qualification and fabrication of motor insulating systems.

Three major steps are involved in qualifying the rewind insulation system as part of the overall motor repair. These steps are:

- Establishing system qualification in accordance with accepted EQ practice
- Specifying, procuring, and accepting the correct insulating materials
- Fabricating the rewind to achieve the desired qualification

Section 4.0 includes a review of relevant regulations and standards, including IEEE qualification standards. The information is intended to help utilities identify and resolve possible concerns that can arise when qualifying and fabricating motor rewinds. The concerns include 1) aging, accident, and performance issues while establishing qualification, 2) bases for material substitutions, 3) additional material procurement and acceptance topics for harsh environment applications, and 4) fabrication issues unique to harsh environments.

Section 5.0 extends the Section 4.0 discussions to address LOCA-qualified systems. The section discusses considerations associated with establishing LOCA qualification using type testing. It also provides additional information on system fabrication and material procurement and acceptance. Finally, it contains an overview of the qualification and fabrication information provided to EPRI for one random-wound LOCA-qualified system.

Section 6.0 extends the Section 4.0 discussion to address HELB outside containment qualified systems. The section presents technical information supporting the use of analysis and partial test data to qualify certain totally enclosed motors for low-pressure HELB conditions. For other HELB applications, it recommends type testing to bounding accident conditions. Additional information on system fabrication, material procurement, and acceptance concerns of relevance to HELBs is also described. Finally, the section provides an overview of qualification and fabrication information provided to EPRI for several form-wound HELB-qualified systems.

Section 7.0 addresses qualification to radiation-only harsh conditions. The section presents technical information supporting the use of analysis and material radiation test data to qualify motors for radiation-only harsh conditions. It concludes that additional fabrication and material control measures are not generally necessary if materials are selected and qualified based on conservatively established radiation tolerance limits for the system materials.

Finally, Section 8.0 presents information to be considered for the development and qualification of motor rewind insulating systems.

During the development of this guideline, questions were raised regarding the acceptability of the common practice of cleaning and retreating motor winding for harsh environment motors. After some discussion, the task group agreed that this issue was beyond the scope of the current document. Several observations regarding this practice are contained in Appendix A.

1.3 Suggested Approaches for Guide Use

The information contained in this guide covers a wide range of topics. Although the guide could serve as a tutorial if read from cover to cover, most personnel involved in safety-related motor rewinds should use the guide selectively as a reference source and focus on specific areas of interest.

To achieve cost-effective qualification of motor rewinds, personnel with diverse backgrounds must integrate their experience and skills. These personnel include:

- Motor rewind shop personnel with expertise in motor repair techniques and materials
- Utility engineers responsible for compliance with NRC EQ requirements
- Utility and shop personnel responsible for evaluating and justifying rewind systems and materials, particularly material substitutions
- Utility personnel responsible for compliance with regulations and practices related to commercial grade item (CGI) procurement and acceptance

This guideline presents general information in each of these disciplines with the objective of facilitating communication and understanding. Readers already familiar with selected topics may skim over that material.

Much of the information in Sections 4.0 through 7.0 was developed for engineers responsible for the qualification of motor rewinds. This information is intended to help them either establish qualification based on available information or identify and resolve qualification issues that cannot be readily dispositioned by existing information. Much of the material in Sections 6.0 and 7.0 describes the use of analysis and partial testing as a qualification basis for selected harsh environment rewinds. Extensive supporting technical information is presented because the NRC generally prefers type testing as a qualification basis.

The following information is provided with the hope that it will help personnel focus on the appropriate guide sections, based on their current knowledge and needs.

Readers are encouraged to refer to EPRI TR-103585 [2] for more detailed information on insulating systems; establishment of thermal classifications; and insulating material selection, procurement, and acceptance.

1.3.1 Establishing Motor Qualification

Section 3.2 contains introductory information regarding environmental qualification. It assumes a working knowledge of 10 CFR 50.49 requirements and current methods of establishing and documenting harsh environment qualification. Section 4.2 provides additional information on the regulations and standards applicable to motor and insulation qualification. Section 4.3 contains more detailed information relevant to qualifying motors for harsh environments, including upgrading, aging effects, and accident stressor effects. Section 5.2.1 provides specific information on establishing EQ for LOCA conditions based on type testing. Section 6.2.1 presents technical information supporting the adequacy of analysis combined with partial test data as an environmental qualification basis for totally enclosed motors exposed to low-pressure HELB conditions. Similarly, Section 7.2.1 presents technical information supporting the adequacy of analysis combined with partial test data as a environmental qualification basis for motors exposed to radiation-only harsh environments. EQ engineers who must evaluate the qualification impact of material variations or substitutions should also consult the information provided in Section 4.4.

Finally, Sections 5.3, 6.3, and 7.3 contain summary qualification information on several insulating systems that have been qualified and can be used for selected plant-specific applications.

1.3.2 Selecting and Fabricating Qualified Motor Rewind Systems and Materials

Section 3.0 provides general information on the types of motors typically qualified for harsh environments and the effects of accident stressors on insulating system performance. Section 4.0 provides general information on issues related to fabricating insulating systems that must function in harsh environments. Additional information is provided in Sections 5.2.3, 6.2.3, and 7.2.3 on issues related to selecting and fabricating systems qualified for LOCA, HELB, and radiation-only harsh conditions.

1.3.3 Commercial Grade Item Procurement and Acceptance

Although this guide is not intended to describe the nuclear power industry's general approach to using commercial grade items (CGI) in nuclear safety-related applications. Section 4.5 provides some introductory information and also references other CGI guidance documents. The remaining guide material assumes a general understanding of the CGI topics and commonly used terms. Personnel involved in the specification, acceptance, and dedication of motor insulating materials as commercial grade items (for example, procurement engineers) should focus on the material contained in Section 4.5, *Material Procurement and Acceptance*, and the expanded discussions in Sections 5.2.3, 6.2.3, and 7.2.3 on the material procurement and acceptance for LOCA, HELB, and radiation-only environments. The procurement and acceptance methods described in this guide are intended to supplement the more detailed discussions and information contained in EPRI TR-103585 [2].

The introductory material on EQ in Section 3.2 and the more detailed EQ information in Sections 4.2 and 4.3 can provide additional insights that might help to establish the adequacy of certain material critical characteristics and related acceptance methods for harsh EQ motor rewinds. Finally, the discussion of substitutions in Section 4.4 contains important information on material characteristics and methods that can be used to establish equivalency.

2.0

TERMS AND DEFINITIONS

EPRI Report TR-103585, “Guidelines for the Selection, Procurement, and Acceptance of Nuclear Safety-Related Mild Environment Motor Insulation for Rewinds”, identifies a number of terms and definitions of relevance to safety-related motor rewinds. Several of these are repeated here for the readers' convenience. Readers should refer to that report for additional terms and definitions.

10 CFR 50.49: A portion of the Code of Federal Regulation requiring certain Nuclear Power Plants (NPP) electrical equipment important to safety to be qualified for operation in postulated harsh environments. Also referred to as the EQ rule.

Aging; Accelerated: Simulation of natural aging effects by increasing the intensity or manner of applying a stressor such that the effects are accelerated in time.

Aromatic: A major group of unsaturated cyclic hydrocarbons containing one or more rings which have six carbon atoms and three double bonds.

Armor Tape: The outer tape layer on form-wound coils principally intended to provide physical protection during fabrication and subsequent resin treatment and aids in resin retention.

Assembly Aids: Materials or products used during winding fabrication or treatment that are retained in the winding but do not provide any electrical, mechanical, or structural functions during motor operation or negatively affect these functions of the insulating system or its materials.

Blocking: Material inserted between individual coil end turns to provide uniform spacing and mechanical support.

Build: The thickness of varnish / resin that is retained on a coil after treatment.

Calendering: Part of a paper's manufacturing process when the paper is squeezed/compressed as it passes through rollers creating a denser material with a smooth and sometimes glossy surface. Not all papers are calendered.

CERN: Organisation Europeenne pour la Recherche Nucleaire (European Organization for Nuclear Research; formerly known as Conseil Europeen pour la Recherche Nucleaire from which the acronym is derived).

Chemical Spray: A water spray, containing chemicals which can occur or are used inside a nuclear power plant containment after a LOCA type accident, designed to remove certain radioactive species and lower the temperature of the containment atmosphere.

Continuous Duty: Operating at a load within the motor's nameplate rating for an indefinite time.

Corona: A form of electrical discharge occurring between conductors when the breakdown voltage of an intervening gas (usually air) is exceeded and the gas ionizes.

Dacron®: The DuPont trade name for polyethylene terephthalate (PET) fabric material. Dacron is often used in place of the more generic term which is polyester fabric.

Daglas: A term referring to Dacron-glass woven fabrics. These fabrics are composed of both fiberglass and polyester (Dacron) fibers.

DGEBA: Diglycidyl Ether of Bisphenol A, the base epoxy resin most often used to treat motor windings.

Dip & Bake: A winding treatment process where the winding is immersed in a tank of varnish/resin and the varnish/resin is cured in a baking oven.

Dissipation Factor: The ratio of the energy dissipated to the energy stored in an insulating or dielectric material during each cycle of an alternating electromagnetic field. When expressed as a number, this value is an indicator of the amount of loss in a dielectric material.

DSC: Differential Scanning Calorimeter (DSC) is a laboratory instrument that measures the temperature and heat flow associated with transitions in small material samples as a function of time and temperature.

EASA: Electrical Apparatus Service Association.

Enamel: Unfilled solution coating applied to magnet wire as an insulating film.

Epoxy Resin: A large class of plastics containing two or more terminal or ring-situated reactive epoxide groups.

End Turns: Portion of a motor winding which extends beyond the stator core.

EPDM: Ethylene Propylene Diene Monomer Rubber.

EPR: Ethylene Propylene Rubber.

Equipment Qualification: The generation and maintenance of evidence that equipment will function when required during nuclear power plant design basis events (DBE).

EQ Rule: See 10 CFR 50.49.

Essentially Void-Free: The desired condition of a winding after Vacuum Pressure Impregnation (VPI) treatment. Such a state minimizes the effects of electrical, mechanical, and environmental stresses.

Felt: A nonwoven fibrous material that is generally highly saturable.

Formette: Form-wound insulating system model made to represent all the essential elements of a complete winding system and its structural supports. See IEEE 275 and IEEE 429.

Form-wound Coils: Coils formed of ordered layers of rectangular conductors.

Hardeners: A class of materials which when combined with rubbers and polymers react to reduce the ductility of a material and to increase its rigidity at relatively constant temperatures.

Harsh Environment: An operating environment associated with nuclear plant design basis accidents that can subject equipment to severe radiation, pressure, temperature, steam, chemical/water spray, or submergence conditions. (See also Mild Environment).

Heat-cleaned: A process whereby the sizing or coating in woven fiberglass products is removed to improved compatibility with saturants. Heat cleaning generally, but not always, refers to complete sizing removal.

HELB: Abbreviation for High Energy Line Break, referring to a hypothesized accident involving a breach in the piping of a nuclear power plant high energy system. A system with pressure >275 psig or temperature >200° F is generally considered a high energy system.

HELB, High pressure: As used in this guide, refers to a plant area's environmental conditions. High pressure HELB conditions occur when HELB steam pressurization in a particular plant area substantially exceeds a few psig.

HELB, Low pressure: As used in this guide, refers to a plant area's environmental conditions. Low pressure HELB conditions occur when HELB steam pressurization in a particular plant area is limited to a few psig, typically less than 3.

Helical Coil: A varnish bond strength test method described in ASTM D2519.

Hot Spot: The hottest spot, generally deep in a winding, reached at equilibrium during rated operation of a motor.

Hydrolysis: Splitting of chemical bonds in a plastic by water.

Infrared Spectroscopy: A laboratory apparatus that provides information on the chemical groups contained in a material based on measuring the material's infrared absorbency spectra.

Kapton®: The DuPont trade name for polyimide films. Kapton is often used in place of the more generic term which is polyimide film.

LOCA: Abbreviation for Loss-of-Coolant Accident, referring to a range of hypothesized accidents involving breaches in the Reactor Coolant Pressure Boundary. A design basis LOCA causes harsh environmental conditions within certain nuclear power plant regions, particularly primary containment.

Mat: Generally refers to the nonwoven fibrous material layer, which is highly saturable, in a paper composite.

Material; Like-for-Like: Another term for equivalent material.

Material Equivalent: A non-identical, substitute material whose suitability has been determined by an evaluation of those characteristics essential to the material's safety-related performance.

Mild Environment: An operating environment that at no time will be significantly different than conditions during normal plant operation, including anticipated operating transients. (See also Harsh Environment).

Mica: A naturally occurring inorganic material with extremely high - temperature, compressive, dielectric, and corona resistance properties.

MSLB: Abbreviation for Main Steam Line Break, referring to a hypothesized accident involving a breach in a nuclear power plant main steam line and the release of high pressure, high temperature steam to certain plant areas.

Motorette: Random-wound insulating system model made to represent all the essential elements of a complete winding system and its structural supports. See IEEE Standard 117.

Mylar®: The DuPont trade name for polyethylene terephthalate (PET) film. Mylar is often used in place of the more generic term which is polyester film.

Nomex®: The DuPont trade name for aramid, a type of aromatic polyamide. Nomex is often used in place of the more generic term which is aromatic polyamide.

OBE: Operational Basis Earthquake.

Partial Discharge: Another term for corona.

Pyre ML®: DuPont trade name for its aromatic polyimide wire enamel.

PDIV: Partial Discharge Inception Voltage.

Polyester: A class of plastics containing repeated ester links in the polymeric chain.

Polyester-imide: A high temperature polymer containing both polyester and polyimide repeating units.

Polyimide: A very high temperature polymer. See Kapton and Pyre ML.

Premium Rewind: As used in this guideline refers to quality rewinds performed under process controls appropriate for safety-related applications and utilizing insulating systems and materials with high thermal and dielectric capabilities.

PSA: Pressure Sensitive Adhesive - used to describe pressure sensitive adhesive tapes.

Qualified Life: Period of time for which a component has been demonstrated, through testing, analysis, or experience, to be capable of functioning within acceptance criteria during specified operating conditions while retaining the ability to perform its safety functions in a design basis accident or earthquake.

Radiation; Alpha: Particle (helium nucleus) radiation possessing very limited penetration power.

Radiation; Beta: Electron radiation possessing a penetrating power between alpha and gamma radiation.

Radiation; Gamma: High energy photon radiation possessing relatively high penetrating power when compared to alpha and beta radiation.

Radiation; Neutron: Radiation due to energetic neutron particles.

Random-wound Coils: Coils formed of randomly ordered round conductors.

Resin: A solventless, solvent-borne, or water-borne thermoplastic or thermosetting polymer used as a component (coating) in insulating systems.

Rewind: The activities involved in replacing the stator, armature, or pole windings in a motor with an equivalent or superior winding. Rewind includes, but is not limited to, old winding removal and forming, inserting, connecting, and resin treating the replacement winding.

Saturation: A term describing the thermodynamic state of a condensable gas (e.g., water vapor) when the gas temperature equals its boiling point based on the gas partial pressure.

Sealed: A term referring to treated windings capable of being successfully tested electrically underwater.

Silane: A class of silicone materials used as coupling agents.

Silicones: Any of a large group of siloaxane polymers based on a structure consisting of alternating silicone and oxygen atoms with various organic radicals attached to the silicone.

Sizing: A coating used to aid in the manufacture of woven fabric products. Special sizing also may be applied after fabric manufacture to achieve improved compatibility with a particular varnish/resin.

Sleeving: The general term applied to tubes woven from fibers and supplied either uncoated or coated with impregnants or elastomers.

Solventless Resin: 100% solids resin.

SSE: Safe Shutdown Earthquake.

Statorette: Another term for formette.

Superheat: A term describing the thermodynamic state of a condensable gas (e.g., water vapor) when the gas temperature exceeds its saturation temperature based on the gas partial pressure.

Surge Ring: A circular ring tied to the coil end turns providing physical strength which minimizes end turn deflection, especially during starting. As used in this guide includes metal rings, woven rings, and other devices providing the same function.

TEAO: Totally Enclosed Air Over.

TEFC: Totally Enclosed Fan Cooled.

Temperature Rise: The increase in temperature of a motor winding occurring as a result of being energized and loaded.

TEWAC: Totally Enclosed Water-to-Air Cooled.

TGA: Thermogravimetric Analysis (TGA) uses a specialized laboratory instrument to measure the amount and rate of change in the weight of a small material sample as a function of temperature or time in a controlled atmosphere.

Thermal Class: A letter designation representing a specific range of thermal index values. The classifications are defined in the NEMA standards.

Thermal Index: A number in degrees Celsius derived from evaluating accelerated thermal aging data and generally based on data extrapolation to a 20,000 hour end-of-life condition.

Thermal Index, Relative: A thermal index based on comparing the extrapolated life values (based on accelerated aging tests) of a known system / material and a reference system / material with considerable service experience.

Thermal Lag Analysis: Mathematical analysis of heat flows and temperatures which determines the delay in temperature changes due to mass and heat transfer considerations.

Thixotropic: The characteristic of certain fluids to become more viscous at rest than when flowing. Generally applied to varnishes containing an additive to create this characteristic.

Threshold Dose: The lowest radiation dose which induces permanent changes in a measured property(s) of a material; also, the first detectable change in a property of a material due to the effect of radiation.

Traceability: Information demonstrating that certain materials are identical.

Twisted Pair: A test specimen, described in several ASTM testing standards, composed of two magnet wires twisted together and used in performing dielectric strength tests. Often the test specimens will be coated with a varnish. The dielectric test may be performed on unaged or aged specimens.

Type Testing: A method of qualification which subjects representative equipment to a sequence of tests which simulate significant aging mechanisms and accident service conditions and verifies that the equipment functioned within its acceptance criteria (also called qualification testing).

VPI: Vacuum Pressure Impregnation - a winding treatment process that is intended to enhance resin penetration through the application of alternate cycles of vacuum and pressure.

XLPE: Crosslinked Polyethylene and applied generically to any Crosslinked Polyolefin.

3.0

HARSH ENVIRONMENT MOTOR CATEGORIES

This section provides the reader with a general understanding of the types of motors potentially used in harsh environment applications and the types of harsh accident environments that are hypothesized to occur in various nuclear plant areas. On the basis of this general information and the results of an industry survey, a matrix of motor types and harsh environments is presented. This motor type - environment matrix is used to evaluate the qualification basis for existing systems and to further amplify the qualification considerations applicable to specific motor type - environment categories.

3.1 Motor Types

A wide variety of motor designs have been developed to meet an enormous number of residential, commercial, and industrial applications, including power plants. There are a variety of ways to classify these motors, including voltage, size, winding design, enclosure type, torque characteristics, etc. For the purposes of this guide, motors are classified by voltage type (AC or DC), winding design (random-wound or form-wound), duty rating (continuous or intermittent), and enclosure type (open or totally-enclosed).

3.1.1 Voltage Type

The vast majority of power plant motors are three-phase, AC, squirrel-cage, induction motors. This design is so pervasive that further discussions of AC motors in this guide refer, unless otherwise noted, to this design. Squirrel cage induction motors have a stator (stationary) winding insulation system. The rotors (the rotor bars and rings resemble a squirrel cage) are normally fabricated from copper or aluminum and do not require insulating systems. Both medium voltage (e.g., 2,300, 4,000, and 6,600 volts) and low voltage (e.g., 460 and 575 volt) AC motors exist in harsh environment applications.

DC motors contain both stator and rotor winding systems. Stator windings are generally termed field windings and the rotor windings are called armature coils. Both the field and armature windings contain insulating systems. Typical DC motors in nuclear power plants are operated from 125 or 250 Vdc systems.

3.1.2 Winding Design

The physical design of both stator and rotor windings can be divided into the random-wound (sometimes called mush-wound) and form-wound categories. Figures 3.1 and 3.2 illustrate the general construction features of these two winding types. Since design, material selection, and fabrication methods differ for these two types, specific insulation system qualification efforts generally focus on one type.

The random-wound construction is almost universally used for the windings of fractional and smaller size integral horsepower motors (i.e., < 250 horsepower and ≤ 600 volts). This includes the stator and rotor windings in both AC and DC motors. The field poles (stator windings) in DC motors are random or layer wound with additional insulation between the layers. Each random-wound coil is formed by using specific size, round, enamel insulated, magnet wire wound into a coil loop of a specified number of turns. Since full coil voltage could exist between adjacent turns, the turn-to-turn insulation must be designed for the maximum coil potential. The remaining random-wound insulating system materials (e.g., phase-to-phase and phase-to-ground insulation, slot wedges, etc.) are then assembled with the coils in the core slots to provide full phase-to-phase and phase-to-ground insulation.

In larger motors, the number and size of the conductors, the physical forces developed during starting and running, and the higher voltages and currents favor the use of the form-wound coil construction. *Form-wound* coils are fabricated of multiple turns of insulated square or rectangular magnet wire which are bent and formed into a precise geometry. Each formed coil is individually insulated prior to being inserted into the core slots. Due to the larger cross-sectional area and the physical strength of form-wound insulating systems, they are used almost universally above 250 HP and for virtually all medium and high voltage applications.

Random and form-wound insulating systems contain similar components. Table 3.1 lists the common elements of an AC stator insulating system. EPRI in TR-103585, *Guidelines for the Selection, Procurement, and Acceptance of Nuclear Safety-Related Mild Environment Motor Insulation for Rewinds,* [1] provides additional information on the function, material, and design of these components. Similar components, with slightly different designations, exist in DC field windings. Armature winding systems, in addition to these components, require banding materials and commutator / ring assemblies. Brushes, brush holders, and connection wires are also required.

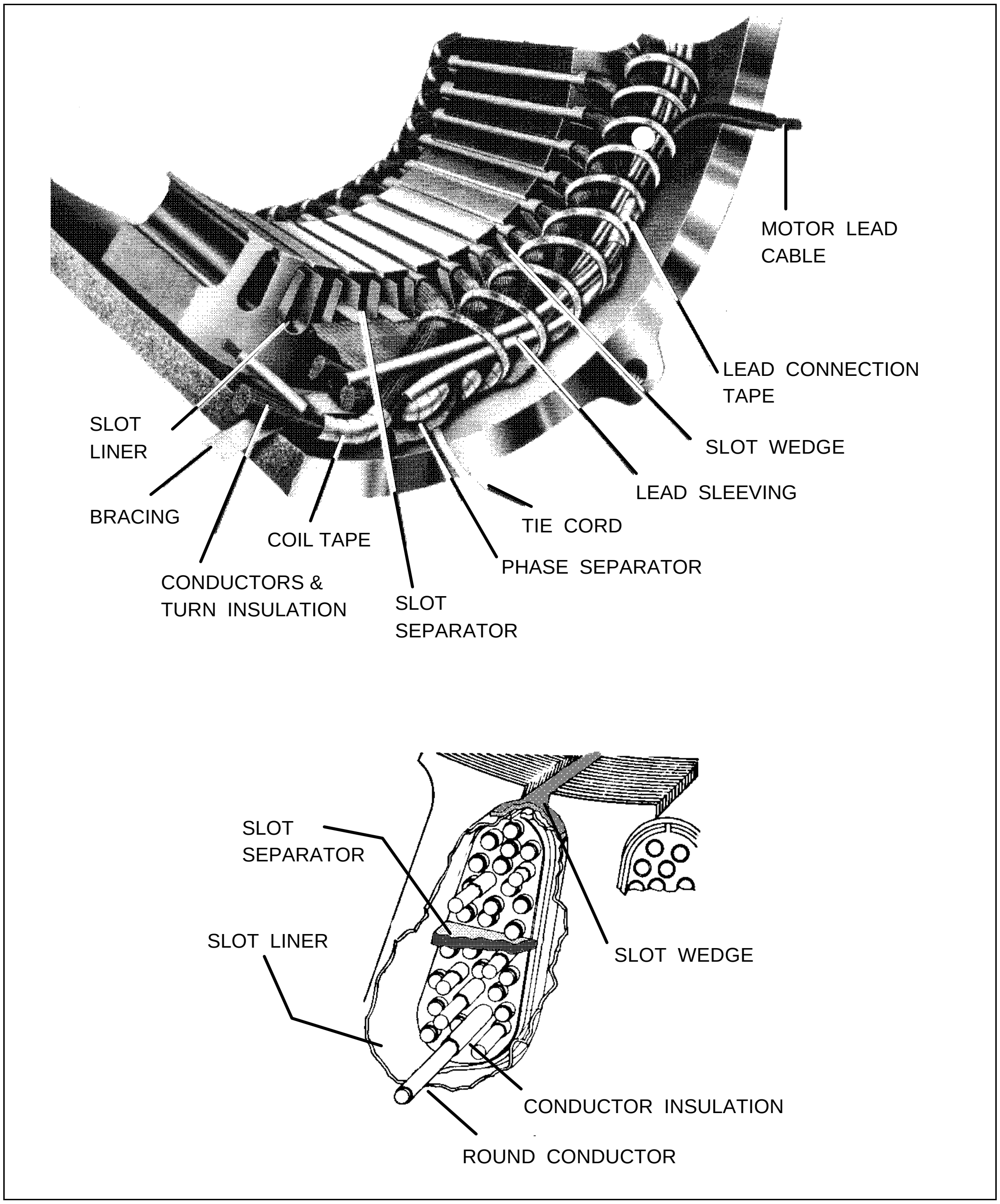


Figure 3.1
Example Random-Wound Construction

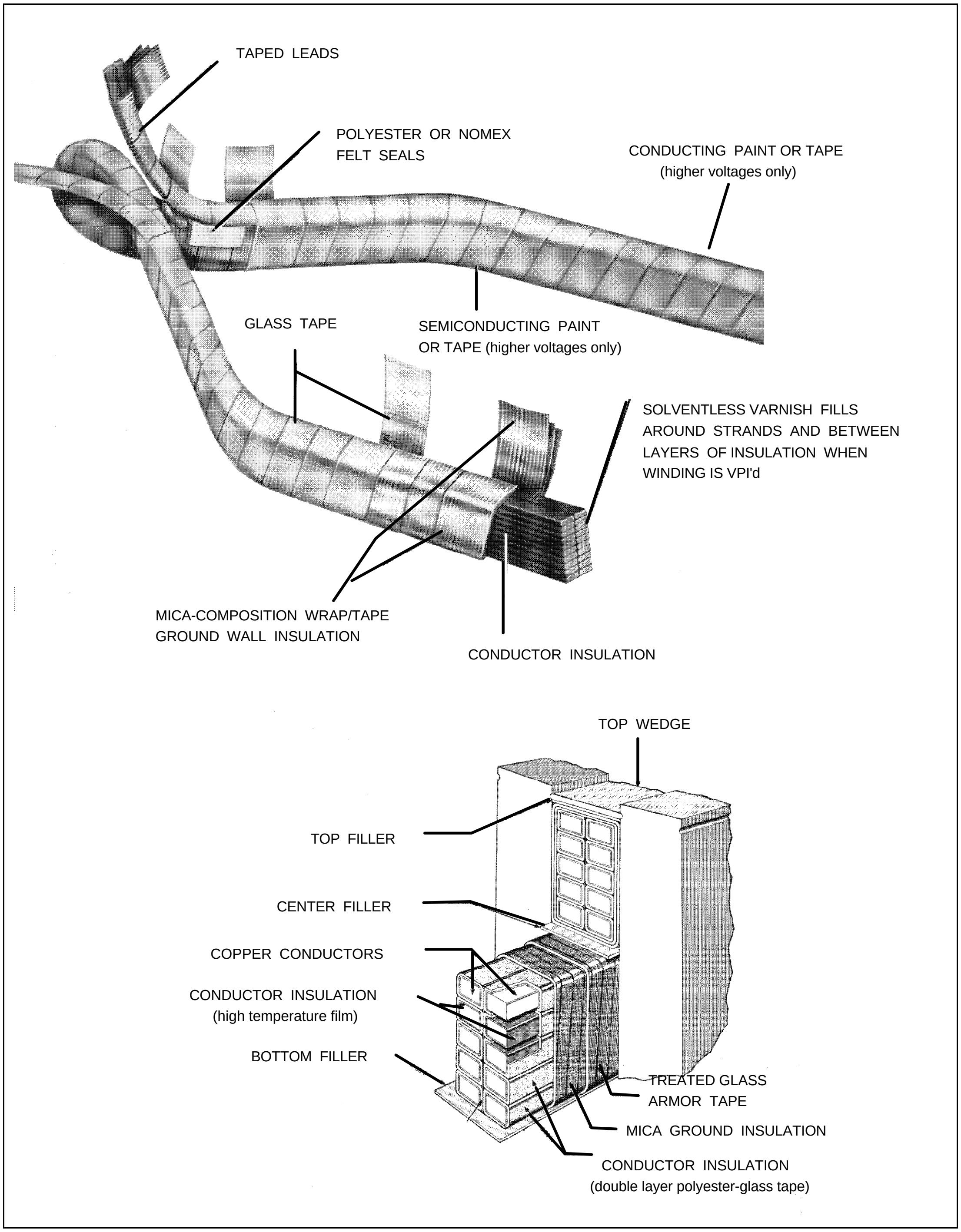


Figure 3.2
Example Form-Wound Construction

Table 3.1
Insulating System Components

1.	Magnet Wire (Turn-to-Turn Insulation)
2.	Phase-to-Ground insulation
3.	Phase-to-Phase insulation
4.	Slot Wedge / Filler Strips
5.	Resin / Varnish Winding Treatment
6.	Coil Electrical Interconnections
7.	Motor Lead Wire
8.	End-Turn Bracing

3.1.3 Enclosure Design

The National Electrical Manufacturers Association (NEMA) has established two broad enclosure classifications, *Open* and *Totally-Enclosed* [2]. Various constructions fall within these basic categories. The most commonly used constructions in power plant service are *Open Dripproof* and *Totally Enclosed Fan Cooled* (TEFC). Totally Enclosed Air Over (TEAO), Totally Enclosed Water-Air Cooled (TEWAC), and Explosion-Proof enclosures are also found in certain applications.

Open machines have ventilation openings permitting passage of external cooling air over and around the motor windings. The *open dripproof* motor is the most common of the open frame constructions.[1] Per NEMA, a dripproof motor is "*an open machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle from 0 to 15 degrees downward from the vertical*". Open dripproof motors are typically used in areas where dripping or falling material comes from overhead. This type of construction is almost universally used in power plants for large motors (and some integral and fractional horsepower motors) located indoors, particularly in areas not generally subject to splashing or dirty atmosphere. The advent of sealed VPI insulating systems has led to the use of dripproof motors in locations considered more severe. Although sealed systems may provide adequate protection of the windings, the bearing and lubrication system may be subjected to environmental conditions beyond their design capabilities.

[1] See NEMA MG-1 [2] for other open and totally enclosed construction types.

NEMA defines a totally-enclosed machine as "*one so enclosed as to prevent the free exchange of air between the inside and the outside of the case but not sufficiently enclosed to be termed air-tight*". The Totally-Enclosed Fan-Cooled (TEFC) design is the most common power plant totally enclosed design. Per NEMA, TEFC motors are equipped for exterior cooling by means of a fan(s) integral to the machine but external to the enclosed parts. TEFC enclosures are not hermetically sealed. In fact, the enclosure is often equipped with drain fittings (e.g., T-drains) which are used at low-points to prevent the accumulation of condensation inside the motor enclosure.

3.1.4 Duty Cycle

The duty cycle refers to the duration of time a motor is capable of providing output in accordance with its ratings. Two duty cycles are of interest in power plant applications: *continuous duty* and *intermittent duty*. Continuous duty motors are capable of operation under the nameplate conditions for indefinite periods of time. Most non-valve actuator motors are rated for continuous duty. Valve actuator motors, such as those supplied by Limitorque Corporation, are usually 5 or 15 minute intermittent duty motors. Since valves are cycled infrequently, valve actuator motors are designed to provide high output levels for short periods of time. Short duty cycle motors would overheat and burn-up if they were operated for prolonged periods at their rated output.

3.2 Harsh Environment Conditions

A harsh environment can be described as the operating environment resulting from a nuclear plant accident that subjects equipment, located in selected plant areas, to significant increases in radiation, temperature, pressure, steam, chemical/water spray, or submergence conditions. The plant accidents producing such conditions involve either: 1) breaches (i.e., pipe breaks or leaks) in the pressure boundary of the reactor coolant system, called loss-of-coolant accidents or LOCAs, or 2) breaches in the pressure boundaries of other plant process (principally steam) systems. Harsh environmental conditions may result: 1) as a direct consequence of the accident, such as steam and radiation releases during LOCA, 2) from the action of plant systems in response to the accident, such as the chemical or water sprays inside primary containment, or 3) from the assumed unavailability or failure of other plant equipment, such as loss of ventilation causing increased ambient temperatures.

Pipe-breaks producing such conditions can be described and classified in several ways. Some of the most common terms, their abbreviations, and general descriptions are presented in Table 3.2.

Table 3.2
Summary Classification of Pipe-Break Accidents

Accident	Abbreviation	Description
loss-of-coolant accident	LOCA	Reactor coolant system breaks within primary containment. For BWRs includes both fluid and steam pipe breaks.
main steam line break	MSLB	Main steam line breaks, both inside and outside primary containment for PWRs, and outside containment for BWRs.
high energy line break	HELB	Typically, breaks in systems with temperatures >200°F *or* pressures >275 psig
moderate energy line break	MELB	Typically, breaks in systems with temperatures $\leq$200°F *and* pressures $\leq$275 psig

3.2.1 LOCA Effects

The term LOCA can refer to a range of breaks in the reactor coolant system up to and including an instantaneous, guillotine break of the largest reactor coolant pipe, often referred to as a DBA (design basis accident) LOCA. Reactor coolant system DBA LOCA mass and energy releases to the primary containment create the most severe inside containment LOCA steam, pressure, and temperature transients. Smaller size reactor coolant system breaks, referred to as small break LOCA or SBLOCA, typically result in less severe transients. Multiple redundant plant safety systems are designed to prevent fuel failure and the release of significant fission products (radiation) during LOCA type accidents. However, for the purposes of equipment qualification, significant fuel assembly failure and an *instantaneous* release of a significant quantity of radiation into primary containment is currently assumed.[2] In PWR (non-ice condenser) plants, containment sprays are initiated in response to the LOCA to reduce containment pressure/temperature and to help remove some of the fission products from the containment atmosphere and surfaces exposed to the sprays. The sprays typically contain borated water and are often buffered with various chemicals to increase the spray pH.[3] BWRs have

2 Ongoing NRC and industry activities to define and implement revised source terms may change some of these radiation release assumptions, including the instantaneous release.

3 Maintaining spray pH above 7.0 assists in the removal of radioactive iodine. After chemical addition spray pH values are typically cited as roughly 11.0.

demineralized water containment sprays which reduce containment temperature and pressure conditions. Figures 3.3 and 3.4, from IEEE 382-1985, present typical LOCA inside containment conditions often used for qualification. Required conditions and accident durations vary from plant to plant.

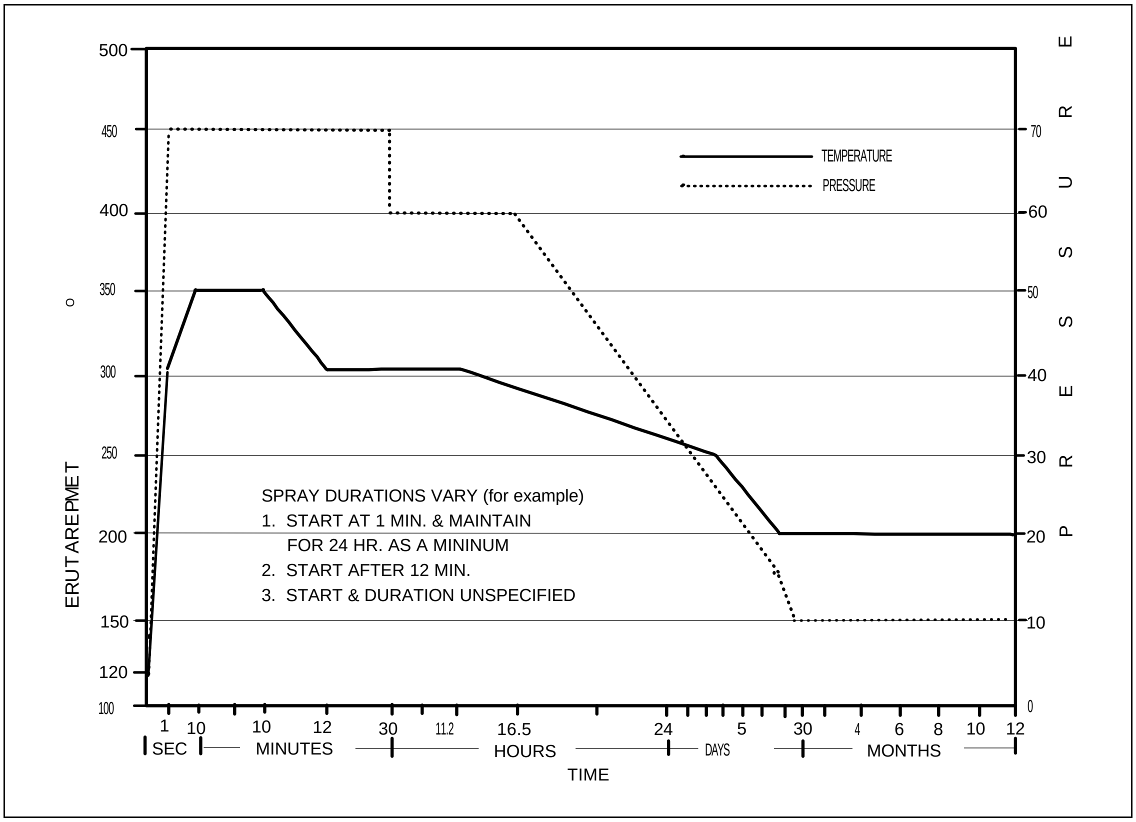


Figure 3.3
Typical Inside Containment PWR LOCA Conditions for Qualification

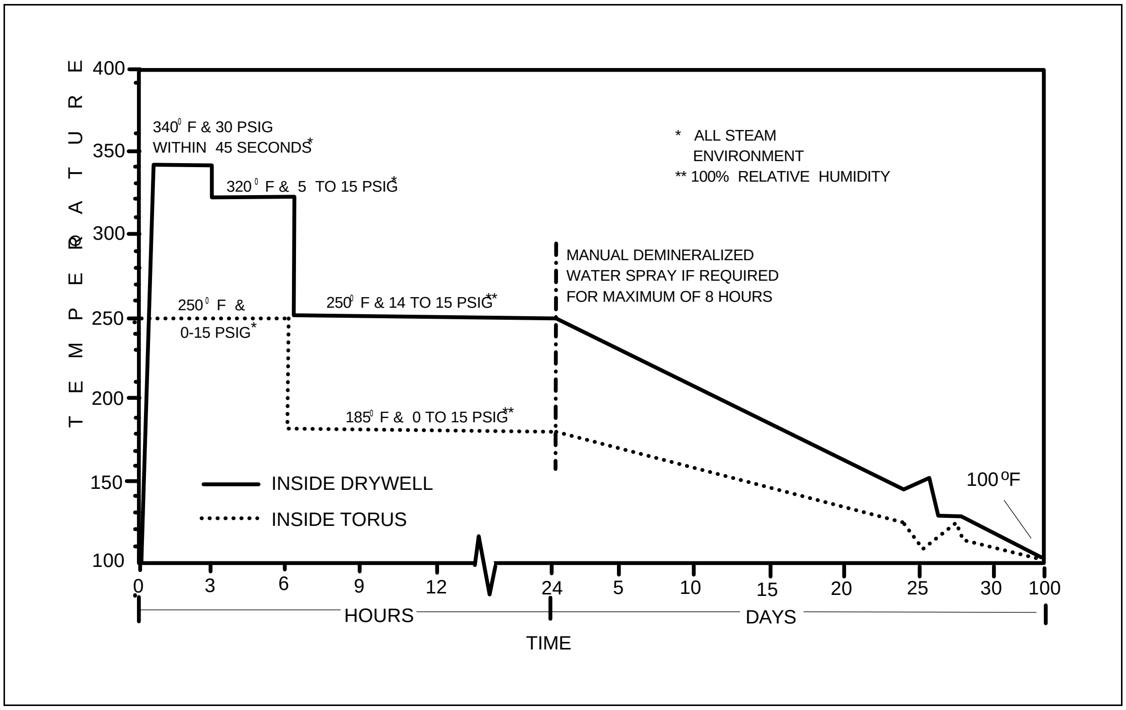


Figure 3.4
Typical Inside Containment BWR LOCA Conditions for Qualification

With the exception of radiation, all the LOCA harsh conditions are confined within the primary containment. LOCA radiation conditions may exist outside primary containment in three instances. First, gamma radiation within the primary containment can penetrate the primary containment walls. Since the containment boundary provides significant shielding for most plant areas, the amount of radiation exposure outside the containment due to radiation sources within containment is relatively low. One exception is the room surrounding the suppression pool (i.e., torus or wetwell) of many BWR plants. Piping and electrical penetrations through the containment wall may also provide less shielding. Secondly, radioactive water (i.e., reactor coolant system, containment sump, or suppression pool fluid) from inside containment can be piped outside containment for the purpose of pumping/cooling, sampling, or cleaning-up the fluids. This radiation source is often referred to as recirculating fluid. The piping systems containing these fluids provide some minimal shielding. The amount of recirculating fluid radiation exposure experienced by equipment outside containment is related to the equipment's location relative to the piping systems containing the radioactive fluids and the containment boundary. Many motors located outside containment and exposed to LOCA radiation provide power to the pumps and valve actuators that are part of these radioactive piping systems. Finally, in BWRs, radioactive leakage from the primary containment is captured by the surrounding secondary containment (termed the reactor building). This radiation is widely dispersed throughout the Reactor Building. The amount of released radiation is based on licensing assumptions, including containment leak rate. Generally, the amount of radiation dose due to this leakage is relatively low when compared to the total dose near pipes with recirculating fluids.

Tables 3.3 and 3.4 provide information on typical inside containment and outside containment radiation levels used for qualification. As Table 3.4 suggests, both normal and accident radiation values for outside containment equipment are highly dependent on equipment location. Those presented in Table 3.4 represent upper limit doses. Section 7 provides additional information on the differences between beta and gamma radiation effects.

Table 3.3
Typical Inside Containment LOCA Radiation Conditions Used for Qualification

Plant Type	Normal Dose (gamma)*	Accident Gamma Dose	Accident Beta Dose	Total Dose
PWR (large dry type)	1 - $2x10^6$ rad	1 - $2x10^7$ rad	1 - $2x10^8$ rad	1 - $2x10^8$ rad
BWR (Mark 1 type)	1 - $2x10^6$ rad	2 - $3x10^7$ rad	4 - $5x10^8$ rad	4 - $5x10^8$ rad

* Total dose over 40 years of operation

Table 3.4
Typical Outside Containment LOCA Radiation Conditions Used for Qualification

Plant Type	Normal Dose (gamma)*	Accident Dose	Total Dose
PWR (large dry type)	0.1 - $2x10^7$ rad	0.2 - $2x10^7$ rad	$<5x10^7$ rad
BWR (Mark 1 type)	0.1 - $2x10^7$ rad	0.2 - $2x10^7$ rad	$<5x10^7$ rad

* Total dose over 40 years of operation

In summary, for equipment located outside containment, the only direct environmental effect of the LOCA is increased radiation. Many outside plant areas containing safety-related equipment may also experience increased temperatures due to the assumed unavailability of ventilation systems or related equipment.

Generally, the resulting ambient temperature increases are fairly gradual and are often considered within the normal design capability of the equipment.

3.2.2 Main Steam Line Break (MSLB) Effects

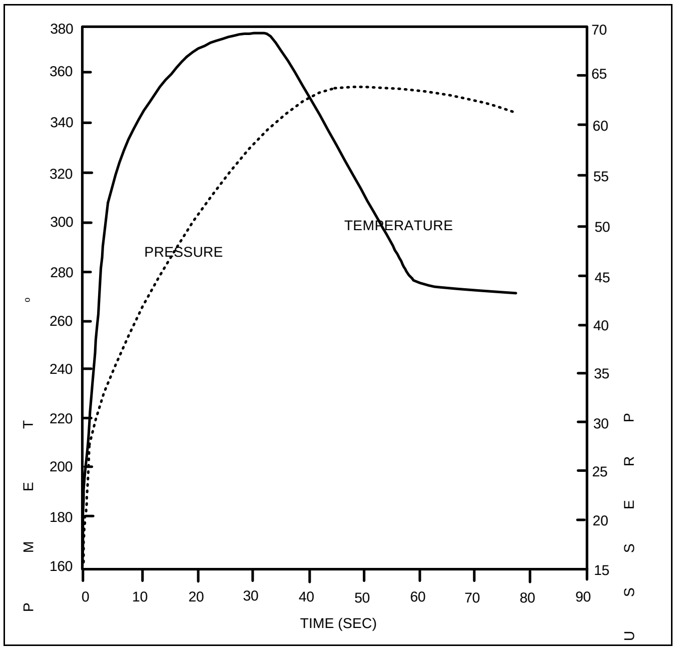
MSLBs can occur both inside and outside containment. Assumed breaks or leaks in these high pressure (e.g., >1000 psig) high temperature (e.g., >500°F) lines can produce significant temperature excursions. With the possible exception of BWR steam line breaks inside containment, most utilities assume that little if any significant radiation is released as a result of these steam line breaks. The pressure and temperature conditions resulting from MSLBs can vary significantly depending on the break size assumptions.

Inside containment MSLBs generally produce lower pressures and higher temperatures than DBA LOCAs. The worst-case inside containment MSLBs used for qualification purposes often exhibit rapid short-term superheated steam conditions that only last a few (e.g., 1 - 4) minutes and rapidly decay to saturation temperatures that are bounded by DBA LOCA temperature curves. In some cases, manual operation of borated water spray (PWR) or demineralized water spray (BWR) is credited. Spray operation rapidly cools the containment atmosphere. Some utilities perform studies to define the different temperature / pressure responses based on varying MSLB break size. Some plants, particularly BWRs, envelope these responses with a single qualification curve. Others select the "worst-case" curve as the basis for qualification. Figures 3.5 and 3.6 present examples of inside containment MSLB conditions.

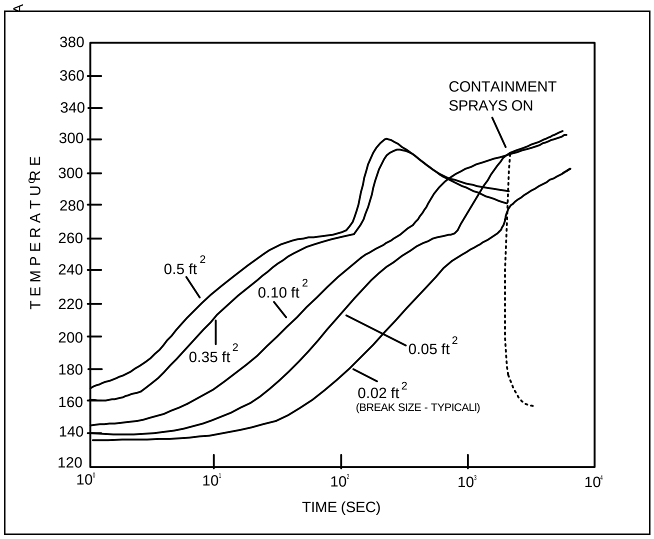
The environmental conditions resulting from *outside containment* MSLBs are highly dependent on the break size and its location relative to the affected motor. Most outside containment pipe breaks are relatively low pressure events (e.g., < 1 psig) since building roofs, blowout panels, and doors fail at low pressures and minimize further pressure increases. However, temperatures can be very high. If large breaks occur in small rooms, superheated temperatures in the range of 450°F - 500°F may exist. Temperature conditions will vary from room to room. The highest temperatures occur in the room housing the break with temperatures decreasing in rooms further removed from the escaping steam.[4] A large, double-ended, guillotine outside containment MSLB is quickly terminated by automatic operation of the Main Steam Isolation Valves. Consequently, the high temperature

[4] Pressurization and venting of the escaping steam can affect a number of rooms and plant areas. In areas slightly removed from the break, doors and other environmental barriers can prevent the steam from penetrating certain plant areas.

condition only occurs for a few seconds. Small steam leaks may exist for longer periods and are generally terminated by manual operations.



Figures 3.5
Example PWR Inside Containment MSLB Conditions



Figures 3.6
Example BWR Inside Containment MSLB Conditions

3.2.3 Other High Energy Line Break (HELB) Conditions

Other outside containment pipe breaks can be classified as either a high energy line break (HELB) or a moderate energy line break (MELB). Motors are not typically qualified to MELB conditions which are limited to water sprays and possible submergence.[4] Outside containment HELB conditions result from steam or high pressure hot fluid lines. Like an outside containment MSLB, these break conditions are dependent on break size and location relative to affected motors. Peak pressure rarely exceeds a few psig; but peak temperatures vary widely, based on room size and mass/energy release rates. Peak temperatures are typically in the range of 150°F to 400°F. In many plants, particularly BWRs, automatic methods are used to sense and isolate the break conditions. Since smaller breaks may require manual detection and isolation, they can exist for a longer duration. However, lower peak environmental temperatures result from these smaller breaks. Most utilities use the environmental conditions resulting from shorter time, higher temperature, double guillotine line breaks as their basis for environmental qualification. Radiation releases associated with HELB events are limited by the sources contained in the piping system fluid. In virtually all cases, for qualification purposes, little if any radiation is released from these breaks.

3.2.4 Accident Environment Groupings

In summary, a LOCA produces high temperature, high pressure steam, and high radiation conditions inside containment but outside containment effects are limited to moderate to high radiation levels. In limited cases, outside containment elevated temperatures may result from the assumed loss of ventilation systems. An MSLB inside containment produces superheated steam conditions inside containment without appreciable radiation releases and with no harsh environments outside containment. An MSLB outside containment can produce high superheat temperatures, with near atmospheric pressures, and without significant radiation releases.

Table 3.5 presents representative accident environmental conditions for both inside and outside containment locations as a result of LOCA and other line break accidents. The shaded portions represent plant areas where one or more environmental conditions potentially become harsh. Examination of Table 3.5 indicates that inside containment equipment would require qualification for two different types of conditions: 1) LOCAs with concurrent high temperature/pressure

[4] Safety-related equipment is usually protected from such water sprays and located where submergence will not occur.

steam and radiation combined with containment spray (Area A) and 2) MSLBs with superheated steam but little radiation (Area B). Similarly, outside containment equipment is exposed to two distinctly different accident conditions: 1) LOCA with harsh conditions limited to radiation (Area C) and 2) HELBs, with superheated (or lower temperature) steam at near-atmospheric pressure but little radiation (Area D).

Table 3.5
Representative Accident Related Environmental Conditions

Accident Conditions	Inside Containment Effects	Outside Containment Effects
LOCA		
Temperature (peak)	250ºF - 340ºF	normal*
Pressure (peak)	60 psig	normal
Steam / Humidity	yes / 100% **AREA**	normal **AREA**
Water / Chem. Spray	yes **A**	none **C**
Gamma Radiation	1.5x10^7 rad**	yes - ≤ 10^7 rad
Beta Radiation	1.8x10^8 rad**	not significant ***
MSLB (occurring inside containment)		
Temperature (peak)	250ºF - 400ºF (superheat)****	normal*
Pressure (peak)	45 psig	normal
Steam / Humidity	yes / 100% **AREA**	normal
Water / Chem. Spray	yes **B**	none
Gamma Radiation	not significant	normal
Beta Radiation	not significant	normal
HELB (occurring outside containment)		
Temperature (peak)	normal*	150ºF - 500ºF (superheat)
Pressure (peak)	normal	0 - 3 psig
Steam / Humidity	normal	yes **AREA**
Water / Chem. Spray	none	none **D**
Gamma Radiation	normal	not significant
Beta Radiation	normal	not significant

Legend: * - Insignificant increases due to loss of ventilation assumptions
** - Per Regulatory Guide 1.89 for typical PWRs. BWR doses may be higher.
*** - For BWR Reactor Building roughly 10^5 rad
**** - Quickly reduced to saturation temperatures due to the action of containment sprays

For the purposes of this guide and its qualification discussions these environmental conditions have been reduced to the following three environmental groupings:

- **LOCA Inside Containment** - Principally the inside containment LOCA conditions, including radiation, but also including various HELB steam conditions producing high temperature steam environments with pressures significantly above ambient pressure. (Table 3.5, Areas A and B).
- **HELB Outside Containment** - Includes steam line break conditions where ambient pressures are not significantly above normal ambient pressure. (Table 3.5, Area D).
- **Radiation-only** - Involves those outside containment applications only experiencing significant radiation during LOCAs. (Table 3.5, Area C).

Certain outside containment motors can be exposed to radiation-only conditions for LOCA accidents and to steam line break conditions for certain HELB accidents. Consequently, these motors can fit within two of these environmental groups. In these cases qualification for the motor insulating system might be established in several ways. In one scenario, radiation-only qualification would be established based on radiation testing data of the insulating system and its materials. HELB qualification would be established based on high-temperature, high-humidity tolerance data for the system. Alternatively, qualification for both the radiation-only and HELB conditions could be based on qualification testing to combined radiation and steam conditions (e.g., inside containment LOCA conditions).

3.3 Guideline Scope Matrix

Table 3.6 summarizes the results of a utility questionnaire regarding harsh accident conditions and the types of continuous and intermittent duty motors requiring qualification to these environments. Based on this information, the remainder of this guideline focuses on three categories of environmental conditions and a limited set of motors within each category. The motor types included within these categories are shaded in Table 3.6.

The first category, *LOCA*, will encompass both inside containment LOCAs and HELBs. These two accidents are combined into the LOCA category since both produce relatively high-pressure steam conditions. However, inside containment HELBs have substantially lower accident radiation doses. This guideline only addresses random-wound (continuous-duty and intermittent-duty) motors under the LOCA category since only a few form-wound motors exist in relatively few plants.

The second category is *low-pressure outside containment HELB*. Virtually, all outside containment motors exposed to steam conditions fall into this category. Since only a few motors, if any, require qualification to higher pressure outside containment

HELB conditions, these higher pressure conditions and motors are excluded from further discussion in this guide. Motor insulating system designs qualified for inside containment LOCA / HELB conditions can be used for these higher pressure outside containment conditions. Random-wound continuous- and intermittent-duty, as well as form-wound continuous-duty motors, are included in the low-pressure HELB category.

The last category, *radiation-only harsh*, includes random-wound continuous- and intermittent-duty as well as form-wound continuous-duty motors. Most plants have a number of radiation-only harsh motors, although in many plants some of these motors must also be qualified for low-pressure HELB conditions.

Table 3.6
Guideline Scope Matrix

Accident Conditions	Random-Wound	Form-Wound
Continuous Duty		
Inside Containment LOCA	Several motors in some PWR plants, particularly containment cooler fan motors *	Only a few Westinghouse plant containment cooler fan motors
Inside Containment HELB	Several motors in some PWR plants, particularly containment cooler fan motors *	Only a few Westinghouse plant containment cooler fan motors
Outside Containment HELB - low-pressure	Several motors in all plants **	Several motors in most plants **
Outside Containment HELB - higher-pressure	Few, if any, motors	Few, if any, motors
Outside Containment radiation-only harsh	Several motors in all plants***	Several motors in all plants***
MOV and other Intermittent Duty		
Inside Containment LOCA	Numerous motors in most plants *	None
Inside Containment HELB	Numerous motors in most plants *	None
Outside Containment HELB - low-pressure	Numerous motors in most plants **	None
Outside Containment HELB - higher-pressure	Few, if any, motors	None
Outside Containment radiation-only harsh	Numerous motors in most plants ***	None

Notes: * - Motors in the **LOCA** qualification category
** - Motors in the **low-pressure outside containment HELB** category
*** - Motors in the **radiation-only harsh** qualification category

3.4 References

1. *Guidelines for the Selection, Procurement, and Acceptance of Nuclear Safety-Related Mild Environment Motor Insulation for Rewinds.* Electric Power Research Institute, Palo Alto, CA: July 1994. Report TR-103585.
2. NEMA MG-1, “Motors and Generators, National Electrical Manufacturers Association”.

4.0

GUIDELINE METHODOLOGY AND GENERAL INFORMATION

This section presents the overall methodology and general guidance on qualification for harsh environment conditions. More detailed qualification guidance, based on environmental and motor categories, is provided in Sections 5.0, 6.0, and 7.0.

4.1 Guideline Methodology

4.1.1 Scope

This section provides information which will permit utilities and their approved motor rewind shops to:

- Establish the harsh environment qualification of a motor rewind system for intended applications in accordance with applicable regulations (e.g., 10 CFR 50.49), regulatory guidance documents (e.g., NUREG-0588), and standards (e.g., IEEE 334).
- Evaluate and determine the acceptability of substitute materials that may not be identical to those originally qualified as part of the rewind system's qualification. This includes manufacturer, material type, or material style variations.
- Procure and accept the selected materials for use in the rewind system.
- Fabricate windings consistent with the methods used to fabricate the originally qualified windings.

4.1.2 Process

The overall process for the repair of EQ safety-related motors is presented in Figure 4.1. The three major elements necessary to successfully achieve a qualified insulating system rewind are:

1. Establishing qualification of the selected insulating system in accordance with accepted EQ practices

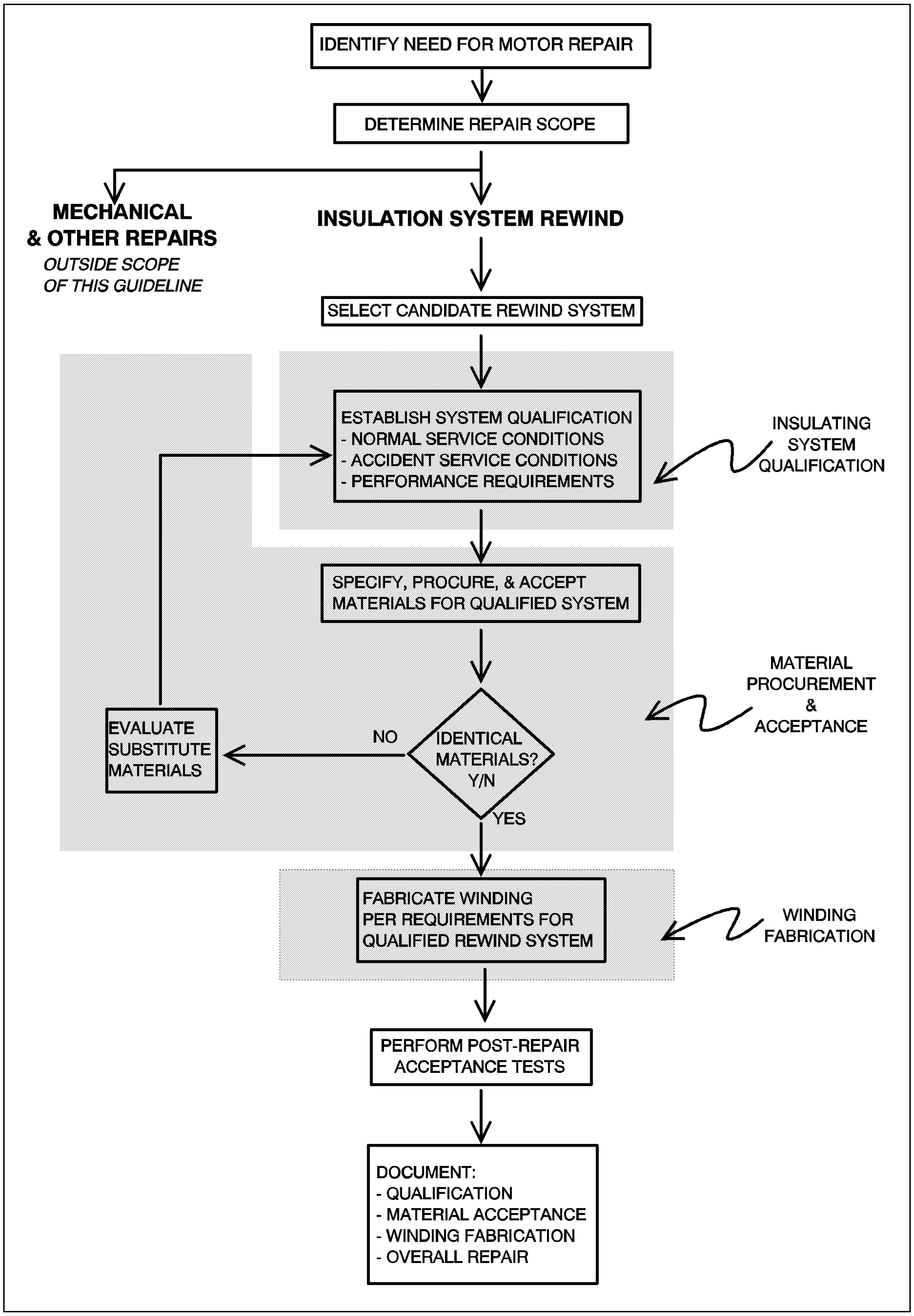


Figure 4.1
Overall Process for Repairing Qualified Motors

2. Specifying, procuring, and accepting the system's insulating materials
3. Fabricating the motor winding to achieve a qualified system
4. Confirm rewind acceptability through testing

Activities within each of these shaded elements are further identified in Figures 4.2 through 4.4 and discussed in this and subsequent sections.

4.1.3 Establishing Qualification

Figure 4.2 depicts activities necessary to establish insulating system qualification. Since this guide separates analysis and discussion of harsh environment motor qualification into three categories based on accident conditions, the figure suggests different methods for each of the following three categories.

1. **Inside Containment LOCA or HELB:** Motors exposed to inside containment Loss of Coolant Accident (LOCA) or High Energy Line Break (HELB) conditions through which the motors must provide their safety related functions (Section 5.0).
2. **Outside Containment HELB:** Motors exposed to outside containment HELB conditions through which the motors must provide their safety related functions (Section 6.0).
3. **Radiation-Only Harsh:** Motors located outside containment whose only harsh environment condition is radiation (Section 7.0).

Utility engineers are ultimately responsible for establishing the qualification of motors and other electrical equipment. Section 4.2 includes background information on environmental qualification and the IEEE standards applicable to motor qualification and establishing the thermal ratings of insulating systems and materials. Section 4.3 discusses qualification topics with particular relevance to establishing environmental qualification of motor rewinds. Both sections focus on motor related issues and assume the reader possesses a working knowledge of current industry EQ practices.

4.1.3.1 Inside Containment LOCA. For inside containment motors, the use of type tests is the preferred method of demonstrating environmental qualification. These type tests must address significant aging mechanisms potentially affecting motor performance and LOCA environmental conditions. Additional information on qualification of rewind systems for LOCA applications is contained in Section 5.

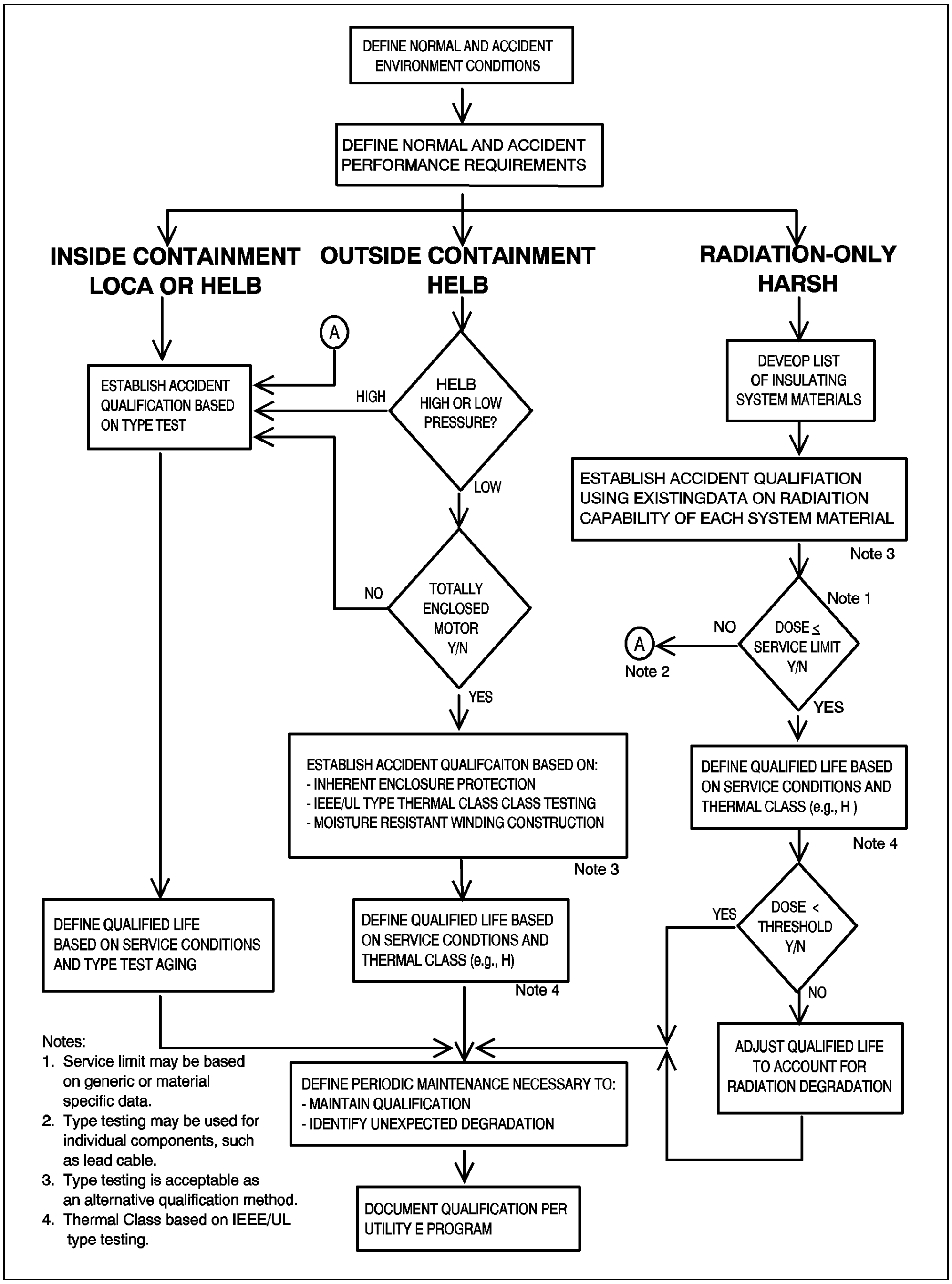


Figure 4.2
Decision Tree for Establishing Qualification of Insulating System Rewind

4.1.3.2 Outside Containment HELB. For motors exposed to outside containment low-pressure HELBs, Section 6 of this guide demonstrates the level of protection provided by the *totally-enclosed* type of motor enclosures (e.g. TEFC). By accounting for this level of protection, the guide argues that premium motor rewind systems in totally-enclosed motors possess the inherent capability to function properly during low pressure HELB conditions.[1] For motors in open-type enclosures exposed to these conditions, type tests remain the preferred qualification method. Information on the qualification of rewind systems for low-pressure HELB applications, including supporting detailed analysis and partial test data, is provided in Section 6. Although most outside containment HELB events are considered as low-pressure events, it is possible for motors in certain locations to be exposed to high-pressure HELB conditions. For motors in these locations, type tests remain the preferred qualification method.

4.1.3.3 Radiation-Only Harsh. For motors exposed to radiation-only harsh environments, total accident radiation doses outside containment rarely exceed $5x10^7$ rad. A significant body of radiation test data demonstrates that the insulating materials used in premium motor rewinds can tolerate, without significant damage, radiation doses in excess of $5x10^7$ rad. By accounting for this test data and other information on aging effects, Section 7.0 of this guide argues that premium motor rewind systems inherently possess sufficient radiation resistance to demonstrate functionality in these radiation-only harsh environments. Information on qualification of rewind systems for radiation-only harsh applications, including supporting detailed analysis and partial test data, is contained in Section 7.0.

4.1.4 Procurement and Acceptance

Figure 4.3 depicts procurement and acceptance activities, including evaluation of substitute materials. NRC regulations require that utilities or their suppliers have a formal acceptance program for those items procured commercial grade and used in safety related applications. Since evaluation of material substitutions can be critical to successfully establishing insulating system qualification, Section 4.4 focuses on this issue. The section includes a component-by-component discussion and provides guidance on material substitutions. The initial portion of Section 4.5 presents an overview of the process for accepting commercial grade items. Subsequent Section 4.5 information addresses traceability of the winding materials. Supplemental information on procurement and acceptance is provided in Sections 5.2.3, 6.2.3, and 7.2.3.

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1 The term *premium* rewind, when used in this guideline, refers to high quality rewinds performed under process controls appropriate for safety-related applications and utilizing insulating systems and materials with high thermal and dielectric capabilities (e.g., Class H).

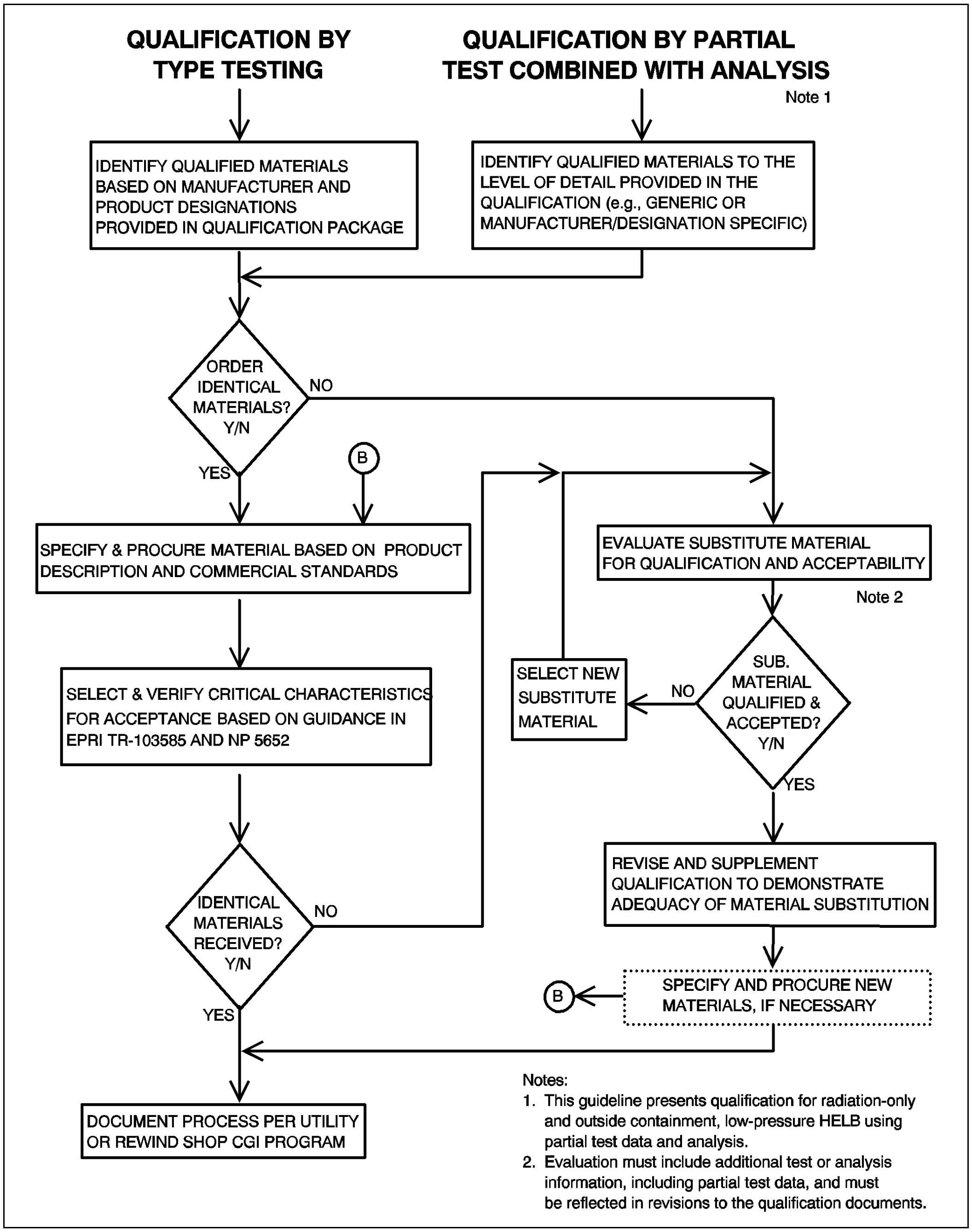

Figure 4.3
Procurement and Acceptance Activities for Insulating System Materials

4.1.5 Fabrication

Ensuring appropriate fabrication is a critical element of the overall qualification process. A motor rewind system may have sufficient documentation demonstrating its qualification in a harsh environment, be composed of the correct materials, and still fail when required because of fabrication deficiencies. Figure 4.4 identifies attributes of fabrication control necessary to demonstrate acceptable fabrication of qualified motor rewinds. Section 4.6 further describes the topics identified in this figure. Additional information on fabrication, with particular relevance to LOCA, low pressure HELB, or radiation-only qualification, is contained in Section 5.2.2, 6.2.2, and 7.2.2.

EPRI, as part of this guide's development efforts, has solicited information on existing motor type test qualification data. TVA has made sufficient qualification and fabrication information available to EPRI and its members so that others may fabricate qualified systems in accordance with the TVA data. Sections 5.3 and 6.3 describe these systems and identify other TVA information, available from EPRI, that can be used to fabricate motor rewinds and document their qualification in accordance with this existing type test data.

4.2 Establishing Insulation System EQ

Conceptually, *Establishing Insulation System EQ* includes all activities necessary to determine that the proposed rewind insulation system is environmentally qualified for the intended application. This involves evaluating the adequacy of existing qualification data (e.g., type test reports) and determining the suitability of the proposed system for the specific motor applications. With the successful completion of these activities, utility engineers will have established an EQ file per the criteria of 10 CFR 50.49 (the EQ rule) and determined suitability of the proposed system.

It is beyond the scope of this document to describe the overall methodology and technical approaches currently used to demonstrate qualification compliance with the EQ rule. Interested readers can refer to utility-specific EQ program descriptions and a variety of industry material on equipment qualification. For example, EPRI has recently published TR-100516, “Nuclear Power Plant Equipment Qualification Reference Manual” [32]. Sections 6.0 and 7.0 of the EQ Manual are particularly relevant to establishing qualification, while Section 12.5 provides some additional information on motor qualification.

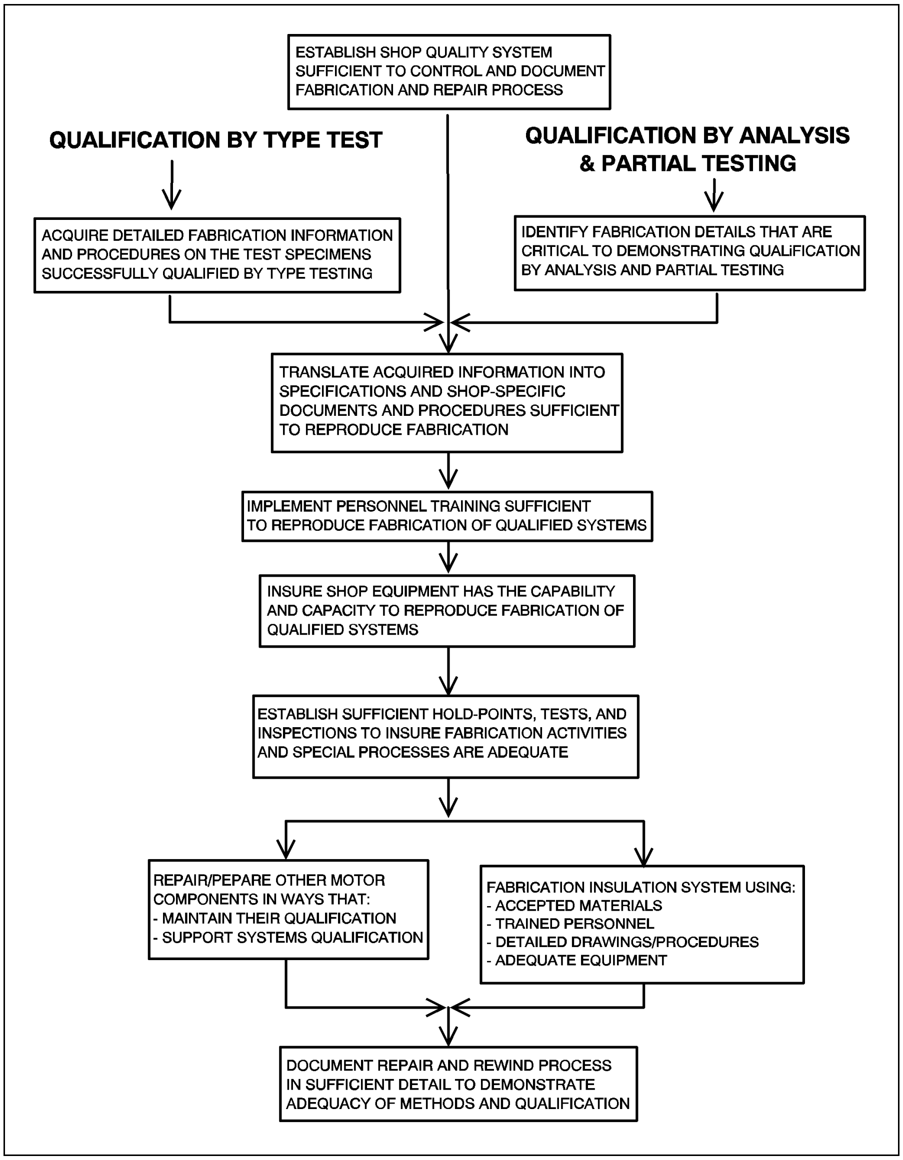

Figure 4.4
Elements of Fabrication Control for Insulating System Materials

4.2.1 Regulations and Standards

The following information summarizes the regulations, standards, and guidance documents related to the qualification of motor insulation systems for harsh environments.

Federal Regulation, 10 CFR 50, Appendix A, General Design Criterion (GDC) 4 - "Environmental And Dynamic Effects Design Basis", states, in part, that components important to safety must be designed to withstand, without loss of function, the environmental effects of normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents (LOCAs).

Federal Regulation, 10 CFR 50.49, "Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants", (often called the EQ rule) was issued in January 1983, and provides criteria for the environmental qualification of equipment in harsh environments. It defines harsh environments as those environmental conditions occurring during design basis events (DBEs) that are significantly different than those occurring during normal operation, including anticipated operational occurrences. The EQ rule recognizes that harsh environment qualification can be established using tests (including partial tests), analysis, operating experience, or a combination of these techniques.[2] Qualification for mild environment conditions is excluded from the rule's scope. The general quality assurance and surveillance requirements contained in other regulations are sufficient to ensure adequate performance of equipment in mild environments.[3] The EQ rule requires *all* significant types of aging degradation affecting equipment functional capability to be considered. When equipment is qualified by testing, the rule requires it to be preaged to simulate its end of life condition prior to accident testing. The DBE conditions must include, as appropriate, temperature, pressure, humidity, chemical spray, radiation, and submergence. The rule requires that margins be applied to account for qualification uncertainties, that qualification address synergistic effects, and auditable documentation demonstrating qualification be maintained for the installed life of the equipment.

The EQ rule permits certain older plants to establish environmental qualification for existing equipment based on the less stringent criteria contained in two NRC EQ guidance documents, the DOR Guidelines and NUREG-0588, Category II. Finally, it requires the qualification of replacement equipment to be upgraded to its qualification

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2 The statements accompanying the rule indicate that qualification developed in accordance with IEEE 323-1974 or NUREG-0588 Category I criteria complies with the rule's requirements.

3 See supplemental information originally published with 10 CFR 50.49.

criteria unless "sound reasons" for not upgrading existed. If such sound reasons for not upgrading exist, qualification for the replacement component may continue to be based on the DOR Guidelines or NUREG-0588, Category II.

Regulatory Guide 1.89, Rev. 1, “Environmental Qualification of Certain Electrical Equipment Important to Safety for Nuclear Power Plants”, June 1984, provides NRC Staff positions and clarifications related to the EQ Rule. The guide indicates that "qualification" is verification of design limited to demonstrating that electric equipment is capable of performing its safety functions under the significant environmental stresses resulting from design basis accidents in order to avoid common-cause failures. Among other things, it provides additional information on the *sound reasons* for not upgrading replacement equipment. Two *sound reasons* examples with relevance to motor repairs, particularly insulating system rewinds, are:

1. The replacement item is an equipment component that is routinely replaced as part of normal maintenance (such as a lubricant or bearing; consumable).
2. The item to be replaced is an equipment component that was part of an equipment item that was qualified as an assembly (such as rewind insulating system).

4.2.1.1 IEEE 323. IEEE 323-1974, “IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations,” [33] is considered the "motherhood" qualification standard for electric equipment. The IEEE has also issued several "daughter" standards, including one for electric motors (IEEE 334), that provide more specific criteria for certain equipment types (e.g., motors, cables, valve actuators, connectors)[4]. These standards require qualification for both environmental and seismic conditions. Another IEEE standard, IEEE 344-1987, “IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations”, [34] (not discussed further here) provides additional seismic qualification guidance.

Two versions of IEEE 323 are currently in use. IEEE 323-1974 is the revision formally recognized by the NRC in 10 CFR 50.49 and in regulatory guidance documents. IEEE 323-1983, a more recent revision, was issued to further clarify requirements and provides additional guidance in several areas. In particular, IEEE 323-83 establishes different criteria for equipment located in harsh and mild environments. It identifies several methods of extending qualified life, including the ongoing qualification methods identified in the 1974 version. Regarding radiation, the 1983 version permits excluding radiation from an equipment type test sequence if it can be shown that the radiation will not affect equipment safety functions and there are no adverse aging

4 For the purposes of this guideline, listing IEEE 334 without an issue date indicates that both the 1974 and 1994 versions are being described.

sequence effects.[5] IEEE 323-1983 requires the qualification program to account for all significant aging mechanisms. According to the standard, an aging mechanism is significant if in the normal and abnormal service environments it causes degradation during the installed life of the equipment that progressively and appreciably renders the equipment vulnerable to failure to perform its safety function(s) under DBE conditions. In virtually all other respects the two revisions are consistent.

IEEE 323-1983 establishes the following harsh and mild environment definitions:

> **Harsh Environment.** An environment expected as the result of the postulated service conditions appropriate for the design basis and post-design basis accidents of the station. Harsh environments are the result of a loss of cooling accident (LOCA)/high energy line break (HELB) inside containment and post-LOCA or HELB outside containment.
>
> **Mild Environment.** An environment expected as a result of normal service conditions and extremes (abnormal) in service conditions where seismic is the only design basis event (DBE) of consequence.

4.2.1.2 IEEE 334. IEEE 334-1974, "IEEE Standard for Type Tests of Continuous Duty Class 1E Motors for Nuclear Power Generating Stations", addresses the qualification of Class 1E (i.e., safety-related) motors located inside and outside containment in harsh or mild environments.[6] The IEEE reaffirmed the 1974 version of IEEE 334 in 1980. In 1991 the IEEE withdrew the standard but has recently issued a new revision, IEEE 334-1994. Both the 1974 and 1994 versions are discussed below.

Some of the provisions of IEEE 334-1974 with particular importance to motor rewind systems were:

1. Motors experiencing "usual air environments" during DBEs should maintain their internal environments such that the test data collected using the guidance of IEEE 117-1974, "Test Procedure for Evaluation of Systems of Insulating Material for Random-Wound AC Electric Machinery" [35], IEEE 275-1992, "Test Procedure for Evaluation of Systems of Insulation Material for AC Electric Machinery Employing Form-Wound Preinsulated Stator

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5 Aging sequence refers the sequential application of the aging stressors (i.e., thermal, radiation, and wear cycling) to the equipment under test.

6 IEEE 334-1974 superseded a 1971 trial-use guide version that was limited to type testing of inside containment continuous-duty motors. The methodologies proposed by both versions are generally compatible. However, the 1971 version proposed the use of five LOCA temperature/pressure transients, each of roughly four hour duration, followed by a post-LOCA simulation of at least seven days.

Coils" [36], or IEEE 429-1994, "Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-wound Stator Coils" [37], is applicable.

2. If abnormal environments are produced within the motor enclosure during DBEs (e.g., operation or cooling from gases other than air), the insulation shall tolerate these conditions. If the testing of IEEE 117, IEEE 275, or IEEE 429 is not directly applicable other testing may be necessary. The testing shall demonstrate that contaminants entering the motor, such as condensation, oil, abrasive solids, or harsh chemicals will not cause failure.
3. Qualification for normal thermal conditions shall be based on IEEE 117, IEEE 275, or IEEE 429 with extrapolation of the regression life-temperature curve to installed conditions.
4. Aging simulations shall address the effects of environment (atmosphere, temperature, humidity, radiation, and contaminants), voltage stress, and mechanical stresses (starting forces, vibration, and driven load) when required.
5. Although accident qualification testing of a complete motor is desirable, the insulation system and materials of all the essential motor components may be qualified by testing representative motorettes, individual components, or component assemblies.
6. Motor qualification must address all essential components, including insulation system, winding design, bearings and seals, lubricants, motor leads, lead seals, splices, and other essential accessory devices and equipment.
7. The tested motor or motor model should be representative of the installed motors, including design features, materials, operating stresses, and loads. Analysis must identify and justify all features not specifically representative of the full-size installed motors.
8. Accelerated aging cannot simulate end-of-life conditions for lubricants, bearings, and bearing seals. They are also periodically replaced during the life of the motor. Efforts should be made to simulate realistic conditions prior to accident simulation tests. For example, these devices should be subjected to both normal and accident radiation levels prior to the accident testing.
9. The accident simulation test conditions, including motor loading, should simulate required conditions. However, the following was suggested to qualify BWR or PWR in containment continuous-duty motors:
   - Motor idle and cool inside test vessel
   - Initiate steam and chemical spray conditions
   - After 15 minutes operate motor at full load and rated voltage
   - After 3 hours stop motor for 5 minutes, restart motor, and operate for 1 additional hour

- Terminate steam conditions, reduce pressure, and cool motor to <50°C.
- Repeat steps 3 and 4 and continue the testing and motor operation for the required post-accident duration.

For several years the IEEE was developing a revision to IEEE 334. The revision was finally approved in 1994. The new standard has changed its title from a "type test" to a "qualification" standard, maintains the general principles contained in the 1974 version, and is restructured to address the provisions of IEEE 323-1983. Several important points identified in the new revision are:

1. The standard covers continuous duty motors and indicates that intermittent
2. The standard's principles may be applied to modified or refurbished motors.
3. Inherent motor design features, accounting for magnetic, starting torque, and load variation stresses, result in motors being inherently rugged to seismic events if properly applied and installed.[7] The basis for this conclusion is general operating experience and the results of industry / NRC activities involved with reviewing equipment operating experience during earthquakes. Additional information on the use of earthquake experience and related industry / NRC activities is contained in [1,2,3] and a number of other sources.
4. Motors that experience only one "environmental parameter threat" (e.g., radiation-only) in harsh environments may be qualified through analytical techniques.
5. Any subsequent test designed to supplement the basic qualification program for the original motor may be done on components or models of appropriate portions of the motor.
6. Qualification is required for radiation levels in excess of 10^4 rad. However, if material tests and an analysis show that direct damage or the evolution of radiation produced substances is negligible at higher exposures, then radiation exposure of the motor, as part of the type test sequence, is not required.
7. Motor lead cable may be qualified to IEEE 323-1983.

4.2.2 IEEE Standards for Determining Insulation System Thermal Capabilities

IEEE 334-1974 and -1994 indicate that the testing methods described in IEEE 117, IEEE 275, or IEEE 429 should be used to define the thermal life characteristics of insulating systems. It also permits tests performed to these standards to be used to demonstrate

[7] This includes proper alignment, rigid bases that prevent relative motion between the motor and driven equipment, elimination of intermediate flexible bases, adequate thrust load capacity, and adequate coupling flexibility.

qualification for certain environmental conditions. The following, based on the information in IEEE-117, provides an overview of the thermal capabilities testing process for random-wound motorettes and complete motors. Subsequent material describes the test protocols of other standards for form-wound coils and DC machines.

Motor and coil insulating system standards, including National Electric Manufacturer's Association (NEMA), Institute of Electrical and Electronics Engineers (IEEE), Underwriters Laboratories (UL), and International Electrotechnical Commission (IEC) define methods to determine the thermal classification of insulating systems. While some standards, such as NEMA MG-1, permit the use of suitable operating experience as a basis for thermal classification, all the standards recognize the acceptability of thermal classifications based on motor or motorette testing. Readers are encouraged to refer to these standards for detailed information on specific testing and analysis methods.

4.2.2.1 Motorette Testing. The general test methodology for motorette testing, per IEEE 117, consists of the following steps:

1. Fabricate at least 3 groups of test specimens, with at least 10 motorette specimens per group, in accordance with IEEE 117.
2. Subject each specimen group to repeated test cycles with each cycle involving the following:
   a. High temperature thermal aging with time and temperature varying among the test groups
   b. Mechanical vibration (e.g., 60 Hz @ 1.5 g for 1 hour)
   c. Moisture exposure (100% RH condensing for 48 hours) at ambient temperature
   d. Voltage test while still wet (phase-to-phase, phase-to-ground, turn-to-turn) for 10 minutes

If a test sample passes the voltage test, it is subjected to another test cycle with the process continuing until failure of a specified number of samples in each group is reached. Thermal aging times are selected with a goal of producing specimen failures between the 8th and 20th test cycles. The times-to-failure (based on the thermal aging times only) are statistically analyzed and a regression analysis is performed to determine the thermal index of the insulation system. The thermal index is typically defined as the projected temperature for an average failure time of

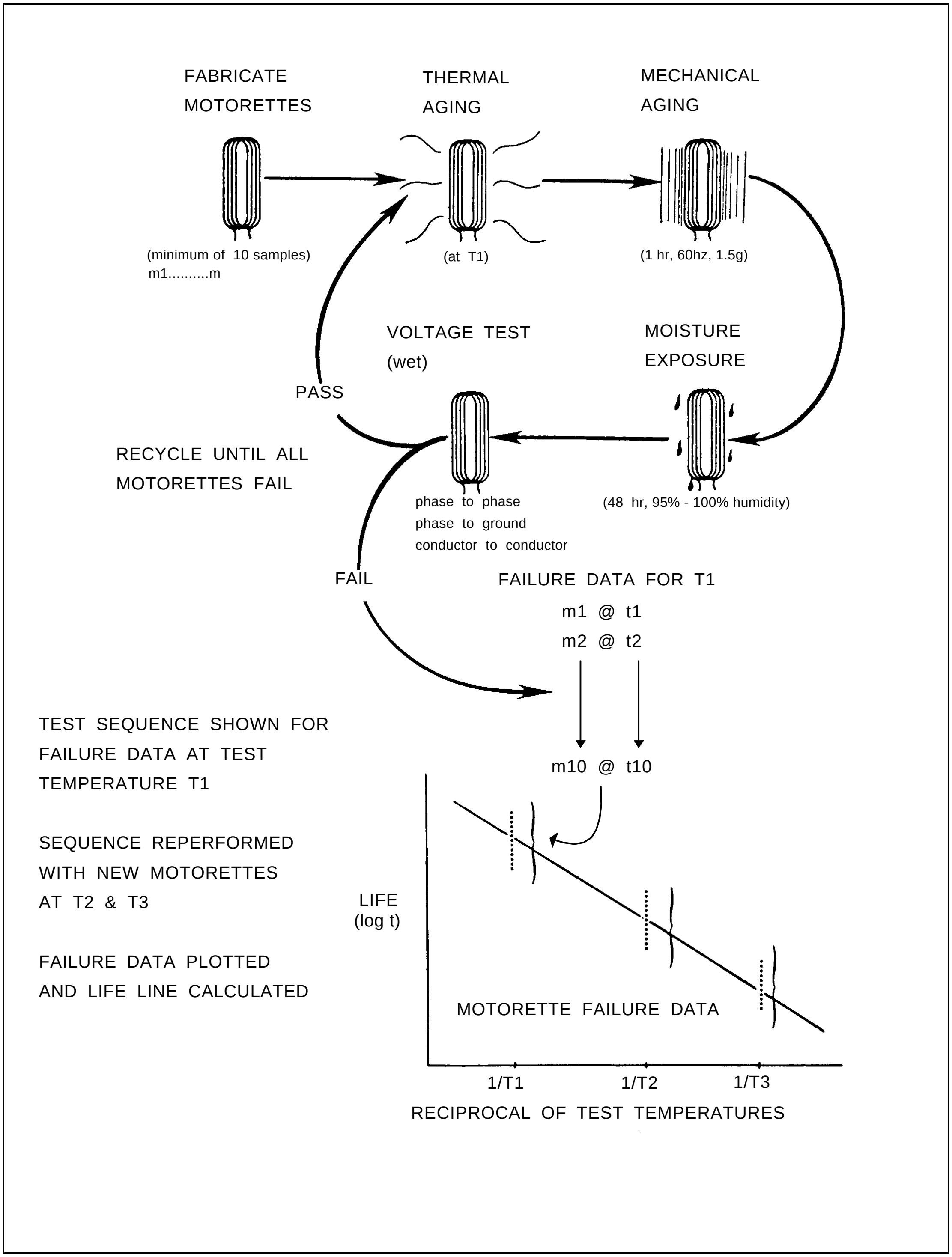

Figure 4.5
Overall Motorette Testing Methodology

20,000 hours. To simplify thermal classification, several thermal classes have been defined. The system's thermal index is generally rounded down to the closest thermal class. Table 4.1 identifies the thermal classes and the associated range of thermal indices that are most relevant to motor insulating systems and materials. Figure 4.5 presents pictorially the overall motorette testing methodology.

Table 4.1
Most Common Motor Thermal Classes and Related Thermal Indices

Thermal Class	Range of Calculated Thermal Index
130 (B)	130ºC - 154ºC
155 (F)	155ºC - 179ºC
180 (H)	180ºC - 199ºC

The test voltages for random-wound motorettes are applied for 10 minutes with failure determined by operation of overcurrent circuit breakers set at 0.5 - 0.75 amps. The test voltages, applied coil-to-ground, coil-to-coil, and turn-to-turn are identified in Table 4.2

Table 4.2
IEEE-117 Motorette Test Voltages

Rated Volts RMS	Test voltages (RMS @ 60 Hz)		
Line-to-Line	coil-to-ground	coil-to-coil	turn-to-turn
110 - 550	600	600	120

Motorettes are constructed to simulate the configuration and interaction among the various insulating system materials. The motorette consists of a rigid base plate, metallic inner and outer plates representing the slot section of the winding core, and the insulating system components. These system components include:

- Wire
- Slot Liner
- Phase Insulation
- Slot Wedges
- Sleeving
- Tie Cord
- Binding Tape
- Insulating Varnish

The assembled system contains two coils insulated from ground by slot insulation, from each other by phase insulation, and held in place with slot wedges. Each coil consists of twenty turns of two parallel 18 AWG magnet wires wound together (i.e., 20 turns of wire wound 2 in hand) so that turn-to-turn electrical tests can be made. The motorette doesn't contain coil connectors or lead wire.

The sequential application of temperature (making samples more brittle), *vibration* (producing cracking in the most brittle parts), humidity (creating moist and wet conditions in the degraded insulation), and then voltage is intended to represent the cumulative deteriorating effects of insulating system service conditions on an accelerated basis. Per the IEEE standard, extensive experience with these types of tests indicates that most of the deteriorating effects of service can be reasonably approximated by this sequence. It also indicates that, since the combined effects of heat, vibration, moisture, and electrical stresses during the test are intentionally made more severe than those normally found in service, the insulation system life in these tests will be shorter than expected during actual service at comparable temperatures. Several other considerations associated with this test method are:

- During actual service only portions of the insulating system are exposed to the "hot spot" temperatures. During the motorette test the entire system is exposed to this temperature. Consequently, life at a given hot-spot temperature during oven aging should be shorter than in actual service.
- The mechanical and electrical exposures are only moderately above those normally experienced in service because abnormally high mechanical or electrical stresses generally produce failures that are not representative of those occurring during actual service.
- In order to shorten the required test time, the temperature and moisture exposures are intentionally more severe than service conditions.
- Experience has shown that prolonged application (i.e., 10 minutes) of voltage in the wet condition is necessary to detect failures. These failures occur along wet surfaces with a gradual buildup of leakage currents.
- Motor leads and lead / coil terminations are not part of the motorette test specimen.

UL requires testing of insulating systems to its standard, UL 1446, “Systems of Insulating Materials - General” [38]. Testing performed per UL 1446 is, in large measure, identical to the testing prescribed by the IEEE standards. However, unlike the IEEE standards, UL 1446 contains guidance on additional tests when major or minor material substitutions occur. The UL testing is also important since a large number of material manufacturers have performed and readily provide UL 1446 testing to establish thermal classifications for systems using their materials.

UL 1446 identifies two classes of insulation system components, major and minor. Major insulation components include ground insulation, resin / varnish treatment, magnet-wire insulation, and interwinding (e.g. transformer) insulation. Other system components, including phase-to-phase insulation, tapes, tie cords, and lead wires are considered minor components. Testing requirements for substitute major and minor components differ. The flexibility provided by the UL standard permits some material substitutions to be made without the need to re-perform time consuming and expensive system testing.

For all minor components, an identical component from an alternate supplier may be used if material tests demonstrate the substitute material is at least equivalent to the original material. The material tests can include infrared analysis, thermogravimetric analysis (TGA), dielectric strength, or other similar tests.

Any magnet wire meeting the same NEMA MW1000 designation can be substituted without additional testing. Alternatively, infrared or chemical analysis can demonstrate that the insulations are generically similar.

Substitute varnishes must have the same thermal class as the original varnish based on any varnish test methods (twisted-pair, helical coil, or curved electrode).[8] These varnish test methods are described further in [4]. If the substitute varnish has at least one thermal class lower than the original varnish, then various combinations of sealed-tube tests and a single temperature thermal aging test are specified. If the varnish has a temperature class *more than* one temperature class lower (i.e., B vs. F) than the original varnish, a completely new motorette thermal-aging test program must be performed.

Ground wall insulation generically similar to the original insulation may be used if material tests demonstrate its equivalency. If generically different materials are used, a completely new thermal-aging test program must be performed.

The sealed tube test is a method of determining overall compatibility of substitute materials with other elements of the insulation system. The sealed tube testing is less expensive and less time-consuming than thermal-aging tests of the insulating system using the new materials. The test involves preparing sealed tubes, each containing samples of the original and substitute materials. Each tube contains a twisted wire pair constructed per ASTM D2307 combined with a proportional amount of all other insulating system materials. Varnish / resin is applied to the magnet wire and cured. The other system materials are provided loosely as pieces. Five tubes containing the original system materials and another five tubes containing the substitute system materials are fabricated and sealed. The sealed tubes are exposed for 336 hours to a temperature 25°C higher than the thermal class rating of the original system. After the thermal exposure, the materials are removed from the tube, examined and compared. The twisted pairs are subjected to dielectric breakdown tests. Other materials credited

8 As described in Section 4.2, thermal index tests for varnishes utilize both electrical and mechanical (bond strength) property measurements.

for dielectric strength (e.g., tubing, phase-to-phase insulation) are also subjected to dielectric strength tests. The color, flexibility, and general appearance are also examined. To be acceptable, the dielectric strength of the magnet wire from the sealed tubes with substitute materials must be at least 50% of the strength for wires from the tubes containing the original materials.

Unlike the IEEE standards, UL 1446 considers lead wire as an insulating system component. UL 1446 permits the lead wire to have a thermal rating lower than the rating of the system in which it is used. If the lead wire thermal rating is lower than the system rating by more than 5°C, then it must be compatible (i.e., sealed tube testing) with the other system materials and separated from the winding by a barrier or envelope of a material compatible with the system. The temperature rating of the lead wire cannot be less than the values specified in Table 4.3.

Table 4.3
Minimum Acceptable Lead Wire Temperature Rating per UL 1446

Insulation System Class	Minimum Lead Wire Temperature Rating
130 (B)	90ºC
155 (F)	125ºC
180 (H)	150ºC

4.2.2.2 Motor Testing. Motor testing to establish an insulation system thermal rating is very similar to the procedure used for motorettes. Due in part to significant cost differences, motorette testing is preferable to complete motor testing when establishing an insulating system thermal rating. There are a number of procedural differences between motor and motorette testing. Since motor testing is rarely used, these differences are not discussed here.[9] The two most significant differences during motor testing are: 1) thermal and mechanical stresses are imposed simultaneously during operation and 2) in lieu of post-humidity voltage test, the motor must be energized at the completion of the humidity exposure while still wet.

IEEE 304-1977, “IEEE Test Procedure for Evaluation and Classification of Insulation Systems for Direct-Current Machines” [39], contains provisions very similar to those presented in IEEE 117. It permits the testing of both system models (formettes and motorettes) and complete motors. The standard does not specify a certain number of samples within each test group, but recommends an adequate number, to obtain a good statistical average, be employed. IEEE 304 provides several recommended

[9] Interested readers should consult the IEEE and UL standards for additional details on motor testing methods.

constructions for field coil and armature motorettes / formettes. For armature system testing, the standard recommends additional procedures to simulate the loads imposed by centrifugal forces and banding pressures. Table 4.4 identifies the recommended post-moisture exposure test voltages.

Table 4.4
IEEE-304 Motorette/Formette Test Voltages

Rated Volts RMS	Test voltages (RMS @ 60 Hz)	
Line-to-Line	**Coil-to-Ground & Coil-to-Coil**	**Conductor-to-Conductor**
35 or less	200	117
36 - 250	500	117
251 - 600	1200	117
> 600	2x(line-to-line)	117

IEEE 275-1992, "IEEE Recommended Practice for Thermal Evaluation of Insulating Systems for AC Electric Machinery Employing Form-Wound Preinsulated Stator Coils for Machines Rated at 6900 V and Below", defines test methods and construction features for formettes. The formettes should be representative of the complete winding system and its structural supports, including end-winding bracing. The standard does not specify the number of samples within each test group, but recommends that an adequate number to obtain a good statistical average be employed. The cycle exposure methods are similar to those employed by IEEE 117. Table 4.5 identifies the recommended post-moisture exposure test voltages. Recommended trip currents substantially below those contained in IEEE 117, are based on the type of voltage test performed (e.g., Surge Comparison).

IEEE 429-1994, "IEEE Recommended Practice for Thermal Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Preinsulated Stator Coils for Machines Rated 6900 V and Below", is patterned after IEEE 275. However, its stated purpose is to evaluate the ability of the insulation system to remain *sealed* throughout its service life. Sealed systems are used in severe environments, including those containing strong chemicals, metal dusts, liquids, or contaminated atmospheres. The testing procedure evaluates the sealed system by requiring a high-potential test with the coil submerged in water after the normal post-moisture exposure voltage testing as part of each test cycle. The immersion voltage test is performed after 30 minutes of immersion using 1.15 times rated line-to-line voltage for one minute. Uniquely, this standard requires that the test coil models (formettes) contain insulated coil lead joints that are representative of the series coil connections used in full-size machines.

The prior revision (1972) of IEEE 429 also contains a short-time acceptance test often used to verify that the insulation system of a fabricated motor is adequately sealed[10]. The test involves submerging the insulating system in water containing a wetting agent. Following immersion the following tests are performed:

1. 500 Vdc, 10 minute dielectric absorption test (useful in determining if the system is sealed)
2. One minute, 60 Hz overpotential test at 1.15 rated line-to-line voltage
3. 500 Vdc, one minute IR measurement -- the IR value must not be less than the minimum recommended by IEEE 43.[11]

Table 4.5
IEEE-275 Formette Test Voltages

Rated Volts RMS	Test voltages (RMS @ 60 Hz)		
	Coil-Ground	Conductor-to-Conductor (alt. tests)	
Line-to-Line	& Coil-Coil	impulse volts*	cond.-to-cond. volts
500 and below	1000	250	115
551 - 1000	2000	250	115
1001 - 1500	3000	250	115
1501 - 2000	4000	250	115
2001 - 2500	5000	250	115
2501 - 3500	7000	250	115
3501 - 4500	9000	250	115
4501 - 5500	11000	250	115
5501 - 6900	13800	250	115

* Surge comparison (impulse) voltage is in peak impulse test volts per turn

4.3 Motor Qualification Considerations

For qualification purposes, motors can be visualized as a *rotor* connected to an *output shaft*, rotating on a *lubricated bearing system*, while input power is supplied by the *stator winding*, and with all these components mounted inside the motor's *enclosure*. Motors also contain various *accessories*. Some, like cooling fans or terminations, may be necessary for proper operation during harsh conditions. Others, such as stator RTDs, space heaters, and vibration switches are not critical to immediate performance. Rather, they are used to prolong motor life and performance. Even these non-safety related accessories must not fail in a manner detrimental to motor performance. Only when each of these motor elements, *rotor, output shaft, lubricated bearing system, stator winding, enclosure,* and *accessories* is adequately qualified, can the complete motor

10 Although removed from IEEE-429, the acceptance test is contained in NEMA MG-1.

11 The minimum IR value in Megohms is equal to rated line-to-line voltage in kV plus 1. For a 4.6 kV motor the minimum IR would be 5.6 Megohms.

be considered environmentally qualified. When qualification is achieved using type testing or operating experience of a *representative* motor, then each of these elements is appropriately represented in the motor specimens. However, when qualification is achieved using analysis, including analysis coupled with partial test data, or when material/design changes exist between the originally qualified and installed motors, then the affected elements must be evaluated and their qualification determined.

A variety of regulatory and industry documents describe fundamental qualification principles, the qualification process, and provide guidance on achieving and documenting qualification on an equipment specific basis. It is not the purpose of this guideline to restate this information. Readers unfamiliar with the qualification topic should refer to the sources of information on equipment qualification identified in Section 4.2. The NRC articulated the broad elements of environmental qualification as follows [6]:

1. The equipment shall be designed to have the capability of performing its design safety functions under all normal, abnormal, accident, and post-accident environments and for the length of time for which its function is required.
2. The equipment environmental capability shall be demonstrated by appropriate testing and analyses.
3. A quality assurance program meeting the requirements of 10 CFR 50 Appendix B shall be established and implemented to provide assurance that all requirements have been satisfactorily accomplished.

If these three general concepts are adequately implemented, then qualification can be established and documented for harsh motor applications. Quality assurance, while potentially applicable to all activities affecting quality, is of particular significance for any activities affecting "traceability". Traceability, from an EQ perspective, refers to information on important characteristics of the motor originally qualified and the motor used in the plant application requiring qualification. Generally, qualification relies on some form of test information using fabricated motors, motorettes, or specific components/materials. This data can only be directly applied to *identical* motors, components, and materials. However, in the real world very few devices are identical, in all respects, to the devices/materials originally qualified. Each difference must be identified, evaluated, and addressed using analysis, experience, or additional test information. Traceability data provides the information necessary to identify such differences. Differences affecting qualification can occur as part of; 1) the motor's design (e.g., voltage rating, horsepower, enclosure type), 2) materials of construction, 3) fabrication methods, 4) environmental or service conditions, or 5) motor performance requirements.

When motor rewinds are being contemplated for harsh motor applications, one implicit assumption is that the original motor was adequately qualified for its harsh application. This assumption has wide ranging implications that can significantly minimize the activities necessary to demonstrate qualification for the rewind insulating system. Some of these implications apply directly to the rewind system, while others apply to the overall motor and other motor components. Several motor qualification topics, if adequately addressed by the original motor qualification, need not be reconsidered simply because a new winding insulation system is being used. Original qualification establishes the adequacy of the following in support of motor functionality for the required accident and seismic conditions:

1. Bearing / lubrication / seal system
2. Shaft / rotor / air gap dimensions, clearances, and materials
3. Protection and structural adequacy provided by enclosure design, including pressure relief paths, drains, and lead wiring sealing
4. Protection provided by the junction box for the enclosed motor lead wires, terminations, and field cables
5. Motor electrical design, including rotor design and winding details, to produce required operating and accelerating torque and speed, while maintaining electrical load and winding heat rise within acceptable limits.
6. Winding's bracing and support system to provide adequate physical support to the winding structure.

Although the original qualification establishes the adequacy of these elements of motor design, several potential concerns might be raised regarding changes in electrical design, weight, and winding bracing. Each of these concerns is addressed below.

Electrical Design: The adequacy of the electrical design is maintained if the size, number, arrangement, and connection of the rewind conductors are identical to those originally used. This, of course, assumes that the rotor structure is not degraded or its design modified as part of the rewind and core performance remains adequate. If changes are made to any of these factors, the adequacy of the electrical design must be reestablished. Continued adequacy of the rotor conductors and laminations should be established by visual inspections and tests. Stator core loss values can be affected by the winding removal procedures (e.g., burnout) used during the motor rewind.[12] To insure that the core is not adversely affected by the removal process, core loss testing, before and after winding removal, should be performed as part of the rewind process. Post-repair heat run testing should also be considered to verify adequacy of the repair process and stator temperature rise.
Weight: Weight changes between the original and proposed winding systems could potentially affect motor seismic capability. However, unless there are major changes

12 Several documents, including the EASA Core Loss Study, and IEEE 1068-1990, *IEEE Recommended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industry,* suggest 650°F as a maximum burnout temperature.

in the winding design or bracing, the winding weight will remain relatively unchanged. Further, the winding represents a very small percentage of the overall motor weight. Since insignificant weight changes occur during rewinding, seismic capability will not be affected by these minor changes. Standard industry practice assumes that weight changes of less than 10% do not affect seismic qualification. [30].

Bracing: It is generally assumed that adequately duplicating (i.e., equivalent or superior) the bracing structure of the original winding is sufficient to address mechanical forces acting on the winding end turns during starting and load increases. There may be situations where, theoretically, additional support might be added. However, operating experience with rewound motors indicates that duplicating the existing structure is adequate. One case where end-turn support might theoretically require improvement involves differences in strength and flexibility of the resin / varnish used for form-wound windings treatment. For example, the rigidity and strength of an epoxy resin may be an important element in the structural strength established in the end-turn area. Silicone resins have considerably lower strength characteristics, particularly at operating temperatures. Simply replacing the epoxy with a silicone resin might significantly lower the rigidity of the end-turns. However, since silicones are more flexible than epoxies, a silicone resin would be more tolerant of end-turn deflection. Conversely, if a silicone resin is replaced with a very rigid epoxy, the end-turn bracing structure might not be sufficient and cracking of the epoxy could result. For random-wound motors, reproducing or improving the compaction and end turn bracing should prove adequate for rewinds, since deflections are minimal in properly designed windings. In form-wound motors, particularly those with large end-turn overhangs, care should be taken to insure that the rewind system is adequately braced. In general, equivalent or more bracing is better, provided that stator cooling is not significantly affected by obstructing air flow.

4.3.1 Upgrading Qualification for Motor Rewinds

The EQ rule requires upgrading of qualification whenever equipment is replaced unless there are "sound reasons" for not upgrading. Per regulatory Guide 1.89, one such sound reason is the item to be replaced is an equipment component that was part of an equipment item that was qualified as an assembly.[13] This suggests that a motor insulation system (an equipment component) originally qualified as part of a motor (equipment item qualified as an assembly) can be replaced with another

[13] The specific language also indicates *these items may be replaced with identical components*. The *identical component* statement has led some to conclude that other non-identical windings cannot be substituted unless their qualification has been upgraded to meet 10 CFR 50.49. However, other provisions of regulatory guide Section C.6 permit the use of non-identical, qualified equipment when sound reasons exist. Consequently, this guideline maintains that the regulatory guide allows the sound reason provisions to apply to non-identical motor rewind systems.

insulating system whose qualification does not meet the upgrade criteria of the EQ rule. Although the replacement insulating system's qualification need not meet the EQ rule criteria, it must, at a minimum, meet the qualification criteria of either the DOR Guidelines or NUREG-0588, Cat. II.[14] A different interpretation of this sound reason might apply if the insulation system was qualified based on motorette testing, since in this case the *equipment item that was qualified as an assembly* is the insulation system itself. Obviously, other interpretations can also be made.[15] The premise of this guide is that rewind insulating systems are an equipment component and, therefore, the "sound reason" cited above can apply. However, the guide also recommends the use of replacement systems, particularly for LOCA inside containment applications, that have been qualified to the EQ rule criteria.

4.3.2 Aging Considerations

NRC and IEEE qualification guidance requires that aging address all significant aging mechanisms. The most obvious aging mechanisms for winding insulation systems are *temperature, radiation, voltage, humidity, vibration, and mechanical stresses* occurring during operation and starting. Each of these is addressed briefly below.

4.3.2.1 Temperature. The qualified life of the rewind is generally based on the accelerated thermal aging performed as part of the rewind system's qualification program. The Arrhenius equation is used to correlate time-temperature conditions.[16] IEEE 334 recommends that the slope of the regression line used to calculate qualified life is the same as the regression line developed when the insulation system life characteristic was determined using the test procedures of IEEE 117-1974, IEEE 275-1992, or IEEE. 429-1994. The accelerated thermal aging performed for qualification purposes may be different than the stated "thermal class" of the rewind system or its individual components. For example, a Class F system may only have been subjected to thermal aging tests to simulate the heat rise in a Class B motor application. Motor operating conditions during normal plant conditions should be considered when evaluating both demonstrated and required thermal aging. Conditions which affect thermal aging include the motor's load profile, its relationship to motor full load, and the percentage of time the motor is energized during plant operation. A common practice involves lowering the assumed winding heat rise based on a load (hp)

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14 The specific criteria applicable (i.e., DOR Guidelines or NUREG-0588, Cat. II.) would depend on the current licensing basis for the nuclear power plant.

15 Since insulation systems can be qualified as a separate assembly using motorette testing, alternate interpretation might require the qualification of rewinds to be upgraded to the EQ rule.

16 See EPRI EQ Reference Manual, Section 4.4 for additional information on the use of Arrhenius model and calculations to determine qualified life.

squared ratio.[17] However, several sources indicate that the load squared relationship is only conservative when applied to overloads. It is less applicable for underloads for several reasons. Winding temperature rise is not zero at zero load. There is an idle heat rise produced by heat generated in the core laminations. Further, the coil losses vary with both current and winding resistance (which also varies with temperature). Stray load losses also affect heat rise. Some parts of it vary with load, slip, or speed; other parts vary with core magnetization (which decreases as load increases). Some sources suggest that other load - heat rise relationships may be more appropriate when estimating winding temperature at less than full load [7,8, 29]. For example, in lieu of the load squared relationship, the following can be used:

$$T_{rl} = T_{fl} \text{ x } (HP_{rl} / HP_{fl})^{1.5}$$

where T_{rl} and HP_{rl} are total winding temperature and horsepower at reduced load and T_{fl} and HP_{fl} are total winding temperature and horsepower at full load.

Use of this or the load-squared relationship should be limited to loads where motor current and load appear to be linearly related (e.g., above 75% full load). A second, slightly preferred relationship is:

$$HR_{rl} = HR_{fl} \text{ x } (I_{rl} / I_{fl})^2$$

where HR_{rl} and I_{rl} are winding heat rise and current at reduced load and HR_{fl} and I_{fl} are winding heat rise and current at full load.

Note that total winding temperature is the sum of ambient and heat rise. In addition, the relationship uses current rather than horsepower. Motor specific data should be used to define reduced and full load currents. Use of this or the load-squared relationship should be limited to loads where motor current and load appear to be linearly related (e.g., above 75% full load).

IEEE 334-1994 describes the procedure for determining the time and temperature for accelerated thermal aging of an insulation system. Figure 4.6 illustrates this procedure which is summarized as follows:

1. Identify an implied average-life characteristic line for the motor insulation system through use of the motorette or formette test procedures (see IEEE 117, IEEE 275, or IEEE 429). This life characteristic should be a straight line on a graph, with an ordinate of log-scale time and abscissa of reciprocal absolute temperature scale (see Figure 4.7 Line A).

[17] For example, it is assumed that a motor operating at 80% load would experience a winding heat rise of $(0.8 / 1.0)^2$ times rated full load heat rise. For an assumed Class B heat rise of 90°C (80°C average winding temperature + 10°C hot spot temperature), this reduces the winding heat rise to 58°C (0.64 x 90°C).

2. Identify the expected maximum insulation temperature of the motor as follows: A representative motor shall be operated at the specified steady state load (not necessarily rated or nameplate load) until thermal equilibrium is reached. The maximum temperature measured shall be corrected and extrapolated to reflect specified operating conditions and load profiles. These corrections account for differences (such as between test and operating ambient temperature, conversion of rise measurement by resistance to hot spot temperature), and variations in motor loading. The temperature test shall be in accordance with IEEE 112.
3. Plot the motor's expected maximum insulation temperature and the desired lifetime as a point on the graph (see Point B).
4. Draw a line through the temperature / lifetime point, parallel to the implied average life characteristic. Identify this line as the qualified life aging line (see Line C). The intersection of this line and the desired accelerated aging time is the aging temperature (e.g., Point D). Conversely, the intersection of this line and the desired aging temperature is the accelerated aging time.

When this procedure is followed, Line C should be to the left of and lower than Line A. The difference in the projected lifetime values of Line A and Line C at any specific temperature reflects conservatism between the desired life (i.e., qualified life) and the average projected life, based on the motorette / formette testing. For example, at 130°C, the average motorette / formette life using Line A is roughly 10^6 hours; while the aged life based on the accelerated aging procedure is $4x10^5$ hours. For several reasons, this conservatism should be as large as possible. First, the motorette testing used to develop Line A, or any other current technology accelerated aging test procedure, does not determine absolute insulation life. This is particularly true when life extrapolations, such as those used during qualification, attempt to predict life at 350,000 hours (40 years), based on very short-time (e.g., 1000 hour) tests. Secondly, in addition to these aging conditions, the winding system undergoing qualification testing will be subjected to further degradation during seismic, radiation, and LOCA steam simulations. Finally, Line A is the average life line. This line does not reflect the statistical confidence limits developed during the motorette life testing. A line representing the lower 95% statistical confidence limits, based on the motorette testing, could result in life values that are only 20% - 30% of average life. The 95% confidence line implies that if a large number of identical motorettes were tested using the IEEE procedure at the time-temperature points defined by this line, approximately 5% of the test specimens would fail.

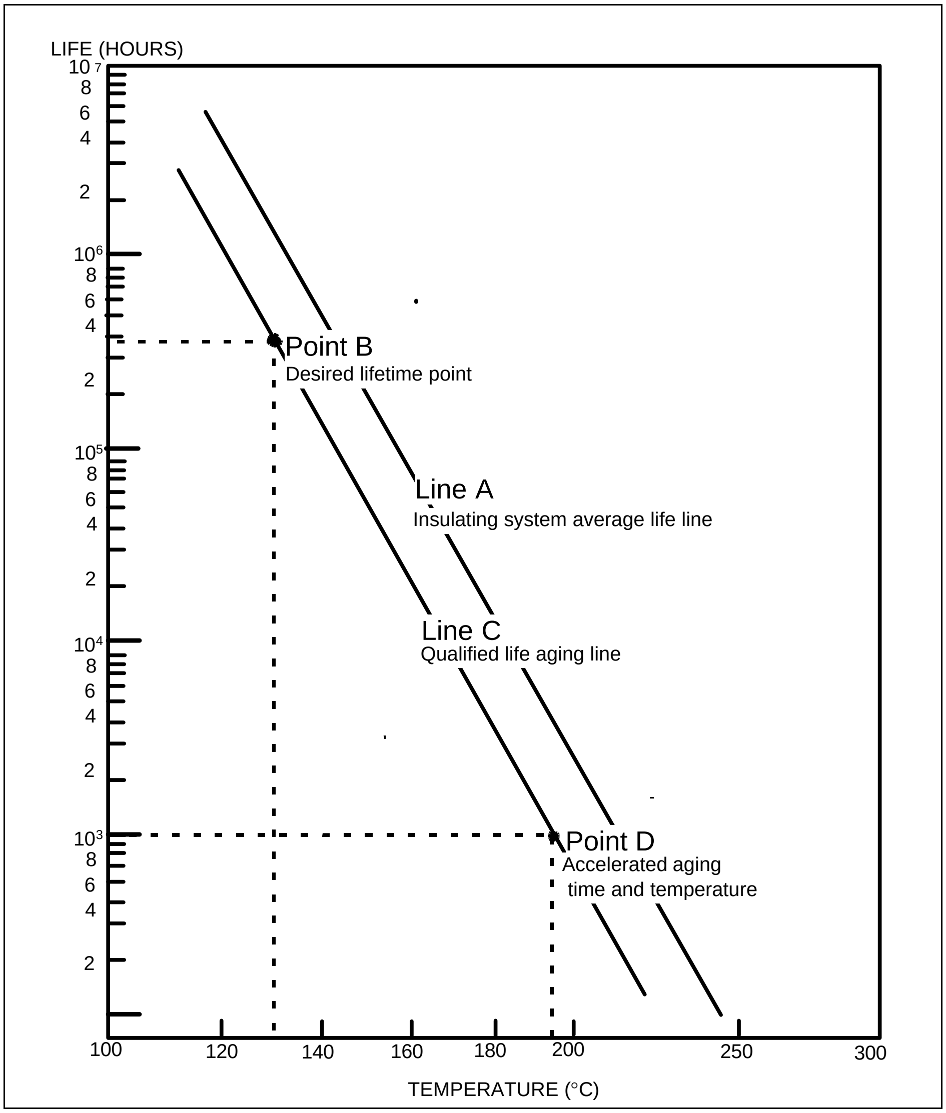

Figure 4.6
Data used to Determine Accelerated Thermal Aging Time and Temperature

4.3.2.2. Vibration and Mechanical Stress. IEEE 334-1994 suggests that vibration and mechanical aging stresses can be addressed by subjecting the motor/motorette under qualification to one hour of vibration at 60 Hz. @ 1.5g with the vibration occurring at right angles to the coil plane. This permits the coils to vibrate as they would under radial end turn forces in an actual machine. This is a substantially shorter total vibration time than the procedures of IEEE 117, IEEE 275, or IEEE 429, which require that exactly the same vibration type and duration be applied for each aging cycle. Since the testing procedures of these standards establish a goal of

8 to 12 testing cycles before failure, the motor / motorette under test are exposed to roughly ten times the vibration aging suggested by IEEE 334. However, motors or motorettes involved in a qualification test program may also be subjected to several seismic vibration tests. These seismic tests impose additional mechanical vibration stresses on the insulating system.[18]

4.3.2.3 Radiation. Rather than subjecting the qualification specimens to a separate radiation aging simulation, the aging radiation dose is normally simulated by increasing the accident radiation dose. The combined aging plus accident total integrated dose (TID) during qualification must bound the combined required aging plus accident dose. Due to the inherent radiation resistance of many insulating system components, the aging radiation dose in many applications is not a significant aging mechanism.

4.3.2.4 Humidity. Humidity, alone, does not produce permanent aging effects in most insulation materials.[19] However, long term exposure to moisture can reduce the electrical characteristics, particularly Insulation Resistance (IR), of insulating systems. Importantly, when thermal and mechanical stressors have degraded an insulation system, moisture provides the electrical pathway among insulation cracks and defects which can produce destructive leakage currents leading to progressive insulation deterioration. Humidity exposure is part of the test protocol of IEEE 117, IEEE 275, and IEEE 429. Humidity aging is not typically part of motor qualification programs based on IEEE 334. It has reasonably been assumed that standard maintenance practices effectively minimize humidity aging effects for safety-related motors. These practices include periodic operation and motor heaters to reduce the relative humidity at windings and periodic electrical tests (e.g., IR) to demonstrate acceptability of the insulating system.

4.3.2.5 Voltage. Voltage aging or voltage endurance of motor insulating systems principally involves progressive material degradation due to partial discharge (PD), corona, and high voltage transients, such as switching surges.[20] Several IEEE

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18 NRC and IEEE documents do not require that qualification demonstrate motor performance for accidents preceded or concurrent with seismic events. However, for convenience the same test samples are often used to qualify for both seismic and accident environmental conditions. The general testing sequence (per IEEE 323 and other documents) is to subject the test specimens to the seismic test conditions before exposing them to the accident environmental conditions. Consequently, the seismic tests can be viewed as a type of vibration aging prior to the accident simulation.

19 Some materials, like certain polyesters, can experience hydrolytic degradation when high moisture is combined with high temperatures.

20 Electrolytic degradation, although conceptually related to voltage, is excluded since it is not a significant aging mechanism for motor insulating systems.

documents related to insulation system aging [9, 10, 11, 12, 13] indicate that prolonged voltage degrades insulation only when partial discharge (corona) progressively erodes the insulation material. When the insulating system is designed to effectively eliminate the potential for partial discharges, prolonged voltage exposure is not a significant aging mechanism. Several considerations suggest that partial discharge will not occur for low-voltage motors and should not be a significant aging mechanism for medium voltage, <7 kV, essentially-void-free VPI windings.[21] Therefore, voltage aging is not normally simulated during type testing.

Partial discharge is not a significant aging mechanism in low voltage motors, due to the extremely low vpm stresses placed on the insulating system materials. The thickness (e.g., 30 mils) of phase-to-phase and phase-to-ground components (e.g., slot liner) limits operating voltage stresses to below 20 vpm. Similar maximum conductor-to-conductor vpm values exist within a single random-wound coil. These extremely low vpm values effectively eliminate the occurrence of partial discharge on low-voltage machines. At medium voltage levels below 7 kV, the use of quality VPI resin treatments produces essentially void free windings. Below 7 kV this construction, in combination with mica paper tapes, minimizes the occurrence and degradation associated with partial discharges. Often winding designs in the 5 - 7 kV range use conductive coatings in the slot and semiconductive coatings on a portion of the coil extensions to further minimize the potential for corona. Consequently, voltage is not a significant aging mechanism when these types of insulation systems are properly designed and fabricated.

Figure 4.7 depicts voltage endurance data for various materials based on an ASTM 2275 testing method using 360 Hz voltage sources. This ASTM test is designed to measure the effect of corona and partial discharge on the insulating material under test. This figure's data suggest that most materials/configurations exhibit a voltage endurance threshold. Below this threshold, voltage aging either does not occur or is insignificant. Figure 4.8 is a similar curve from [12] representing the typical voltage-time curve for mica insulation. Both these curves suggest that voltage degradation is not significant at the relatively low vpm values used for low and medium voltage motors.

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21 Additional information on the need for corona protection in form-wound VPI windings at voltages <7 kV is contained in Section 3.3, *Electrical Stresses* of EPRI TR-103585, *Guidelines of the Selection, Procurement, and Acceptance of Nuclear Safety-Related Mild Environment Motor Insulation for Rewinds.*

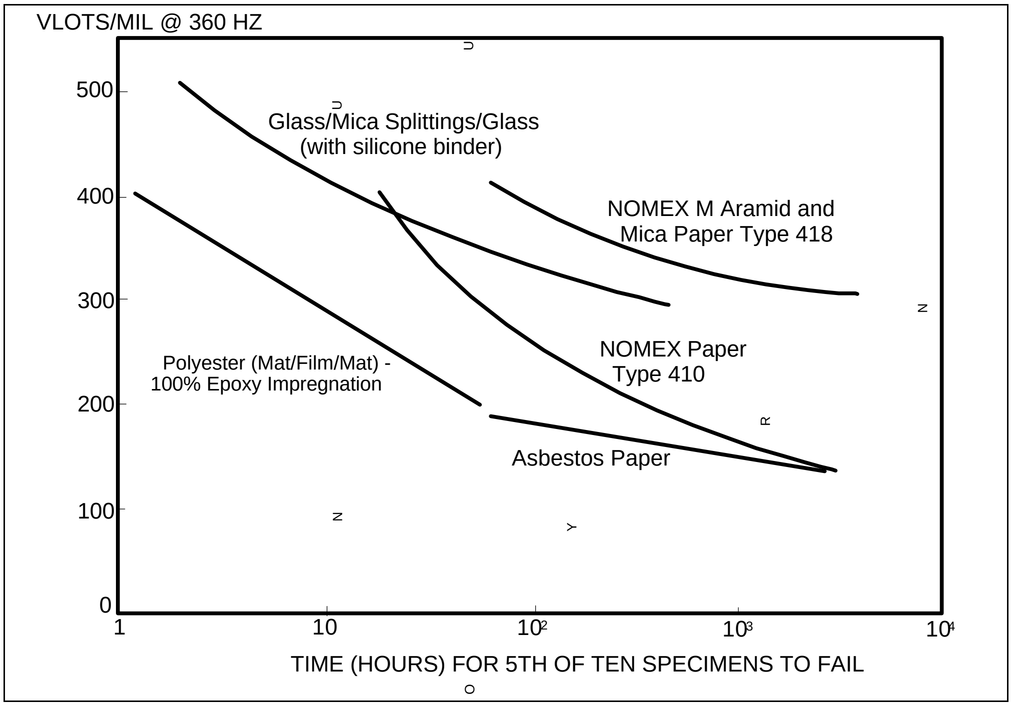

Figure 4.7
Voltage Endurance of Various Insulating Materials (10 mil)

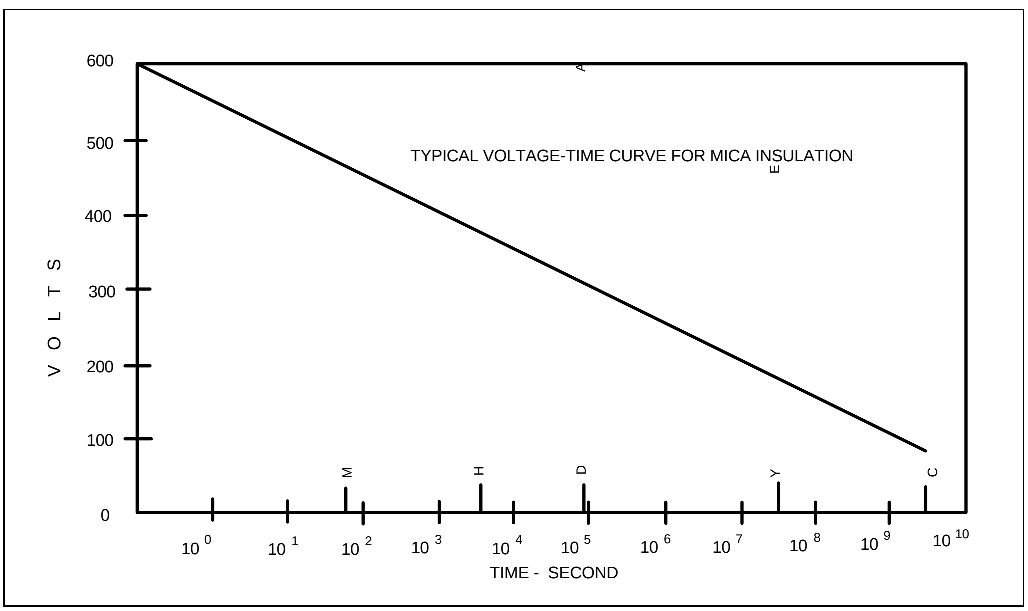

Figure 4.8
AC Voltage Endurance for a Typical Mica Based Insulation System

Partial discharge occurs when the electric field intensity is high enough to locally ionize the air adjacent to the solid insulation. In motor insulating systems, corona or partial discharge can occur at the following locations:

- within insulation system voids
- on voids / defects at the surface of the ground wall insulation
- on the coil surface where it exits the core
- between adjacent coils in the end turn winding area.

In order for corona or partial discharge to occur, the air space adjacent to the insulation or inside the void must ionize. Paschen's Law indicates that the breakdown strength of a gas is based on composition, pressure, and electrode separation. Each gas has a minimum voltage (Paschen's Minimum); below this level voltage breakdown will not occur for any electrode spacing. The Paschen's Minimum for air is 335 volts. Figure 4.9 from [14] depicts the breakdown of air at small spacings based on Paschen's Law at ambient conditions.

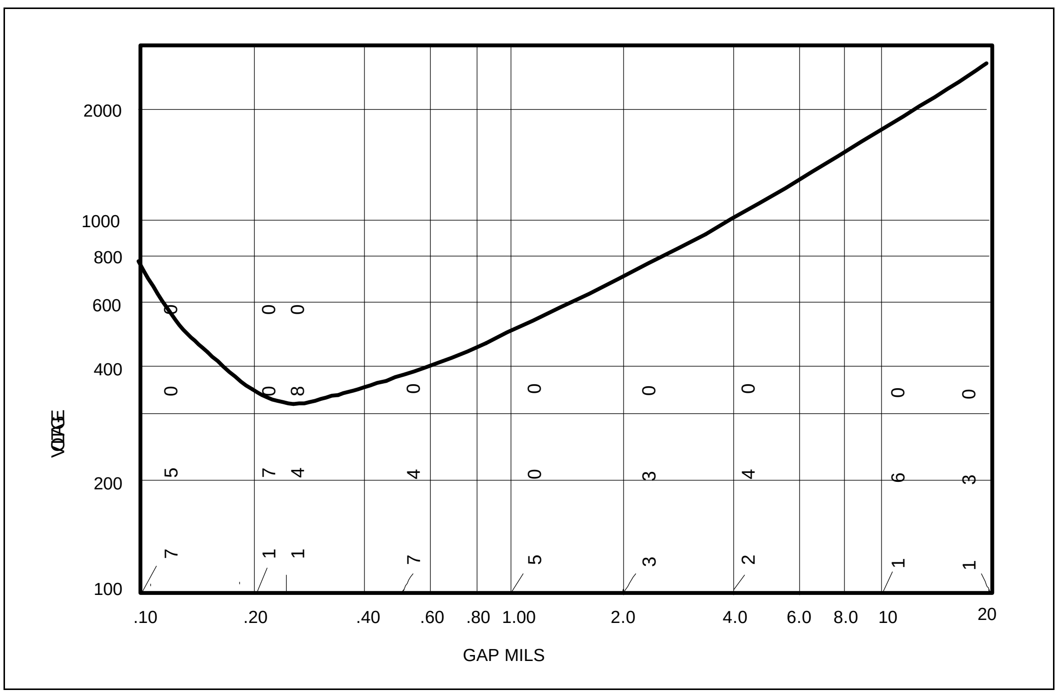

Figure 4.9
Breakdown of Air at Small Spacings

Partial Discharge Inception Voltage (PDIV) is a term used to describe the voltage threshold associated with long-term voltage endurance; below the PDIV partial discharges and corona do not occur. The PDIV depends on insulation thickness, dielectric constant, size, orientation, and the geometry of the specimen, and whether the air void is external or internal [15].

When magnet wire enamels are tested using twisted pair specimens, the PDIV is around 550 - 600 V (200 - 300 vpm) with new materials, but can be reduced by aging and elevated temperature to less than half that amount [16]. The thickness of phase-to-phase and phase-to-ground insulation for low voltage motors is generally in the range of 10 mils. Based on Figure 4.9, in excess of 1 kV is required to produce breakdown at this value. For 600 Vac systems, phase-to-ground voltage (346 V) is slightly above Paschen's Minimum for air. This suggests that breakdowns are unlikely at this and lower voltages for any insulation thickness.

If unfavorable designs and geometries produce air gaps exceeding 5 mils, it is possible to experience a PDIV as low as 1.4 kV. However, in standard commercial motors, corona does not become a potential problem until the 5 - 7 kV range and above [15]. At these higher voltages, manufacturers have historically used conductive tapes or coatings in slot areas and semiconductive tapes or coatings on the end-turn area where coils exit the slots. For medium voltage machines ≤ 7 kV, the effects of corona and partial discharge are minimized by designing the systems with vpm stresses substantially below 100 vpm (e.g., 50 vpm), using micacious insulations, and using VPI resin treatments that achieve essentially-void-free constructions. By producing an essentially-void-free construction, the VPI treatment minimizes the occurrence of internal corona and slot discharges. One EPRI report [17] indicates that modern VPI treatments render conductive coatings in the slot area unnecessary at voltages below 7 kV because the VPI process eliminates internal winding voids and fills any small air spaces between the slots and coils. The VPI treatment, coupled with the inherent voltage tolerance of mica-based systems, helps insure that voltage is not a significant aging mechanism for < 7 kV medium voltage machines. Figure 4.10 from [18] illustrates typical voltage endurance data for form-wound mica based constructions. This manufacturer, by limiting vpm values to approximately 50 vpm, demonstrates that voltage endurance is not a significant aging mechanism for the insulating system.

In addition to normal operating voltages, motors may be exposed to impulse and surge voltages due to switching, electrical faults, and lightning discharges. The magnitude and frequency of these occurrences are application and plant site specific. The IEEE has a guide, IEEE 522 [31], containing recommended surge test procedures which demonstrate an insulating system's tolerance to system surges. High voltage transients, including certain high potential tests, can progressively weaken insulating system dielectric capability through the production of partial discharges or corona. Low voltage systems do not generally experience the switching surges encountered at higher voltages. Most power plant medium voltage systems have been designed to minimize the significance of switching surges and other voltage

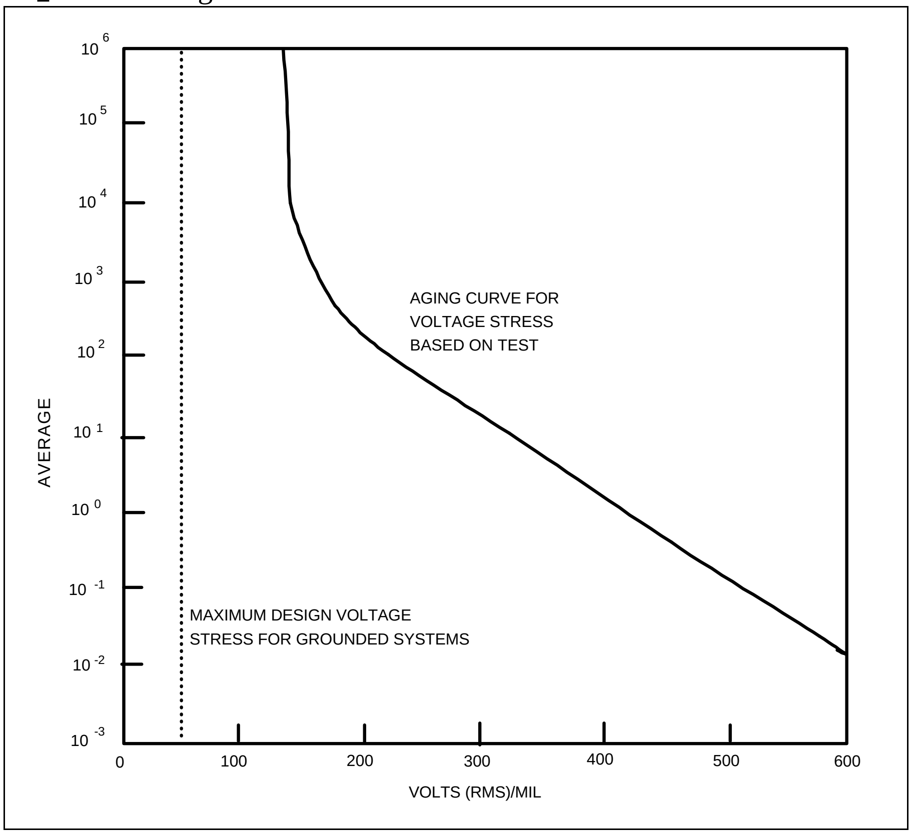

Figure 4.10
One Manufacturer's Voltage Endurance Data

transients, such as lightning. Proper electrical distribution system design is intended to minimize the occurrence and significance of surge voltages. Consequently, accelerated aging need not simulate these transient voltage conditions. High potential tests, as part of motor preventive maintenance, are infrequently performed. Some utilities have stopped using AC high potential tests to determine insulation system condition, due to concerns the tests might produce degradation. The generally accepted view is that periodic (e.g., once per refueling cycle) high potential tests should not significantly degrade insulating systems.

The IEEE standards involved with motor qualification and establishing system thermal ratings contain voltage tests; but these tests were not intended to assess voltage endurance. The test protocols of IEEE 117, IEEE 275, and IEEE 429 require a voltage test as part of the test sequence. The voltage test is used to define winding failures and is not considered an aging mechanism. The voltage test, in the presence of moisture, reveals winding degradation caused by thermal and vibration aging. IEEE 334-1994 includes a 1 minute AC high-potential test, 2/3 x (2 x rated voltage + 1000), termed a voltage stress test, as part of the aging sequence. Discussions with several IEEE members involved in developing the standard indicated that the voltage stress test was intended to establish adequate post-aging winding condition and represent the type of high potential testing which may be conducted during a motor's installed life. They also noted that there are no currently accepted methods for performing and extrapolating accelerated voltage endurance tests to simulate the degradation that may occur during normal operation. The task group agrees that the voltage aging performed in IEEE 334-1994 is acceptable for qualification purposes.

4.3.3 Accident Stressor Effects on Insulating Systems

The following information provides a brief overview on the effects of harsh accident environmental conditions,(i.e., temperature, pressure, humidity/spray), and radiation on motor elements.

4.3.3.1 Temperature. Adverse ambient temperature effects can arise from both absolute and rate-of-change considerations. Rapid ambient temperature changes can produce differential heating and expansion in motor components, including winding system and bearings. Differential thermal expansion could affect tolerances, clearances, and loads on critical motor components, particularly the bearing system. Significantly different enclosure and shaft/rotor temperatures could produce preload (thrust) forces on bearings. Significant preloads would cause bearing overheating and failure. Fortunately, the relatively large motor mass, coupled with other design factors, produces "thermal lag" effects that minimize the significance of differential temperatures. Section 6 contains several figures illustrating thermal lag effects during several steam tests. Since these transient thermal conditions were considered as part of the motor's original qualification, they need not be reevaluated for mechanical components as part of rewind qualification. Similarly, the adequacy of bearing systems qualified as part of the original motor design is not affected by rewinding the motor insulating system.

Prolonged high ambient temperatures can adversely affect both electrical and mechanical motor components. Bearing internal clearances during operation depend on a number of variables including both shaft and housing fits and operating temperatures. Bearing designs are also affected by operating temperature with special lubricants and heat treated materials recommended for higher temperatures.

Motor insulation systems are designed and rated for long life at a maximum temperature based on the insulating system's thermal class. Somewhat higher operating temperatures can be tolerated for relatively short periods. If the insulation temperature significantly exceeds its thermal class rating, rapid failure may occur. Similar operating temperature limits can apply to mechanical parts such as seals.

Increases in temperature could affect the electrical and magnetic characteristics of motor components. Magnetic effects might result if the magnetic permeability of the rotor or stator laminations were significantly affected by temperature excursions. Fortunately, the characteristics of magnetic steels, including properties of the interlaminar insulation, used for laminations, are not affected by temperatures in the range associated with harsh accident conditions, including the internal heat rise produced by motor operation.

Temperature also affects both rotor and stator resistance and the associated electrical performance characteristics. The most significant effect is increased winding and rotor I^2R losses due to increased copper and aluminum resistance at higher temperatures. This increase in resistance affects several motor performance parameters. In particular, efficiency is reduced due to greater I^2R heating. This will increase winding current and heat rise and slightly increase rotor slip (i.e., reduce speed) at any load point including full load. The increased rotor and stator resistance will also affect the motor's speed-torque characteristics. For example, Limitorque notified utilities that increased ambient temperatures will reduce both starting current and torque in its intermittent-duty rated valve actuator motors [19]. However, increasing rotor resistance could cause a motor's starting torque to increase. The specific effect of temperature on starting torque (increase or decrease) is based on resistance and reactance of the rotor and stator. These values are design specific and are evaluated as part of the motor's original qualification. Motor rewinds, assuming there are no changes in winding electrical characteristics (e.g., resistance and impedance), will not impact this design characteristic or its original qualification.

Significant increases in motor winding losses are similar in effect to increasing load. Tolerance to overload conditions varies with motor design. The operating temperatures of all motors will increase during overload conditions. Increasing load increases I^2R losses which further increases winding resistance, which in turn increases I^2R losses. This spiraling temperature - resistance cycle reaches equilibrium if the overload is within the physical design limits of the motor. However, at some overload point determined by the motor's physical design, the motor is incapable of removing sufficient heat to establish new equilibrium conditions. At this point, termed thermal runaway, the winding temperature continues to increase and the motor will quickly burn-up. Motor manufacturers provide motors for high ambient temperature applications by derating existing motor designs or using larger motor enclosures with greater heat transfer capabilities. Additional information on estimating the effect of higher ambient temperatures on winding operating temperature is provided in Section 5.

Increasing temperature also reduces air density, theoretically affecting motor cooling. A similar effect occurs during high altitude operation as a result of pressure reductions. NEMA MG-1 recommends derating motors operated at altitudes greater than 1000 meters (3300 feet). Experience indicates that minor density related cooling reductions are generally insignificant for most motors. However, for some designs (e.g., TEWAC), density variations will affect heat exchanger performance and allowable maximum load.

4.3.3.2 Humidity. Steam conditions occur in the vicinity of motors as a direct result of most pipe break events. Steam / humidity conditions can include 100% RH (i.e., saturated) conditions at relatively low temperatures (e.g., 150°F), saturated steam conditions during LOCA events, and short-time superheat conditions during certain MSLBs. The temperature effects of the steam environment are discussed above. Steam exposure produces more rapid heating when compared to a hot air exposure at the same temperature. This occurs because the latent heat of vaporization is released as the steam condenses on a cooler surface. The most significant steam / moisture effects involve performance degradation due to condensed moisture. Moisture is known to play a significant role in motor failures. Moisture provides an electrical pathway along insulation cracks, defects, and exposed conductors and between cracks, defects, and exposed conductors to ground. Pathway currents become progressively more severe due to increasing path conductivity produced by carbonized insulating materials. Subsequent flashovers and insulation failures often occur. In addition, many organic insulating materials under high humidity conditions continue to absorb moisture for extended times. The moisture can cause swelling and loss of physical and electrical strength. Some materials, such as certain polyesters, hydrolyze (decompose) when exposed to the combined effects of high temperatures and moisture.

Obviously, the type of motor enclosure plays a significant role in defining the steam / moisture exposure of motor windings. Open type enclosures provide little protection to the windings from external moisture and condensation. Totally-enclosed designs can limit significantly the amount of steam / moisture penetrating the motor enclosure. In totally closed designs, moisture penetration is limited to two mechanisms, pressurization and diffusion. Moisture intrusion via pressurization occurs when a pressure difference exists between ambient pressure and the motor internals. This transient pressure difference exists initially during pipe breaks but the pressures quickly decay and are equalized through motor enclosure drains.[22] During this short time, motors near the pipe-break may be exposed to an external steam environment. Motors further removed from the break will not experience an external steam environment

22 External pressurization during pipe-breaks outside containment are often limited to very short times (few seconds) due to the operation of "blow-out panels" or other building closures that quickly equalize building pressures subsequent to large pipe-break events.

during this initial pressurization period. For motors near the break, the pressurization will force some amount of the external steam / air mixture into the motor where it may condense on cooler internal surfaces. This condensation (and the associated reduction in internal pressure) can draw some additional external environment into the motor until pressures equalize. Modest amounts of moisture may accumulate inside the motor during this time. After pressure equalization, moisture would only be drawn into the motor via. diffusion through openings and cracks. Diffusion through such small openings requires significantly longer times (e.g., hours to days).

Motor stopping and starting may also affect moisture intrusion for totally enclosed designs. Some amount of the external environment is drawn into the motor enclosure each time an operating motor is deenergized and allowed to cool. As the cooling internal air becomes denser, its pressure decreases and the outside environment is drawn into the motor to equalize pressure.[23] Conversely, as a motor heats-up during starting or load increases, operating temperatures increase and the internal air expands. This expansion serves to reduce the rate of external moisture diffusion into the motor.

If a surface below the saturation temperature is exposed to superheated steam, the steam will condense on the surface as it heats up quickly to saturation temperature. Once the surface is at saturation temperature, further heat-up does not occur via steam condensation. Further surface temperature increases can only occur from convective heat transfer from the "dry" superheated steam. In fact, for the surface temperature to increase above saturation temperature, all moisture must be removed or evaporated from the surface. Any motor components operating at temperatures greater than the steam environment's saturation temperature will not become moist or wet.

Relative Humidity (RH) is a measure of the partial pressure of water vapor in the air compared to the partial pressure of saturated water vapor at the particular air temperature. At surface temperatures below the "dew point" (i.e., saturation temperature based on the partial pressure of ambient air's water vapor), condensation will occur. Motor heaters are designed to prevent condensation by raising the motor and its windings a few degrees (typically 5°C) above dew point temperatures.

When motors are operating, moisture effects become much less significant. For example, the maximum winding temperature at full load for a motor rated with a Class B heat rise is 130°C (40°C ambient temperature + 80°C average winding heat rise + 10°C hot spot allowance). For outside containment pipe-breaks with near ambient pressures, saturation temperatures will not increase significantly above

23 The ideal gas equation, $PV = nRT$, where P is pressure, T is temperature, V is volume, and nR is a constant provides insight into the relative volume effect occurring with temperature changes.

100°C.[24] Therefore, motor windings operating at or near full load prior to the outside containment pipe break conditions should not experience any moisture or wetness during the pipe break. This would be true for both open and totally-enclosed designs. For motors operating at lower ambient temperatures or significantly below full load, the winding temperature could be lower than 100°C (e.g., 25°C ambient + 60°C winding heat rise) prior to the HELB. The heat rise and churning action occurring in rotating bearings also minimizes moisture effects on greases and other lubricants. Moisture effects on rotor assemblies, including the commutators of DC motors, are also minimized during operation, since condensed moisture is hurled off the rotating assemblies by centrifugal force.

4.3.3.3 Water and Chemical Spray. Chemical and demineralized water sprays can occur inside containment during LOCA or MSLB accidents. The containment spray systems use special nozzles that release significant amounts of water as a very fine mist or fog. The rate at which sprayed liquid impinges on a motor depends on the motor location, orientation, and spray system design. Typical spray rates range between 0.15 and 0.7 gal/min. per square foot of containment horizontal cross-sectional area. This is a significant amount of water equivalent to 14.4 - 67.2 in/hour (roughly 1 to 5 feet/hour) of rain. This amount of water/fog could have a significant effect on windings in open type enclosures as the moisture is swept through the motor. Properly designed and installed totally-enclosed motors, using motor enclosure drains/breathers, shaft seals, and gasketed terminal boxes should adequately protected motor internals from the direct effects of these sprays.[25] PWR containment sprays contain chemicals that raise the pH to values from 7.2 to 11.0. Certain metallics, such as aluminum, can experience significant amounts of corrosion (releasing gases such as hydrogen) when subjected to these caustic sprays. Consequently, totally enclosed, fan-cooled (TEFC) enclosure materials for inside containment motors are generally limited to steel or cast iron. Similar concerns would exist for any other uncoated aluminum components potentially exposed to these sprays, including cooling fans, rotors, and termination boxes.[26]

4.3.3.4 Pressure. Pressure as a single stressor does not have a significant effect on the performance of motor components. For open type enclosures no pressure differential will exist between the inside of the motor and the outside environment. For TEFC and other totally enclosed designs, pressure equalization will be

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24 Even at a steam pressures of 2 psig, saturation temperature is less than 220°F (104°C).

25 In one successful motor qualification test of a form-wound, epoxy VPIed motor, post-test inspection indicated some moisture-related abrasion of the winding resin in the end turn area. However, the abrasion did not penetrate the glass binder tape.

26 In order to effectively protect aluminum from spray effects, coatings must be able to tolerate the environmental conditions associated with LOCA type accidents.

achieved in a time interval dependent of the type and size of enclosure openings and the pressure transient. In one proprietary test of a form-wound inside containment motor, pressure differentials in the range of 10 - 15 psi existed during the rapid (roughly 10 psi / sec) initial LOCA pressurization. However, pressure equalization would occur within 1 - 2 seconds once external pressures stabilize. For TEFC designs, pressures equalize through the unplugged drain holes, down the shaft through seals and bearings, and through other unsealed enclosure openings, if any, such as motor lead holes. This pressurization will help drive the external environment into the motor. It could also force some grease out of the bearings and into the motor. Testing experience with totally-enclosed designs indicates that bearing / shaft seals, coupled with open low point drains, eliminate concerns regarding grease extrusion due to LOCA or HELB pressurization. Pressurization can also facilitate moisture related degradation by attempting to force moisture into insulation system components and bearing lubricants.

4.3.3.5 Radiation. With some exceptions, the degrading effects of radiation on organic materials are somewhat similar to the effects produced by prolonged exposure to high temperatures (e.g., brittleness, decrease in strength, cracking, shrinkage). Consequently, a radiation exposure could be thought of as shortening the insulating system's thermal life or lowering its thermal class. In general, the properties of organic materials progressively deteriorate as the total radiation dose increases. The rate of degradation can be a complicated function of dose, dose rate, material configuration, and other factors (such as temperature) and is generally nonlinear. In a simplified model of radiation effects on organic materials, the ionization induced by the radiation causes bonds to break between atoms in organic molecules and creates free radicals (highly reactive sites on molecules) and smaller molecules. These free radicals and molecules interact chemically with each other and with other organic molecules in the material to form new / modified organic molecules. As the mixture of these new molecules grows and the amount of the original molecules decreases, the overall material properties change (usually degrading). Gas molecules (such as methane and hydrogen chloride) can be produced when some organic materials are irradiated.[27] These gases, if produced rapidly (due to very high dose rates), could generate pressure within a sealed insulating system which might affect the system's overall integrity. However, even at the accident dose rates encountered in some motor applications (e.g., 1 Megarad / hour), gases can diffuse from the interior of materials and there is little evidence that gas production even during accident radiation rates adversely affects motor insulating systems.

The principal source of radiation is the fission products contained in the reactor core. Assumptions associated with LOCAs and other types of accidents assume that fission products are released from the reactor into containment and into piping

[27] Some materials, like silicone, will produce more gas than other materials such as polyimides.

systems communicating with the reactor or containment sump. The most commonly used radiation dose unit is the rad, which is the quantity of radiation necessary to deposit 100 ergs of energy per gram of material. The international radiation dose unit is the Gray (1 Gy = 100 rad).

There are principally four types of radiation in a nuclear power plant; alpha, beta, gamma, and neutron. Alpha radiation, due to its very low penetrating power, is contained within the pressure boundary of process systems. Neutrons interact with materials in complex ways. However, neutron radiation only exists in the vicinity of the reactor during power operation. Consequently, alpha and neutron radiation are not relevant to motor qualification. Additional information on radiation effects on organic materials is provided in a wide range of documents, including several EPRI reports [20, 21, 22, 23].

Gamma radiation is highly penetrating and exists in the vicinity of the reactor and other plant equipment and systems containing radioactive materials. Gamma radiation levels significantly increase as a result of LOCA type accidents. Due to its penetrating power, gamma doses can be considered essentially constant throughout an insulating system, although metals and concrete, due to their high density, can attenuate gamma radiation.[28]

During normal operation, the radiation levels in most plant areas are dominated by gamma radiation and are insignificant even assuming equipment operation for 40 years. For example, if one assumed a total radiation dose of 10^6 rad exists due to normal radiation exposure for 40 years, this exposure is roughly equivalent to 3 rad/hour. This dose rate is significantly higher than the normal radiation levels encountered by most motors requiring environmental qualification. Since 10^6 rad is below the threshold damage dose for virtually all but a few motor insulating materials (e.g., teflon, etc.), radiation aging is not significant for most plant motors.

Beta radiation (high energy electrons), although possessing somewhat greater penetrating power than alpha particles, is similarly retained by process systems during normal operation. Beta radiation levels are significant during LOCAs whenever fission products are released into the containment atmosphere. This occurs to a lesser degree outside containment due to containment leakage into other plant areas. When present, airborne beta radiation doses are roughly 10 times the gamma dose levels. However, the low penetrating power of beta radiation (compared to gamma radiation) limits its effect to equipment surface layers. The penetrating power of beta radiation is principally a function of a material's density and the beta's energy. For energies typical of LOCA beta radiation (e.g., 0.235 MeV), roughly 60 - 70 mils of

[28] For example, roughly 12 inches of concrete and 3.5 inches of carbon steel are required to reduce gamma doses by a factor of 10.

organic material or 10 mils of steel will attenuate (shield) virtually all the beta radiation. Totally enclosed motors will, therefore, have no direct beta dose.

4.3.4 Accident Considerations

4.3.4.1 Enclosure. The rewind motor enclosure system must provide protection that is equivalent or superior to the enclosure protection provided when the insulation system was qualified. This is only relevant to LOCA and other pipe-break events, since the enclosure provides partial protection for the motor winding. Enclosure type is not a factor when qualifying for radiation-only conditions.

Conceptually, insulating systems qualified with no enclosure (e.g., motorettes) should be acceptable for use in motors with virtually any enclosure design (e.g. totally-enclosed or open). Conversely, insulating systems qualified using "totally-enclosed" designs would not be considered acceptable without further evaluation for motors with "open-type" enclosures. This assumes that no additional information is available on the conditions within the enclosure. When the test motor enclosure's internal environment is adequately defined, this environment could be used to qualify the insulating system to equivalent or less severe external environments for open type motors. Similarly, when an insulating system is qualified for severe pipe-break conditions using a totally-enclosed design, this system might be acceptable for open type designs that are exposed to significantly less severe pipe-break conditions. The general hierarchy for the level of protection provided by motor enclosures is presented in Table 4.6.

Table 4.6
Hierarchy of Protection Provided by Motor Enclosures During Accident Testing

Enclosure Type	Level of Protection
Totally-Enclosed	High
Open	Moderate
None*	None

* no enclosure exists when some motorettes are tested

4.3.4.2 Voltage. Motor design voltages may differ for tested and installed motors. Voltage differences can exist for turn-to-turn, phase-to-phase, and phase-to-ground voltages. Phase-to-phase and phase-to-ground voltages are directly related and will be discussed first.

Phase-to-Phase and Phase-to-Ground Voltages: Medium-voltage form-wound insulation system designs vary the ground wall insulation thickness to achieve a desired volts-per-mil (vpm) value. Generally, the vpm design requirements are similar for otherwise similar machines with ratings between 2300 and 7000 volts. These values are typically in the range of 50 vpm. Most designs require one 1/2 lap layer of 5 to 7 mil thick insulating tape per kV. However, the total ground wall insulation thickness (and resulting vpm) is based on the total thickness of conductor insulation, insulation tape, and armor tape. This results, assuming the 1/2 lap-layer per kV rule, in lower total vpm values for lower voltage machines. A second consideration related to voltage and insulation thickness is resin penetration. It is generally assumed that resin penetration and fill, particularly the essentially void-free constructions desired during VPI, are more difficult for the thicker insulation used in higher voltage machines. Both the vpm and resin penetration considerations suggest that qualification for higher voltage form-wound designs can be applied to lower voltage designs. Ideally, both the vpm and operating voltage of the qualified system should be equal to or greater than those of the rewound motor. Considering other conservatisms and uncertainties, including those associated with motor fabrication, acceptable qualification for any medium voltage levels below 7 kV should be acceptable for other voltages in this range when the vpm of the rewind system is bounded by the qualified vpm value. Form-wound systems qualified at medium-voltage levels should be acceptable for low-voltage form-wound applications, since the design vpm for these low-voltage systems is generally much lower than the design vpm for similar medium-voltage machines.

For three phase random-wound motors, typical nameplate voltages are 460 and 575 volts. However, the insulation system design voltage value for these and lower voltage (e.g., 120 V) motors has been standardized at 600 volts by NEMA. Consequently, identical insulation systems are typically provided for both 460 and 600 volt motors. This suggests that operating voltages during qualification tests should be equal to or exceed those found in service. In other words, insulating systems qualified for 575 v motor applications could be directly applied to 460 v designs. However, the converse may not be true.

Turn-to-Turn Voltages: Volts-per-mil considerations are less clear-cut for turn-to-turn voltages. Motor rewinds often are standardized with a particular conductor insulation. For the round magnet wires used in random-wound motors, the insulation is often standardized as heavy, triple, or quad build insulation. For the rectangular/square magnet wires used in form-wound motors, the insulation is often specified as Double Daglas (DDG) or DDG over heavy film. For both round and rectangular/square magnet wires, the actual insulation thickness varies based on wire size. The turn-to-turn operating voltage can vary substantially for different machines and is not related simply to conductor size. In random-wound motors, due to the random placement of loops within each coil, full *coil* voltage could exist between adjacent turns. Coil voltage is determined by the motor design and is based on a variety of factors, including number of poles, number of coils per coil group, and group connections. In form-wound motors, turn-to-turn voltages can be precisely defined and controlled. However, they will vary based on coil voltage, number of turns per coil, and connection scheme. Since turn-to-turn voltages are relatively low (e.g., ≤50 volts), testing of a representative motor has generally been considered acceptable to demonstrate the adequacy of the turn-to-turn insulation design criteria applied on similar machines.[29] For random-wound motors (i.e., round magnet wires), the magnet wire build should be equal to or greater than that used during qualification. For form-wound designs, conservative design practices should be used to keep the turn-to-turn vpm values within acceptable values.

4.3.4.3 Temperature Rise at Full Load and Loading during LOCA Exposure. The load profile imposed on a motor during the LOCA simulation may include no load, full load, or some intermediate load. As previously noted it requires several hours for typical continuous-duty motors to achieve thermal equilibrium at full load. Consequently, motors will rarely reach maximum heat rise conditions during the initial transient portion of the LOCA or HELB when external temperatures are highest. For motors continuously operated during the LOCA, maximum winding temperatures will occur after several hours. However, with an ambient temperature greater than 100°C and a 90°C heat rise at full load hot spot, winding temperature could be in the range of 200°C or higher. The test motor's design may not achieve the maximum heat rise for its insulation class. For example, a winding rated for a class B heat rise is generally designed with conservatism for a somewhat lower hot spot rise (e.g., 75°C). This minor temperature difference is less significant than the impact of motor loading during qualification testing. For motors requiring intermittent operation during the LOCA, the load profile for the test motor is not as significant a concern unless the motor application requires multiple repetitive starts. For applications requiring continuous operation at significant loads, the qualification test should include prolonged operation at a loaded condition. Since winding temperature is a combination of ambient temperature and heat rise, the difference between required ambient temperature and test temperature can be used to justify LOCA testing of motors at less than full load conditions.

4.3.4.4 Operating Sequence. Moisture and heat are the two most significant stressors for motors during steam accident conditions. Different modes of motor operation and loading during accident simulations can alter the significance of both moisture and heat degradation during these pipe-break accident conditions. As described below, it may be difficult to adequately simulate both temperature and humidity stressors for a range of applications with a single qualification test.

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29 When turn-to-turn voltages exceed 50 volts peak, IEEE 1068-1990, *IEEE Recommended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industry,* recommends the following application of turn mica paper tapes:

> 50 V peak	one 1/2 lapped layer
> 80 V peak	two 1/2 lapped layers
>120 V peak	three 1/2 lapped layers

Motor insulating systems that continuously operate before and during steam type accidents should be less prone to moisture related failures since the insulation system's heat rise minimizes condensate formation, moisture intrusion, and the surface tracking phenomena associated with *wet* windings. However, these motors, particularly those operating at full load, can experience extremely high insulation temperatures during the LOCA simulation. While motors idle during the high temperature, LOCA transient might only experience a peak temperature of 340°F, Class B rise motors running at full load could experience temperatures as high as 485°F - 500°F (250°C - 260°C) during this transient.[30] Conversely, motors idle prior to the LOCA exposure and at ambient temperature will experience significant amounts of steam condensation on those surfaces exposed to the steam conditions. Surface moisture in the presence of insulation cracks, defects, and exposed conductors can cause leakage currents, insulation flashovers, and failures. Moisture penetration into the insulating system can also degrade electrical characteristics. Certain materials (e.g., certain polyesters and polyimides) chemically degrade when exposed to high temperature and moisture. Some motors can experience repeated starts and stops during accident conditions (e.g., valve actuator motors). This cycling service could introduce the most severe moisture conditions during LOCAs, depending on the specific cycling sequence and duration of operating and idle periods. For example, as a TEFC motor cools, the external environment is drawn into the motor and its insulating system.

The rate of motor heat-up and cool-down further complicates this issue of operating sequence. Most continuous duty motors typically require 2 - 3 hours to heat up from ambient temperature to steady-state full load temperature [8,24] with a rapid initial temperature rise (e.g., 55% - 60%) during the initial 30 minutes. This is a broad generalization that appears to apply to most motors. However, larger motors generally require somewhat longer and smaller motors somewhat shorter times to achieve equilibrium operating temperatures. This heat-up information conservatively represents the shortest times for operating motors to achieve temperature equilibrium during high temperature steam conditions, since the motor temperature is initially lower than the LOCA chamber's steam temperature. This suggests that motors must be operated for at least several hours during LOCA / HELB conditions to reach steady-state continuous operating temperatures. The cooling rate upon deenergization or load reduction is dependent on several factors, including load characteristics.[31] It is reasonable to conclude that, when a motor is de-energized, cool-down times are longer than heat-up times since, the heat transfer characteristics of the motor remain relatively unchanged, except for motor

30 340°F ambient plus 145°F - 160°F Class B heat rise.

31 A large inertial load, by prolonging shaft rotation during coastdown, can aid in motor cool-down.

rotation. Motor rotation during operation aids heat removal, but is absent during most of the cool-down cycle.[32] Once a motor is operated for some reasonable time during LOCA / HELB tests, it is unlikely to return to chamber ambient temperature conditions unless it is idle for prolonged periods of time (at least several hours). Some amount of idle time during the initial portion of the LOCA simulation may be necessary to fully simulate the conditions of motors that do not require immediate energization after the high pressure steam conditions are established.

Intermittent-duty motors, at rated load, heat-up much faster than continuous-duty motors. Intermittent-duty motors, by definition, must remain at or below the insulating system's thermal rating when operated at rated load for the duration of the nameplate duty cycle (e.g., 15 minutes).

4.3.5 Qualification Based on Motorette or Complete Motors

IEEE 334 permits qualification testing of motor insulation systems using either 1) complete motors or 2) insulating system models, but prefers the use of complete motors. These insulating system models are referred to by a variety of names, such as motorette, formette, or statorette, depending on the type of insulating system design being modeled. In subsequent discussions, we will refer to all such models using the generic term, motorette. The use of motorettes, to establish insulating system qualification, evolved from commercial industry testing practices for determining the thermal classification of insulating systems. There are certain advantages and disadvantages associated with the use of either motorette or motor test specimens during qualification testing (e.g., LOCA steam simulations). These include:

- Operation under rated load can be demonstrated during motor qualification testing. However, problems are often experienced when mechanically simulating loaded conditions inside a LOCA / HELB steam test chamber. Motorette testing can simulate the thermal heat rise conditions associated with motor loads, but cannot simulate the mechanical forces acting on the winding system during starting and operation.

- Both motor and motorette testing can simulate the internal heat rise occurring during motor operation. A "representative" motor can best simulate the heat distribution in motor windings including the cooling of fans. Motorette heat rise distributions, accomplished by passing current through the test specimens, depend on the motorette design and the methods used to simulate the core. When the core slot section is simulated using fabricated sheet steel plates, the

[32] TVA's experience with RCP motors indicates that heat-up times are in the range of 1.5 - 2 hours but cool-down times are at least 8 - 12 hours and can be much longer (e.g., 20 hours).

motorette winding heat rise for a particular current might be less than experienced by a winding situated in an actual core.

- Both motor and motorette testing can simulate the changes in winding temperature caused by load changes or periodically starting and stopping motors.

- Motor testing can simulate the mechanical forces -- due to starting, operation, and load changes -- acting on the windings during the LOCA steam exposure. Motorette testing, as currently practiced, cannot simulate these mechanical forces while the motorette is subjected to the steam exposure. These mechanical forces are most significant in the "end turn" winding area. However, properly designed and braced winding end turns should not experience significant degradation due to normal starting and operating forces. This is particularly true for most random-wound motors which have short overhangs and compacted end-turn areas. It is less true for form-wound motors where bracing and surge rings are relied on to provide structural strength. However, due to size limitations of most LOCA / HELB steam test chambers, the larger size form-wound motors cannot easily be LOCA tested. The insulating systems in these larger motors are often qualified using motorette testing.

- Motorette qualification tests have been performed with the test specimens directly exposed to the chamber steam and spray conditions. This is a very severe exposure that can cause unrealistic failures and is generally more degrading than the environment inside the motor. Motorettes have also been installed in dummy cores and enclosures during qualification tests. Testing of complete motors provides protection to the winding based on the enclosure design. For totally enclosed type motors (e.g., TEFC), the degree of protection can be substantial. Lesser protection is provided by open-type enclosures.

- Motorette samples can be easily designed and tested to subject the insulation to independently adjusted turn-to-turn, phase-to-phase, and phase-to-ground voltages and load currents. This can be used to impose test voltages and volts-per-mil stresses that encompass anticipated operational voltages in fully fabricated motors. Motor test samples have heat rise and turn-to-turn, phase-to-phase, and phase-to-ground voltages that are based on the electrical design of the test motor. While the test motor may represent insulating systems in qualified motors installed in plants, the test motor heat rise, voltages, and volts-per-mil stresses may not encompass all anticipated applications.

- Testing of complete motors can be used to demonstrate operability of not only the insulating system, but the bearing / lubrication / seal system, the motor rotor, and other motor components including fans, housing drains, paint, etc. Motorette testing only addresses the capabilities of the insulating system, lead wire, and terminations. When qualifying the insulation system with motorette testing, qualification of the other motor components must be achieved using other tests, analysis, or operating experience.

4.4 Manufacturer and Material Substitutions

Ideally, once qualification is established, no manufacturer or material substitutions should be needed. Material substitutions may be needed when the originally qualified material cannot be used due to obsolescence, unavailability, material quality issues, or winding fabrication problems.[33] The suitability of any substitutions should be based on the component function, the severity of the required environment, the amount of conservatism existing between required and qualified conditions, type and severity of aging, and the methods used to establish qualification (e.g., type testing, analysis). Figures 4.1 and 4.3 suggest that evaluating the suitability of substitutions is part of procurement and acceptance. The need for such evaluations may also exist earlier in the process. Importantly, these evaluations are formal engineering activities that must be reflected in the qualification documents.

Generally, substitutions are more easily justified when qualification is based on analysis combined with partial test data. These substitutions can be justified whenever the proposed material characteristics would have been found acceptable if they were evaluated during the original analysis. For example, conservatively established radiation service limits for silicone insulated lead wire should apply generically to silicone insulated wires provided by several different manufacturers. When qualification is by type testing, particularly to severe LOCA steam and radiation conditions, variations in material characteristics or manufacturers and their effects on insulation system performance become more difficult to assess. Under these severe accident conditions, some materials are stressed to the limits of their functional capability. At these limits it is often the combined characteristics of materials, fabricated into a system, that determines suitability. Consequently, variations in individual materials should be assessed for their impact on the overall system or interfacing materials. The following observations regarding the acceptance of motor insulating materials for harsh environment applications should be considered whenever material changes are contemplated.

For insulating materials whose suitability for use in harsh applications requires EQ testing, special material controls may be necessary in order to establish the applicability of the EQ test basis to the supplied insulating system materials. Several types of material changes are possible. First, although the originally qualified

33 For example, fabrication problems are often encountered with silane treated fiberglass tapes because the treatment renders the tape very fragile and difficult to apply.

manufacturer and product designations may be specified, the manufacturer may have made design / material changes which can impact the qualification and suitability as a component in the qualified insulation system. While the changes may be reflected in design revisions or documented by the manufacturer in some forms, in some cases no manufacturer information on the changes may be available. Secondly, alternative suppliers of equivalent components may be specified based on meeting a general product description or compliance with a commercial standard or federal specification. A variety of manufacturers provide round enamel wire meeting NEMA class MW-35C. The insulating enamels on these wires may be slightly different formulations. A number of manufacturers can provide heat-cleaned fiberglass cloth in accordance with a particular specification. Finally, certain material or product changes may actually enhance capability. An insulating system may have been qualified with a polyester based magnet wire coating; however, a particular utility may desire to use the higher temperature and radiation resistant polyimide (e.g., Kapton or ML) insulation.

Under normal (i.e., mild) conditions, minor material or formulation changes do not significantly affect the system's capability. Furthermore, if the product meets the applicable required characteristics, adequacy is confirmed. However, the characteristics and tests cited in these commercial specifications do not necessarily address the degrading influences of harsh accident environments. Since these harsh conditions characteristics are not reflected in the commercial specification characteristics, other methods of insuring acceptability of the supplied materials are needed. These methods can be conceptually divided into two groups, Material Traceability and Material Substitutions. Material traceability is considered part of the CGI material acceptance process and is discussed in the next section on procurement and acceptance.

Evaluation of substitutions determines suitability and qualification of the substitute material. Generally, material substitution activities involve special tests or analyses demonstrating that the materials are either sufficiently similar or superior to those used in the EQ test and, therefore; qualification is preserved.[34] Determining adequate performance is usually achieved by a combination of analysis and limited testing such as environmental screening tests.[35] These limited tests should focus on specific critical characteristics, such as radiation resistance or resin compatibility. In most cases analysis and limited testing can address minor substitutions. In cases

34 Plant EQ licensing commitments for the acceptability of analysis and similarity evaluations vary.

35 Screening tests could include comparing the original and substitute materials' physical, electrical, or mechanical parameters after an exposure to thermal aging, steam, or high levels of gamma radiation.

where significant material changes occur, it may be necessary to perform a new insulating system qualification test. As noted above, comparative testing of the original and substitute materials is one way of establishing adequacy.[36] Retaining samples of certain materials used to construct the original EQ test specimens can aid in performing subsequent comparisons. Tests and analyses may also show that certain generic materials are inherently tolerant of the required aging or accident conditions and; therefore, minor material changes are not significant.

The following information provides guidance and suggestions on material substitutions for each of the major insulation system components. Although both the IEEE standards and UL 1446 define protocols for determining the thermal rating of insulating systems, only UL 1446 provides guidance on the suitability of material substitutions and their impact on the system's thermal rating. The guidance provided by UL 1446 is used below to assist in the development of material substitution guidelines for harsh applications. Generally, the suitability of substitute materials is based on several factors, including the type of harsh environment (LOCA, low-pressure HELB, or radiation-only), method of qualification (i.e., type testing or analysis plus partial testing), severity of the required accident environment compared to qualified environment, severity of required aging compared to level of qualified aging, and the insulation system component (e.g., lead wire armor tape) under evaluation. Table 4.7 summarizes the following discussions of insulation system component substitutions.

The following abbreviations are used in Table 4.7: Comparative Screening Tests or data for Aging tolerance (**CSTA**), Comparative Screening Tests or data for Radiation tolerance (**CSTR**), Comparative Screening Tests or data for Steam tolerance (**CSTS**), Selective Screening Tests for material Compatibility (**SSTC**), and Sample Coil Inspections or Tests for resin penetration, fill, and build (**SCIT**). Comparative testing or data involves evaluating the relative performance or properties of the original and proposed substitute materials. The screening test methodology is generally product specific. When performance is related to material combinations, consideration should be given to testing specimens with the combined materials. Screening tests for compatibility generally involve compatibility of a substitute material with the treatment resin but can involve other material compatibility. Inspection and testing of sample coils is recommended whenever substitute materials could adversely affect resin penetration, fill, build or sealing of the overall coil or connections. Some samples should be withheld from testing and maintained for future comparison.

36 For example, a silicone lead wire substitution might be evaluated through analysis, limited radiation testing, and a short steam or boiling water exposure that demonstrated similarity in loss of elongation for the original and substitute silicone lead wires.

4.4.1 Magnet Wire

NEMA MW1000 defines a number of magnet wire classifications for both round and rectangular wire with enamel or fibrous insulation or both. UL 1446 considers any magnet wire product meeting the NEMA requirements for a particular MW classification to be an acceptable substitute in rated insulating systems for other products with the same NEMA wire classification. This generic acceptance is due, in part, to the chemical and physical similarity of wire products in the same MW classification and the resulting generic compatibility of these enamel and fibrous coverings with the other insulating system components. This conclusion has been based on a considerable amount of testing experience demonstrating the generic characteristics of products meeting these magnet wire classifications. For non-bondable film coated wire, in addition to requiring the same MW classification, UL also requires: 1) that the enamel coating, by either infrared analysis or comparative chemical analysis, is determined to be generically similar to the original wire enamel, and 2) the thermal rating of the magnet wire, based on ASTM D2307 or similar thermal aging tests, is at least equivalent to the rating of the original magnet wire. When wires from differing MW classifications are substituted in an insulating system, UL 1446 requires a new thermal aging test program.

This guideline considers the general guidance provided in UL 1446 regarding magnet wire materials to be suitable for substitutions in harsh motor rewind applications. Harsh motor applications subject the magnet wires to stressors (e.g., radiation) not encountered in commercial applications. However, several factors suggest that magnet wire substitutions within the same MW classification will not affect insulation system performance in harsh environments. First, the radiation resistance of the high temperature magnet wire enamels used for harsh applications is extremely high. As discussed in Section 7.0, radiation threshold doses for these materials (e.g., polyester (amide) (imide) polyimide) are generically in excess of the required qualification doses, even for inside containment LOCA applications. Secondly, these magnet wire enamels are all classified as 180°C or better materials. The enamels most often used (e.g., MW35 and MW16) have thermal ratings of 200°C and 220°C. Furthermore, the cut through resistance and thermal aging tests prescribed by MW1000 demonstrate tolerance to even higher temperatures for short periods of time. Per NEMA MW1000, the MW16 material (polyimide) must tolerate heat shock testing at 240°

Table 4.7
Summary Substitution Guidance

The following abbreviations are contained in this table:

CSTA Comparative Screening Tests or data for Aging tolerance
CSTR Comparative Screening Tests or data for Radiation tolerance
CSTS Comparative Screening Tests or data for Steam tolerance
SSTC Selective Screening Tests for material Compatibility
SCIT Sample Coil Inspections or Tests for resin penetration, fill, and build

Material	General Guidance	LOCA/HELB Type Testing	Low-Pressure HELB*
Magnet Wire (enamel) See 4.4.1	• use same NEMA MW classification • establish system thermal rating for other MW class	• use same manufacturer & enamels where possible • use same enamels for alternate suppliers • use same MW class but different enamels - CSTA, CSTR, CSTS, & SSTC with resin	• See general guidance
Magnet Wire (fibrous) See 4.4.1	• use same NEMA MW classification • establish system thermal rating for other MW class	• use same manufacturer & materials where possible use same materials for alternate wire suppliers • use for same or superior MW class with different materials - CSTA, CSTR, CSTS, & SSTC with resin	• See general guidance
Mica Paper Tape See 4.4.2	• same layers, composition, & thickness • SSTC with resin • SCIT	• same manufacturer and product designation where possible, or • don't vary use of films • SSTC with resin • SCIT	• See general guidance
Resin See 4.4.3	• establish system thermal class for resin and other system materials • SCIT	• same manufacturer and formulation, or • minor formulation changes - CSTA, CSTR, CSTS, SSTC with resin, & SCIT, or • new EQ test for new resin	• See general guidance
Slot liner & phase separator (Nomex) See 4.4.4	• 410 and 414 considered equivalent • don't substitute calendered & uncalendered • don't substitute film laminates for uncalendered	• don't substitute between Nomex papers and Nomex based laminates unless CSTA, CSTR, CSTS, & SCIT	• See general guidance
Armor Tape See 4.4.5	• SCIT suggested for different materials, finish, thickness, or weave	• no material substitutions without CSTA, CSTR, CSTS with resin & SCIT or new EQ test • fiberglass for Dacron or Daglas acceptable with SCIT	• See general guidance

Table 4.7 (continued)
Summary Substitution Guidance

Material	General Guidance	LOCA/HELB Type Testing	Low-Pressure HELB*
Lead Wire See 4.4.6	• appropriate thermal rating for system thermal class • establish resin compatibility	• use same manufacturer & formulation where possible • use same insulation material type from alternate suppliers with CSTA, CSTR, CSTS • for alternative materials CSTA, CSTR, CSTS, & SSTC with resin or new test	• See general guidance
Sleeving uncoated See 4.4.7	• use same or higher thermally rated materials • establish resin compatibility for substitute materials	• use same manufacturer & formulation where possible • use same material, finish, and weave from alternative suppliers • for alternative materials CSTA, CSTR, CSTS, & SSTC with resin • additional screening tests desirable if part of connection insulation and sealing	• See general guidance
Sleeving coated See 4.4.7	• use same or higher thermally rated materials • establish resin compatibility for substitute materials	• use same manufacturer & formulation where possible • use same design, woven material and coating from alternative suppliers with CSTA, CSTR, CSTS, & SSTC with resin • for alternative materials or designs CSTA, CSTR, CSTS, & SSTC with resin or new EQ test • additional screening tests desirable if part of connection insulation and sealing	• See general guidance
Wedges & Laminates See 4.4.8	• use same or higher thermally rated materials • alternative materials or forms should result in equivalent or superior coil structure	• use same manufacturer & product where possible • different suppliers of Nomex based wedges are acceptable • laminates of the same or superior grades are acceptable	• See general guidance
Bracing Materials See 4.4.9	• use same or higher thermally rated materials • establish resin compatibility for substitute materials	• use same manufacturer & product where possible • use same material and finish from alternative suppliers • for alternative materials CSTA, CSTR, CSTS, & SSTC with resin	• See general guidance

* For Radiation-Only conditions use information in General Guidance column. Additionally, data must exist demonstrating adequate radiation tolerance.

C and thermoplastic flow testing at a minimum of 400°C. The MW35 material, typically a high temperature polyester overcoated with polyamideimide, must tolerate heat shock testing at 220°C and thermoplastic flow testing at a minimum of 300°C. Typical values quoted by manufacturers are even higher. For example, one manufacturer has published the "typical" values shown in Table 4.8. The thermal value is the actual projected life temperature based on thermal aging tests.

Table 4.8
Published Magnet Wire Typical Thermal Capabilities

Wire Class	Thermal Value	Thermoplastic Flow	Heat Shock
MW16	252°C	500^{+}°C	260°C
MW35	217°C	350°C	260°C

For the Class B heat rise motors typically found in nuclear applications, average heat rise is limited to 80°C or less. Even assuming peak LOCA temperatures of 340 °F (170°C), average winding temperatures at full load would not exceed 250°C. Since thermal lifetimes at 250°C - 260°C are in excess of 1000 hours, based on the published test data for these wire enamels, peak operating temperatures during LOCA are within the generic capabilities of these particular enamels. Although the long-term moisture tolerance (hydrolytic stability) of these enamels may vary, the enamel insulation is isolated from other environmental stressors, such as moisture, by the other insulating system materials, particularly the winding resin treatment. Finally, polyimide, polyamide imide, and high temperature modified polyester enamels are only supplied to the magnet wire industry by a limited number of companies, such as Schenectady International, P.D. George, and DuPont. As a result, magnet wire manufacturers use the same enamel formulation.

For fibrous coverings, we assume the fibrous magnet wire coverings are limited to fiberglass, Dacron (polyester fiber), and mixtures of these materials.[37] Most rectangular wire products with these coverings employ a polyester, epoxy, or silicone binder resin to help adherence of the fibrous covering to the copper wire during coil bending and forming operations. The classification and thermal rating of these fibrous insulations is generally defined by the type of bonding resin used. The selection of bonding resin type is often related to compatibility with the final resin selected for the VPI winding treatment. When generically similar (e.g., polyester) wire binding and winding treatment resins are used, compatibility is generally assured. When generically different resins are used, some form of resin compatibility data is needed. Since the binder principally functions as an assembly aid, variations among manufacturers should not be significant, except for resin

37 Nomex papers can be used but are rarely found in harsh applications.

compatibility. The Dacron (woven polyester) and fiberglass coverings from all manufacturers employ the same generic materials. The federal specification for magnet wire (J/W-1177) requires that the Dacron and fiberglass fibers conform to MIL-Y-1140.[38] Most magnet wire manufacturers meet both the NEMA and federal magnet wire specifications.

For form-wound and random-wound VPI systems, the magnet wire is isolated from steam/humidity conditions by the mica paper and armor tapes and VPI resin. The radiation resistance and compatibility of wire enamel and binding resin with the VPI resin are the characteristics important to qualification. The UL 1446 guidance is considered an acceptable basis to establish compatibility of enamels with resins. For fibrous coverings, resin compatibility can be established by comparative inspections and tests (e.g., power factor tip-up) on sample coils. It is recommended that any testing employ coils fabricated from both the original and substitute magnet wire with the results compared to determine suitability. It is also recommended that several samples (e.g., 5) of each product be tested and the average results compared to minimize the effect of sample variations.

For all harsh applications, if the substitute wire uses the same generic materials as the tested wire (i.e., same MW class for enamels, same material type, such as Daglas for the fibrous covering), then equivalent radiation resistance can reasonably be assumed.

For random-wound Dip & Bake applications, portions of the magnet wire may be exposed to high humidity conditions due to voids and incomplete penetration of the treating resin. In these applications, overall quality and moisture stability of the round magnet wire enamel may be critical to performance during LOCA/HELB conditions. Multiple enamel builds combined with compliance with NEMA criteria should maintain consistent capability among resins in the same MW class. However, additional comparative humidity/steam screening tests, such as sealed-tube testing, could be done to establish acceptability of substitute enamels.

4.4.2. Mica Paper Tape

For the purposes of this analysis, it is assumed that mica paper tapes will only be used in VPI processed form-wound windings. Mica paper tapes are composed of reconstituted mica paper, a variety of film and woven backing materials, and, like rectangular wire coverings, a resin binder to consolidate the materials and minimize separation during coil taping, bending, and forming. Variations among various styles of mica paper tape can exist in one or more of the following areas:

38 For additional information on these specifications refer to EPRI TR-103585 [5].

- Thickness and composition of woven layers (if any)
- Thickness and composition of mat-type layers (if any)
- Thickness and composition of film layers (if any)
- Thickness and composition of mica paper
- Type, amount, and composition of resin binder

The primary function of the woven tape layer is to provide mechanical strength during tape application, thus minimizing damage to the mica tape layers. If thickness and composition variations in the woven layer facilitate fabrication and minimize damage, then superior coils should result if equivalent or superior VPI resin penetration and curing occurs. Certain thickness and composition variations could *theoretically* affect VPI resin penetration and curing, resulting in a cured system with weakened physical and electrical strength. Variations in the open structure of the woven layers will have an insignificant effect on resin penetration and curing. These woven layers are fabricated from either polyester (e.g., Dacron) or fiberglass materials. The polyesters may exhibit some shrinkage during preheating of the coils prior to VPI processing. This shrinkage, by consolidating the tape layers, might positively or negatively affect resin penetration and curing.

Mat layers are provided as a lower cost alternative to glass cloth that provides mechanical strength and aids in winding fabrication. A mat layer is often found on tapes applied with high speed winding machines. The mat layer is typically a polyester material (e.g., Dacron). Coil compaction and resin penetration might be affected by inclusion or exclusion of the mat material.

Film layers are rarely used with VPI coils. There is a widely held belief that the film, by inhibiting resin penetration, will adversely affect the winding's electrical and physical characteristics. There is also a divergent view that the film provides the cured system with a number of slip planes that aid in distributing thermal expansion and other mechanical stresses, thus minimizing large crack formation. Films provide the tape with added strength and a smooth surface that facilitates the taping and coil forming process. In either view, films are a critical element in the tape design. Films also increase the dielectric strength of untreated coils and can prevent dielectric failures when minor tape degradation occurs during fabrication. Virtually all film layers are polyester (e.g., Mylar), although other specialized films (e.g., Kapton) are available with specialized tapes.

The principal concern with tape binder resins is their compatibility with the VPI processing resin. Incompatibility can inhibit VPI resin penetration or curing. Often tape resin and VPI resins of the same generic designation (e.g., polyester or epoxy) are used to minimize compatibility concerns. Power factor tip-up testing and sample coils are widely recognized as valid methods of determining resin compatibility. The tape or VPI resin vendors may have data or can perform testing to establish compatibility for the two products. A second concern with the binder resin is its radiation capability. As described in Section 7.0, polyester, epoxy, and silicone thermosetting resins all possess excellent radiation resistance characteristics. Further, there is a relatively small amount of binder resin when compared to the quantity of VPI resin in the overall coil structure. Consequently, the variations in binder resin type should not effect the overall radiation resistance of the fabricated coil. Finally, variations in the thermal classification of the mica paper tape might affect both its aging and accident performance. The mica tape's thermal rating is generally defined by the thermal classification of the binder resin. Tapes with silicone resin binders typically have a 220°C thermal class, while polyester and epoxy binder tapes are typically rated at 155°C or 180°C. The substitution of an epoxy or polyester binder tape for silicone might theoretically affect the thermal aging characteristics of the insulating system, if the projected qualified life is beyond the capabilities of 155°C rated materials.

The *Mica paper* layer possesses high dielectric strength, corona-resistance (i.e., long-term voltage endurance), and withstands high compressive loads. Mica is unaffected by the thermal and radiation levels encountered during normal and accident conditions. Maximum use temperature for both natural and synthetic mica exceeds 500°C [25]. In form-wound applications below 7 kV, where essential void-free VPI winding structures are achieved, minor variations in the material or thickness characteristics among mica papers should not be significant. Mica papers from one manufacturer are generally identical in composition and manufacturing methods. Quality and content may vary among manufacturers. Comparative voltage endurance testing could be used to demonstrate similarity between such papers. Mica paper thickness typically accounts for less than 50% of the total mica tape product thickness. Minor variations in paper thickness (e.g., ±1 mil*)* should not significantly affect the overall characteristics of the winding system, if the total mica build on the taped coil is equivalent or greater.

In summary these discussions indicate that the most significant effects of mica tape variations are related to coil fabrication, VPI processing, and resin compatibility. Tapes that improve the overall quality of the green winding and facilitate VPI resin penetration and curing should produce coils with improved environmental qualification characteristics. The power factor tip-up test is a universally recognized test used to determine the overall quality of winding fabrication, VPI processing, resin penetration, and compatibility. Fabricated coils with voids due to poor resin penetration or partially cured resin due to compatibility problems will produce high power factor tip-up results. Comparative power factor tip-up tests, comparing the characteristics of sample coils using both the old and new mica tapes, is one method of establishing the suitability of substitute mica tapes for environmentally qualified VPI windings. Changing the number and type of film layers in the tape is not recommended. Although, the power factor tip-up testing can address the impact of films on resin penetration, the long-term mechanical performance characteristics of the winding might be altered by inclusion or exclusion of film layers. Finally, using substitute tapes with different thermal ratings or a different generic binder resin (e.g., epoxy) is not recommended unless additional information, as listed below, establishes suitability and compatibility.

For radiation-only conditions, the use of generically similar materials in the original tape and the proposed substitute tape should provide adequate confidence in radiation capability. For LOCA / HELB applications, qualified by type testing, the substitute tape must result in equivalent: 1) void-free construction after VPI treatment, 2) post-VPI mechanical properties, 3) and long-term dielectric strength. This can be achieved reasonably if the tested and substitute tapes contain the same number of layers of equivalent thickness, materials, and binding resins. Additional selective testing can also be used to confirm resin compatibility and voltage endurance. Since long-term dielectric strength is directly related to the quality of the mica tape layer combined with essentially-void-free VPI resin impregnation, comparative accelerated voltage endurance tests on cured mica tape-impregnating resin samples could be used to evaluate substitute tapes. Inspection and power factor tip-up testing of sample coils, containing the substitute tape, should also be considered.

Some shops may prefer to use wrappers in lieu of tapes in the coil slot section. If motors are qualified with fully taped coils, wrappers should not be substituted without further evaluation and comparative testing of fully fabricated coils. Mica tapes can be supplied in various widths. Different tape widths will effect both the overlap dimension (e.g., 1/2" for 1/2-lap 1" tapes) and void sizes between layers. Widths should not be changed from those tested, unless different widths would produce superior coils, particularly for an unusual winding configurations (e.g., very small radius end-turn).

4.4.3 Dip & Bake and VPI Resins

Resins are critical to the environmental tolerance of qualified winding systems. In both Dip & Bake and VPI systems, the resin provides an environmental barrier protecting the other winding system components, including connections, from external contaminants (e.g., steam and moisture). In these systems the cured resin consolidates the winding structure, including end-turn bracing, and provides physical strength. In VPI systems the resin must possess flow, viscosity, and chemical characteristics that facilitate resin penetration, retention, and the achievement of an essentially void-free winding structure. In addition to strength, the resin must have thermal expansion and flexibility characteristics (new and aged) that minimize cracking and the subsequent ingress of moisture and conductive contaminants. As discussed in Section 7.0, the generic radiation resistance of polyester, epoxy, and silicone resins is high, minimizing concerns with the radiation tolerance of substitute resins. However, it should be noted that test data demonstrate that the radiation resistance of epoxies can be influenced by modifying the hardener system or adding flexibilizers (see Section 7.0). UL 1446 requires compatibility testing of substitute resins of equivalent or superior thermal class to the original resin. If the thermal class is "greater than one class lower than the original resin", a new thermal classification test program must be performed. All these considerations suggest that resin substitution may critically affect the performance of the insulating system during harsh environments, particularly LOCAs. However, their impact on performance is difficult to evaluate without performing new tests, including qualification testing. It may be possible to perform a variety of physical, electrical, and chemical tests on candidate substitute resins or coils using the resins to determine similarity and compatibility. However, the use of these tests to determine suitability should be reserved for minor formulation variations in a base resin that has already been qualified. For qualification by type testing, new programs should be initiated if substitute resins are used.

For all applications, substitute resin compatibility with other insulating system components and the thermal class of modified insulating system must be established. The guidance provided in UL 1446 is suggested. For *radiation-only* applications, radiation suitability of the substitute resin can be established by analysis and partial test data for the generic resin class or by comparative radiation tests of the new and substitute resins. For systems qualified by type tests for LOCA and HELB applications, the following is suggested for relatively minor formulation variations between the original and revised resins. First, the processing and physical characteristics of the substitute resin must result in equivalent or superior coil impregnation and build. This can be addressed by fabrication, inspection, and testing of sample coils using the substitute resin. Secondly, the effects of aging on the physical and electrical characteristics of the substitute should be equivalent or superior to those of the original resin. Comparative twisted-pair dielectric and helical-coil bond strength tests after aging can be used to address the aging characteristics. Finally, steam / moisture tolerance should also be equivalent or superior to the original resin. After exposure to a short-term steam screening test (e.g., 100°C for 24 - 48 hours), comparative twisted-pair dielectric and helical-coil bond strength tests could be used to address relative steam / moisture tolerance. Similar tests could be made with aged and / or irradiated test specimens.

4.4.4 Random-Wound Slot Liner and Phase/Slot Separators

Nomex paper is the material of choice for slot liners, slot separators, and phase separators in random-wound motors. However, the Nomex papers are available in a variety of thicknesses and types. Consequently, Nomex substitutions can involve different thicknesses or types. Slot liner and phase separator thickness is generally defined by voltage rating and standard practice. The required thickness is not usually varied for applications at or below 600 volts with 15 mil used as a common requirement. The types of Nomex paper currently available are listed in Table 4.9.

Table 4.9
Types of Nomex Paper

Type	Available Thickness	Characteristics
410	2 to 30 mils	original calendered form
411	5 to 23 mils	uncalendered version of 410 with lower specific gravity and electrical and mechanical strength
414	3.4 to 15 mils	calendered form, similar to 410 but slightly more flexible with slightly lower electrical and physical properties
418	3 to 14 mils	calendered product with 50% mica composition, electrical characteristics superior and mechanical characteristics inferior to 410
419	7 and 13 mils	uncalendered version of 418

Generally, only the calendered types are used in random-wound motors due to their superior mechanical properties. Given the similarity in their characteristics, Types 414 and 410 should be considered interchangeable from a qualification perspective. Preference is largely dictated by fabrication results. Type 418 could be substituted for either 410 or 414 if the lower 418 mechanical properties do not cause damage during fabrication. However, substitution in LOCA / HELB systems, qualified by type test, is not recommended. In low-voltage random-wound motors the superior long-term voltage endurance capabilities of the type 418 is not needed. Dip & bake and VPI resins have difficulty permeating the calendered Nomex papers. Consequently, resin penetration should not be a substitution concern when substituting one calendered paper for another. DuPont has stopped production of two saturable grades of Nomex paper designated types 424 and 425. Since resins could penetrate and saturate these papers, the other papers might not provide equivalent performance. However, DuPont does offer a spunlaced fabric of Nomex that is a non-woven saturable structure offered in 3 and 5 mil thicknesses. This spunlaced fabric, designated as Type E-88 and supplied in various styles, has characteristics suggesting it could be substituted for the Type 424 and 425 papers.[39] Additional comparative testing would be needed to address this substitution.

Nomex is also found in a variety of flexible laminate constructions, generally sandwiched with a film layer of Mylar or Kapton. The film layer in these composites is impermeable to resins. Since the thermal, radiation, and hydrolytic stability of

39 The "E" designation by DuPont indicates the product is experimental and long-term availability cannot be assumed.

Mylar is inferior to Nomex, it should not be used in a substitute laminate unless additional tests or data support its suitability. Comparative screening tests are recommended if substituting between Nomex calendered papers and Nomex-based laminates or between laminates with different film materials.

4.4.5 Armor Tapes

The armor tapes used in form-wound coils are typically manufactured with Dacron, fiberglass, or a combination of these two yarns. Aramid fibers (e.g., Nomex and Kevlar) can also be manufactured as woven tapes but higher cost limits their use as armor tapes. There are several differences between Dacron and fiberglass yarns that may limit their substitution without further evaluation. Some Dacron tapes shrink (e.g., 10%) during stator baking prior to varnish treatments; fiberglass tapes will not shrink. This shrinkage will consolidate the green winding structure which may aid or hinder VPI processing. Dacron tapes are more conformable than fiberglass tapes, making them easier to apply. Dacron is also considered more resin wettable than fiberglass, although bonding between resins and fiberglass can be improved by heat-cleaning and surface treatments. Fiberglass tapes can be supplied as either heat cleaned or non-heat cleaned. Surface treatments (e.g., silane) can also be applied. Resin bonding to the fiberglass and strength of the composite are affected by heat-cleaning and surface treatments. Unfortunately, heat cleaning and surface treatments also make the fiberglass tapes more difficult to handle which can adversely affect the quality of coil taping. Dacron is inferior to fiberglass in radiation, thermal aging tolerance, and hydrolytic stability.

Fabric characteristics, such as weave (e.g., plain or satin) and the number of end, picks per inch, yards per pound, and width, can all affect coil fabrication and resin penetration and retention. In form-wound coils, the armor tape - resin composite structure forms the coil's outer surface. This surface must resist cracking due to aging, thermal, and mechanical forces and is the winding's initial environmental barrier. Consequently, the characteristics of this composite must not be compromised. Since Dacron and Mylar polyesters are prone to hydrolytic degradation in the presence of moisture and high temperatures, the armor tape Dacron material might degrade during LOCA steam conditions since it is near the coil surface. Finally, other variations in tape construction, such as width, weave, and weight, by affecting resin penetration and retention, can adversely affect the void-free quality of cured coils. These variations may also have some effect on the mechanical strength characteristics of the resin-fabric composite.

Based on these considerations, the following guidelines for armor tapes substitutions are provided:

1. Tapes supplied by different manufacturers to the same tape specification (material, surface treatment, width, weave, ends, picks per inch, etc.) are considered be interchangeable.
2. Variations in physical tape characteristics, such as width, weave, etc., can be made if inspections, evaluations, and screening tests demonstrate that an essentially void-free winding structure results. Power factor tip-up and dissipation factor tests, coupled with inspection of dissected coils, should be used to verify the void-free nature of test coils.
3. Fiberglass tapes can be substituted for Dacron or Daglas tapes if inspections, evaluations, and tests demonstrate that an essentially void-free winding structure results. Power factor tip-up and dissipation factor tests, coupled with inspection of dissected coils, should be used to verify the void-free nature of test coils.
4. Dacron tapes should not be substituted for Daglas or fiberglass tapes in applications requiring LOCA / HELB qualification by type testing without additional supporting analysis and test data. In other applications, the substitution would be acceptable if inspections, evaluations, and screening tests demonstrate that an essentially void-free winding structure results. Power factor tip-up and dissipation factor tests, coupled with inspection of dissected coils, could be used to verify the void-free nature of test coils.

4.4.6 Lead Wire

There is a significant body of qualification testing and research information demonstrating that variations in the formulation of cable insulations can affect performance during LOCA conditions. Environmental qualification tests are generally required for each insulation formulation used for power, control, and instrument cables in nuclear power plants. Obviously, if different formulations of a generic material (e.g., EPDM) can affect performance, one cannot assume that different types of materials (e.g., EPDM, silicone, XLPE) are interchangeable. The lead wires must also interface with the winding insulation system. Bonding between resins and wire insulation will vary based on resin and insulation materials. In some cases, there are material incompatibilities between the resin or resin solvent and the wire insulation that cause problems in commercial applications. One lead wire manufacturer catalog recommends that compatibility between the individual lead wire size, bake / varnish process, and the varnish always be checked. For example, some resins may bond to certain EPDM materials which can cause subsequent cracking if the EPDM is flexed. Similarly, braidless silicone in certain rigid varnishes has been known to crack when severely bent.[40] Finally, the interface between the lead wire insulation and winding resin is a potential weak spot where moisture and contaminants (during LOCA / HELB) can penetrate the winding and cause failures. Bonding (or lack of adequate bonding) between the resin and lead wire insulation can compromise moisture resistance and the dielectric strength of this interface.

Based on these considerations, the following guidelines for lead wire substitutions are suggested:

1. For systems requiring LOCA / HELB qualification by type test, variations in material, manufacturer, or formulation should not be permitted without additional tests to establish adequacy.
2. The acceptability of formulation or manufacturer differences for a generic insulation type (e.g., glass braided silicone rubber) can be established by resin compatibility tests coupled with radiation, thermal aging, and steam (autoclave) screening tests comparing the characteristics of the original and substitute insulation materials. In lieu of the screening tests, LOCA qualification testing of the substitute insulation may be performed. The LOCA / HELB testing of the substitute wire insulation may be accomplished as part of another insulation system, if resin compatibility tests are also performed.
3. Different types of one generic insulation (e.g., silicone, EPDM) may be acceptable in LOCA / HELB systems qualified by type test if the substitute insulation was LOCA qualified and resin compatibility tests are performed. The LOCA testing of the substitute wire insulation may be accomplished as part of another insulation system.
4. For HELB and radiation-only conditions, substitute wire insulations may be accepted, based on resin compatibility tests and generic information on radiation tolerance (see Section 7).

4.4.7 Sleeving

Sleeving is used to protect coil and lead wires and their connections. Virtually all the sleeving is woven fiberglass tubes, with some types coated or impregnated with vinyl, acrylic, and silicone materials. Sleeving can be critical in applications where it is intended to absorb and retain resin in order to form a moisture barrier. Sleeving is

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[40] Belden recommends that lead wires be tested for resin and curing temperature capability. Other example problems cited by Belden include: cracking of cotton braids if baking temperatures exceed 250°F, shrinkback of PVC during oven curing, softening or swelling of Hypalon when exposed to aromatic and chlorinated hydrocarbons, EPDM degradation when exposed to greases and oils, and solvent swelling / softening of silicone -- especially with chlorinated, aliphatic, and aromatic hydrocarbon type solvents.

particularly important when used, in combination with other materials and the treating resin, as a component for insulating connections. Coated sleeving is also important when used as additional insulation for coil or motor leads. In VPI and Dip & Bake systems intended for LOCA qualification, the sleeving (and underlying materials such as a Nomex felt) is applied to absorb resin and provide a post-cure structure that resists moisture intrusion and provides adequate dielectric strength in the connection area. The sleeve coating is used to provide some dielectric strength during pre-treatment dielectric strength tests. Different sleeve coating materials can affect the integrity of the final sleeve - resin structure. The thermal class of vinyl coating (130°C) is rather low. Conversely, silicone coated sleeves possess very high thermal ratings (200°C - 240°C) but many resins have difficulty bonding to silicone elastomers. Compatibility of the substitute sleeve coating and the winding resin should be established.[41] For uncoated fiberglass sleeves, compatibility tests need not be performed. For LOCA qualified systems where the sleeving - resin structure is relied upon to establish a moisture barrier, additional information should be developed for substitute coated sleeves to establish the suitability for intended service. In cases when sleeving is an integral element of insulating connections, particularly when the sleeve must retain sufficient resin to form a environmental barrier, comparative screening tests could be used to demonstrate the acceptability of the connection insulation. For example, immersion high-potential tests could be used to demonstrate that a representative insulation connection using the substitute sleeving is sealed.

4.4.8 Wedges and Rigid Laminates

Wedges in premium insulating systems are fabricated of either Nomex pressboard (a thick version of Nomex papers) or rigid laminates. The Nomex can be supplied in square or curved form shapes in varying thicknesses. The rigid laminates are composite fiberglass and resin structures. A number of resin types (e.g., epoxy, silicone, polyester, melamine, phenolic) are used. Both NEMA (NEMA LI-1) and military (MIL-I-24768) specifications define a number of rigid laminate grades based on composition and construction.

Wedges do not typically have a dielectric function; their only purpose is to help secure the winding into the slot during fabrication, treatment, and operation. Rigid laminates are also used as phase separators and fillers in the slot area of form-wound motors. In phase separator applications, the laminates can provide some dielectric strength. However, the dielectric strength of the composite ground wall insulating system is the principal phase-to-phase dielectric barrier. The wedge materials must have sufficient thermal and radiation capability to maintain their physical strength during normal operation and accident conditions. Shrinkage of

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41 Compatibility may be established by performing the seal tube tests described in UL 1446.

wedges or phase separators, due to thermal aging, radiation exposure, or accident conditions could cause the winding to loosen in the slot area. Nomex materials have excellent tolerance to both radiation and high temperature conditions. Most rigid laminates have excellent radiation resistance. Thermal capabilities vary based on the specified grade. Based on these considerations, the following guidelines for wedges and laminates substitutions are suggested:

1. The use of different suppliers for Nomex wedges in random-wound applications should have no significant effect on winding performance.
2. Different suppliers of rigid laminates are acceptable provided the laminate is supplied to the same specification grade as the laminate used in the qualified motor.
3. Wedges of different configuration (e.g., square or curved) may be justified if they provide an equivalent or superior coil structure.

4.4.9 Bracing Materials

Blocking, lacing, and surge materials are used to secure the winding end turns, connections, and leads. Generally, the fabrication methods are more important than the specific form or composition of these bracing materials. Adequate strength is achieved by the composite structure once the winding has been treated with resin. Consequently, compatibility of these materials with resin is important. Substitution of an equivalent material (e.g., fiberglass tape) from another manufacturer should not affect performance and qualification. Similarly, substitution of a superior material should be acceptable. Evidence should be developed demonstrating such superiority for both aging and accident conditions. In general, woven fiberglass and Nomex fabric tapes can be considered superior to woven Dacron products. In some cases there may be an interest in substituting mat or felt for woven tapes or vice versa. If the substitution results in a stronger integral winding structure, the substitution may be justified. For LOCA and HELB applications qualified by type testing, identical or equivalent materials are recommended. For radiation-only and other applications qualified by analysis and partial testing, suitability of alternative materials should be based on the overall quality of the integral winding structure and adequacy of the material for the environmental conditions.

4.5 Material Procurement and Acceptance

A companion EPRI guideline on mild environment motor rewinds [26] provides technical information on the various materials and products used in motor rewind systems. The guideline describes the related industry standards, critical characteristics for design and acceptance, and recommends procurement and acceptance methods. Although that guideline focuses on mild environment motor applications, the information presented is directly applicable to motor materials used in harsh environment rewind applications.

4.5.1 CGI Procurement and Acceptance Process

A number of methods are available to utilities, manufacturers, or rewind shops for the acceptance of insulating system materials based on their critical characteristics. Several EPRI publications and NRC guidance documents providing additional information on the general concepts of commercial grade item CGI dedication are listed in Table 4.10. The concepts and recommendations contained in these documents should be utilized when accepting commercial grade items, including insulating system materials. In addition, the Joint Utility Task Group (JUTG) Commercial Grade Item Data Base provides information and guidance. Access to the data base is available through EPRINET.

Table 4.10
CGI Guidance Documents

• EPRI NP-5652, "Guideline for the Utilization of Commercial Grade Items in Nuclear Safety-related Applications", June 1988.
• EPRI TR-102260, "Supplemental Guidance for the Application of EPRI Report NP-5652 on the Utilization of Commercial Grade Items", March 1994.
• EPRI NP-6895, "Guidelines for the Safety Classification of Systems, Components, and Parts Used in Nuclear Power Plant Applications", February 1991.
• EPRI NP-6406, "Guidelines for the Technical Evaluation of Replacement Items Used in Nuclear Power Plants", December 1989.
• NRC Inspection Procedure 38703, "Commercial Grade Procurement Inspection".
• EPRI NP-6630, "Guidelines for Performance-Based Supplier Audits", June 1990.
• EPRI NP-7218, "Guideline for the Utilization of Sampling Plans for Commercial Grade Item Acceptance", June 1992.
• EPRI TR-101752, "Guideline for using Items Manufactured to Other Industry Standards in Nuclear Safety-Related Applications", March 1993.

Figure 4.11 illustrates the generic process for acceptance of commercial grade items for use in safety-related applications. The two major elements of the process are the Technical Evaluation and the Acceptance Activities. The Technical Evaluation determines if the item performs any safety-related functions and if it meets specific NRC regulatory criteria regarding CGI procurement. For items without safety-related functions, such as some assembly aids, CGI acceptance is not required and the items can be purchased nonsafety-related. For items with safety-related functions, the items' critical characteristics must be identified and acceptance

methods selected and implemented. Acceptance must be performed under the controls of a 10 CFR 50, Appendix B quality assurance program. Table 4.11 identifies the acceptance methods, individually or in combination, that can be utilized by a utility or any supplier/rewind shop with an audited and approved 10 CFR 50, Appendix B quality assurance program. In practice, for most insulating materials and products, Method 1 and Method 2 are the methods most likely to be successfully applied. Method 4 would typically need to be combined with one of the other acceptance methods. However, other documents, such as those listed in Table 4.10, with specific details on each of these methods should be consulted before implementing these acceptance methods.

Table 4.11
Four Acceptance Methods

Method	Description
1	Special Tests and Acceptance
2	Commercial Grade Survey
3	Source Verification
4	Acceptable Supplier/Item Performance Record

4.5.2 Material Traceability

For insulating materials whose suitability for use in harsh applications requires EQ testing, special material controls may be necessary in addition to those used to meet the MATERIAL characteristics defined in commercial standards/specifications. These methods are conceptually divided here into two groups, *Material Traceability* and *Material Similarity*.

Material traceability activities provide evidence that the material used to fabricate the EQ test specimens is *identical* to the material currently being supplied for use in motor repair. For products with the same manufacturer designation that undergo "product improvements" not reflected in product literature, traceability may require additional controls or a freeze on the product design. The material similarity activities involve special tests or analyses demonstrating that materials, with different product designations, are identical or sufficiently similar to those used in the EQ test. Material similarity is further described in the previous section under substitutions.

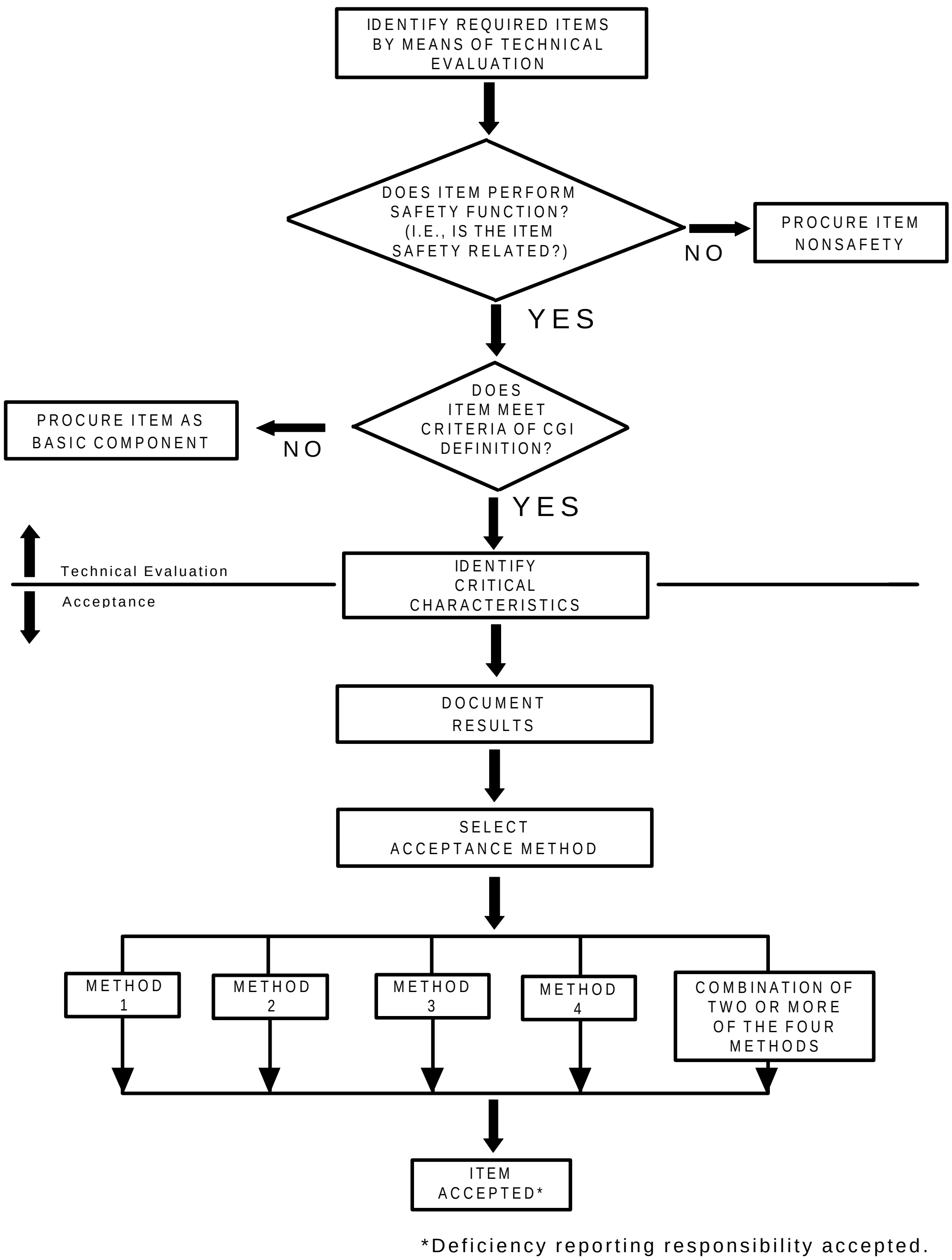

Figure 4.11
Generic Process for Acceptance of Commercial Grade Items Used in Safety-Related Applications

Although the procurement and acceptance guidance contained in the mild environment motor rewind guide [26] can be applied to harsh environment rewinds, harsh environment applications often require that certain *inherent,* but not specified, characteristics of a particular insulating system component (e.g., radiation resistance or hydrolytic stability) must exist in the procured component in order for the insulating system to acceptably represent the system originally qualified. Qualification of the original system established the acceptability of these inherent characteristics. Acceptance of the procured component provides reasonable assurance that both specified and inherent characteristics are maintained.

Under normal (mild) conditions, minor material or formulation changes do not significantly affect the material's capability. Further, if the product meets the applicable commercial specification's required characteristics, adequacy is confirmed. However, the characteristics and tests cited in these commercial specifications do not necessary address all the degrading influences of harsh accident environments. Since these harsh conditions are not reflected in the commercial specification's characteristics, other methods of ensuring acceptability of supplied materials are needed. Certain of these inherent characteristics, such as radiation resistance, can be verified by special tests (Method 1) conducted after receipt. Determining the adequacy of other characteristics through measurement might only be possible after winding fabrication and treatment or after a qualification test. The preferred method of addressing the adequacy of these inherent characteristics is to insure that there have not been any significant material formulation or processing changes that could affect harsh environment performance.

For commercial grade materials purchased from the same manufacturer under the same designation or specification and with no apparent material or fabrication changes, the CGI acceptance methods used for mild environment applications should be sufficient for harsh applications. For certain products with the same manufacturer designation that may undergo uncontrolled product changes, traceability may require additional controls, special tests, or a freeze on the product design. When materials are purchased from vendors with 10 CFR 50 Appendix B approved QA programs, certification to the designation or specification should suffice. Acceptance based on vendor survey and source inspections should determine if any composition or fabrication changes have occurred that may affect qualification and performance.

Special tests and inspections can be performed to help establish traceability. These tests and inspections can be specific to certain materials and uses. They can also be more generalized. Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), and Infrared (IR) spectrographic techniques can be used to verify no compositional changes. TGA and DSC are laboratory analytical methods which use a very small material quantity. They compare the weight changes or calorimetric response of the sample to a programmed heating sequence in a defined gas environment. Spectrographic techniques also use small material samples to determine the material's absorption spectra. They are useful in material identification and quality control since many materials have unique spectrographic "fingerprints". Underwriter Laboratories uses TGA, DSC, and IR methods to provide confidence that there have not been significant compositional changes in a UL listed material/component. This use requires that baseline measurements are performed on the original material. When addressing traceability or substitutions, these techniques are most useful when such comparisons are made between the original and the current material. They are less useful in determining the composition of a particular material. Since comparative testing is an important way of supporting traceability and substitutions, samples of the originally qualified materials should be preserved for future use.

4.5.3 Insulating Material Critical Characteristics

Table 4.12 reproduces the recommended critical characteristics for acceptance contained in the mild environment rewind guide [26]. Note that material is identified as a critical characteristic for all these items.

4.6 Insulation System Fabrication Guidance

Most nuclear utilities have access to shops that repair non-safety related motors. However, because safety-related motor repairs comprise a small percentage of total repairs, it is often not cost-effective for these shops to establish quality assurance programs and documentation methods which provide objective evidence that safety-related motors are properly repaired. Only motor repair shops with adequate process controls and documentation should be used to repair safety related motors. Figure 4.4 illustrates an established repair shop quality system as one of the necessary elements of adequate rewind fabrication.

To assist utilities and motor repair shops in achieving adequate objective evidence, EPRI developed guidance on the establishment and implementation of a motor repair shop quality program and documentation in [27]. Such a program and associated documentation form a minimum acceptable set of objective controls for all safety-related motor repairs. When properly implemented, such controls are adequate for the repair of mild environment safety-related motors. However, additional measures may be necessary for certain harsh environment motor repairs because of the severe environmental stresses imposed on the motor and its insulating system. These severe accident stresses and the potential for them, in combination with inadequate repairs, to create common-cause failures

Table 4.12
Insulating Materials - Recommended Critical Characteristics For Acceptance

(Italics characteristics are optional based on application. See description in [26].)

Insulating System Component	Critical Characteristic
Magnet Wire	Markings & Identification Materials Dimensions Dielectric Strength *Adherence & Flexibility* *Elongation* *Springback* *Heat Shock* *Continuity*
Solvent / Water Based Varnish	Markings & Identification Material Viscosity Specific Gravity pH (water based only)
Solventless Varnish	Markings & Identification Material Viscosity Thixotropic Index Gel Time
Films	N / A (Not procured as a separate rewind material)
Nomex Papers (typical for other papers)	Markings & Identification Material Dimensions Dielectric Strength *Tear Resistance*
Mica Paper Tapes	Markings & Identification Materials & Configuration Dimensions Dielectric Strength *Impregnation Time*
Woven Glass Tapes	Markings & Identification Material Width & Thickness Surface Conditioning Weave / Count (warp, filling)
Rigid Laminates	Markings & Identification Material Dimensions *Dielectric Strength*

**Table 4.12 (continued)
Insulating Materials - Recommended Critical Characteristics
For Acceptance**

(Italics characteristics are optional based on application. See description in [26].)

Insulating System Component	Critical Characteristic
Flexible Laminates	Markings & Identification Material Dimensions Dielectric Strength *Tear Resistance*
Sleeving (coated or uncoated)	Markings & Identification Materials & Configuration Dimensions *Dielectric Strength (coated sleeve only)*
Motor Lead Wire	Markings & Identification Materials & Configuration Dimensions Dielectric Strength
Pressure Sensitive Adhesive Tape	Markings & Identification Materials & Configuration Dimensions *Dielectric Strength**
Lacing, Surge & Banding	Markings & Identification Materials & Configuration Dimensions *Bonding & Curing* *Break Strength*
Compression Lugs (See EPRI JUTG CGIEL02, 03)	Markings & Identification Materials & Configuration Dimensions
Solder (See EPRI JUTG CGISO01)	Markings & Identification Material Composition, or Melting Range, or Electrical Conductivity
Resistance Temperature Detectors (See EPRI JUTG CGIRT01)	Markings & Identification Materials & Configuration Dimensions Time Response Insulation Resistance Temperature / Resistance Characteristic *Pressure Boundary*

during an accident suggests that additional control measures should be considered. The following information summarizes the minimum set of controls needed for all safety-related motor repairs and describes other considerations and controls which may be needed for certain harsh environment motor insulating system repairs. Sections 5.2.2, 6.2.2, and 7.2.2 provide additional fabrication guidance specific to LOCA, HELB, and radiation-only qualified systems.

4.6.1 Quality Control

To assist in the development of an overall motor repair quality assurance program, NP-6407 {27} contains a Nuclear Supplier Quality Assurance Committee (NSQAC) QA specification for a safety-related motor supplier. While originally developed for a motor manufacturer, virtually all the QA program elements are applicable to motor repair shops. The NSQAC document, consistent with 10 CFR 50 Appendix B and other regulations/standards on quality assurance programs, requires that the QA program address the eighteen criteria identified in Table 4.13.

Table 4.13
Eighteen Criteria Addressed by Motor Repair Shop Quality Assurance Programs

1.	Organization
2.	QA Program
3.	Design Control
4.	Procurement Document Control
5.	Instructions, Procedures, and Drawings
6.	Document Control
7.	Control of Purchased Items and Services
8.	Identification and Control of Materials and Items
9.	Control of Special Processes
10.	Inspection
11.	Test Control
12.	Control of Measuring and Test Equipment
13.	Handling, Storage, And Shipping
14.	Inspection, Test, And Operating Status
15.	Control of Non-conforming Items
16.	Corrective Action
17.	Quality Assurance Records
18.	Audits

QA programs developed in accordance with other guidance documents on motor repair, such as EASA Q and ISO-9002, *Quality Management Standard*, contain essentially the same criteria. The EASA-Q system has been developed by the

Electrical Apparatus Service Association to provide a consistent and performance based standard for quality and customer satisfaction in the motor service industry. EASA-Q incorporates the provisions of ISO 9002. Table 4.14 lists the quality criteria in the ISO 9002 standard.

Table 4.14
ISO 9002 Criteria Addressed by EASA-Q Quality System

1.	Management responsibilities
2.	Quality system
3.	Contract review
4.	Document control
5.	Purchasing & subcontracting
6.	Purchaser supplied product
7.	Product identification & traceability
8.	Process control, Inspection & testing
9.	Measuring & testing equipment control
10.	Inspection & test status
11.	Control of non-conformance
12.	Corrective action
13.	Handling, storage, packaging and delivery
14.	Quality records
15.	Internal quality audits
16.	Training
17.	Statistical techniques

4.6.2 Procedures, Personnel, and Equipment

In addition to a quality control program, Figure 4.4 indicates that procedures, personnel, and equipment are important to acceptable fabrication. EPRI NP-6407 provides several motor repair job instructions / procedures that are models which can be used during the development of shop-specific procedures and controls. Table 4.15 identifies the seventeen model instructions / procedures contained in the EPRI guideline. Additional recommended practices for repair and rewinding of motors are provided in [4].

For mild environment motors, motor repair shops with approved quality programs should have a proven history of implementing quality repairs. There are a variety of techniques and methods, often varying from shop to shop, that have been developed to achieve quality repairs. However, for harsh applications, particularly HELB and LOCA, that have been qualified by type testing, it is imperative that qualified rewinds are fabricated equivalently to the tested motors. The types of controls needed to assure equivalent fabrication can

Table 4.15
Model Motor Repair Job Instructions/Procedures (JI/P) In EPRI NP-6407

JI/P Number	Title
1.	Motor Repair Traveler
2.	Processing Non-conformance Reports
3.	Procurement, Acceptance, and Traceability of Parts and Materials
4.	Instrument, Gauge and Test Equipment Calibration
5.	Motor Receipt and Shipping
6.	Initial Inspection and Tests
7.	Disassembly, Parts Data, and Work Scope Definition
8.	Winding, Cleaning, and Retreating
9.	Core Preparation for Rewinding
10.	Winding AC Random-Wound Stators and Rotor Cores
11.	Winding AC Form-Wound Stators and Rotor Cores
12.	Winding Form- and Random-Wound Armature Cores and Field Poles
13.	Resin Treating of Windings
14.	Shafts
15.	Endshields, Frames, Bearing Caps, Fan Covers, and Other Metallic Parts
16.	Commutator, Slip Rings, Brushes, and Brush Rigging
17.	Final Tests

vary based on the winding design (e.g., VPI vs. Dip & Bake), severity of the application, and the type of harsh environment. Motor insulating systems exposed to steam / moisture conditions must be constructed in ways that minimize the potential for moisture intrusion during steam break accidents. The construction must tolerate these conditions when new and after the degrading effects of aging and accident radiation. For motors exposed to radiation-only harsh conditions, additional controls, beyond those used in mild applications, may not be needed since a winding's radiation resistance is largely a function of materials and is less affected by fabrication variations.

There may be ways (such as post-production submersion high-potential and insulation resistance tests which demonstrate that a winding is "sealed") to inspect / test a winding to determine if it has been adequately fabricated. Additional process controls for harsh applications usually focus directly on fabrication rather than post-production tests.

In order for any rewind to adequately reproduce critical elements of the motor(s) originally qualified, sufficient information, training, and fabrication controls must be in place at the rewind shop. Table 4.16 identifies critical factors affecting a shop's ability to adequately fabricate qualified rewinds. The first factor, information on the originally qualified system, must be provided to the rewind shop by others (e.g., the original qualifier). This information includes material specifications, drawings, and relevant fabrication procedures for the originally qualified insulating system. These documents should contain much of the needed information. However, some shop-specific techniques and practices relevant to the fabrication may not be well documented since they are common practices in a particular shop. Other shops may not have equivalent methods. For example, certain equipment and techniques for spreading form-wound coils can minimize damage to the turn insulation.

In cases where insufficient information exists to adequately reproduce critical fabrication activities, other clarifying information must be available. It may be helpful to provide photographs of critical fabrication steps illustrating information that cannot be clearly defined in procedures. It is also possible, during development and implementation of the initial qualified rewinds, that the rewind shop will require more information from the original qualifier.

All the information critical to proper fabrication must be incorporated into shop procedures and included in the training of personnel involved in fabricating the qualified rewind. Personnel performing critical fabrication activities must have adequate skills and sufficient training in practices unique to the fabrication of qualified rewinds. Finally, the rewind shop must have the proper fabrication tools and equipment. For example, VPI resin treatment equipment may limit the motor size which can be adequately treated.

In cases where the rewind shop cannot adequately implement certain portions of the fabrication, the activities may be subcontracted to others who have the capabilities and controls. Two obvious examples are VPI resin treatment and fabrication of form-wound coils.[42] The need for adequate controls and procedures applies equally to subcontracted services.

Table 4.16
Factors Affecting a Shop's Ability to Properly Fabricate Harsh Rewinds

1.	Clear, unambiguous information on critical fabrication activities for the originally qualified insulating system
2.	Incorporation of the fabrication information into shop procedures and personnel training
3.	Shop personnel with sufficient training and experience to duplicate the fabrication
4.	Shop equipment capable of producing winding characteristics critical to qualification
5.	Objective evidence that critical fabrication activities have been properly controlled

42 Since shipping may damage the coils or introduce contaminants, special controls should be implemented.

In addition to the controls directly associated with winding fabrication, other elements of the motor repair must be properly implemented in order for the repaired motor to be qualified. Incoming inspections and tests must establish the condition of each motor component and determine the repair activity scope. All mechanical repairs, including bearing and lubricant replacement, must be conducted in ways that preserve qualification of the motor's mechanical components. Winding removal and core condition are critical to assuring adequate electrical performance for the rewind. Core loss testing should be performed before and after winding burnout and the results compared. Abnormal core hot spots must be repaired or the core replaced. Rotors, particularly cast alloy rotors, should be examined and tested to verify lack of conductor and end ring cracking or other damage that can affect motor performance or produce premature failures. In cases where there is significant motor damage and the motor is required for prolonged duty under severe accident conditions (e.g., LOCA), it may be appropriate to replace, rather than repair the motor.

If cost and resources were unlimited, representative motors from all original manufacturers and repair shops could be periodically *type tested* to confirm continued qualification of repaired motors. Although such *type testing* is impractical and unnecessary, some limited *proof testing* of a sample rewind would strengthen confidence in the overall quality of the rewind process and the shop's ability to adequately reproduce the fabrication methods used for the originally qualified motor. Such limited testing would only be necessary when the fabrication requires very precise techniques or critical control of certain activities. For example, fabricating a sealed VPI random-wound system is much more difficult than fabricating a random-wound motor with multiple Dip & Bake cycles. Limited testing could address either the complete winding or recognized critical elements of the repair. Although limited testing might be performed on all repaired motors, it may be more appropriate to test prototypes representing the rewind shop's methods and techniques. For example, a sample VPIed rewind could be subjected to high-potential immersion or insulation resistance tests to demonstrate that it is a sealed system. Other types of short-term proof tests could be performed on a prototype or motorette/formette. For example, a sample winding might be exposed to short-term steam conditions in an autoclave or pressure cooker and then subjected to limited electrical testing. Similarly, several sample insulated and resin treated connections could be subjected to immersion testing to provide additional confidence in the fabrication methods, since connection insulation is considered a weak-link in systems exposed to steam conditions. Proof testing is most meaningful when similar tests are performed by both the rewind shop and the fabricator of the originally qualified system and the results are compared.

4.7 References

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5.0

LOCA QUALIFIED SYSTEMS - DETAILED GUIDANCE

This section discusses the qualification methodologies, guidance, and related considerations specific to LOCA in-containment motor applications.

5.1 Technical Approach and Justification

The in-containment environmental conditions associated with LOCAs are the most severe plant conditions through which safety-related motors must function. The high temperature, high pressure steam environment combined with radiation on the order of tens to hundreds of Megarads can seriously degrade insulating systems and are a radical departure from the normal operating conditions experienced by power plant motors. Due to the severity of these conditions, the most rigorous qualification methodologies should be implemented to demonstrate motor qualification. The preferred method of demonstrating the qualification of rewind insulating systems is type testing of either a representative motor or an insulating system model. This testing should be consistent with the guidance in IEEE 323 (1974 and 1983) and IEEE 334-1994, including consideration of significant aging mechanisms and the establishment of a qualified life. Separate qualification of the rewind motor insulating system assumes that other critical motor components (i.e., bearing, lubricant, seals, rotor, accessory devices) are maintained in accordance with the motor's original qualification. Further, it is assumes that the electrical design (coil groups, wire size, coil interconnections, voltage, etc.) of the motor winding remain unchanged from those originally qualified.

5.2 Detailed Guidance

5.2.1 Establishing EQ for LOCA Qualified Systems

IEEE 334-1994 recommends the following type testing sequence for LOCA type accident conditions:

- Inspection
- Functional Test

- Thermal Aging
- Mechanical Aging
- Irradiation
- Voltage Stress
- Seismic Simulation
- DBA Simulation
- Post-DBA Simulation
- Review Results

Sections 4.2 and 4.3 describe a variety of topics associated with establishing qualification, specific topics related to the use of type testing, and provide clarifying information on the provisions of IEEE 334. Additional considerations associated with evaluating the suitability of LOCA type tests for plant specific motor rewind applications are described below. Figure 5.1 illustrates, in flow chart form, the steps involved in establishing qualification for LOCA conditions through the use of type tests.

5.2.1.1 Aging Simulation. Section 4.3.2 notes that both NRC and IEEE qualification guidance documents require that aging address all significant aging mechanisms. It also discusses the significance of *temperature, radiation, voltage, humidity, vibration, and mechanical stress* as aging mechanisms. Thermal, mechanical, and voltage stress aging as part of LOCA qualification are discussed further below. As described in Section 4, humidity aging is not normally simulated as part of type testing and its effects can be assessed as part of motor surveillance and maintenance. Since radiation doses during normal operation are insignificant when compared to accident doses, it is common practice to simulate the combined aging and accident doses during the LOCA radiation simulation. Finally, the Section 4 information indicates that voltage is not a significant aging mechanism for the low-voltage and medium voltage motors <7 kV covered by these guidelines.

Thermal Aging: Per IEEE 334 the accelerated thermal aging parameters should be based on system aging data established in accordance with IEEE 117-1974 or IEEE 275-1992. Extrapolation of a life-temperature curve obtained using these procedures should intersect a temperature-life point representative of winding temperatures during normal operation and the temperature-time point used for the accelerated thermal aging portion of the type testing. While this procedure is preferred, an alternative procedure (not addressed in IEEE 334) utilizing the lowest (i.e., most conservative) activation energy for the individual insulating system materials (including lead wire) has been used and is considered acceptable. Experience indicates that this procedure yields an activation energy for the aging simulation that is generally more conservative than one developed using the procedures of IEEE 117-1974 or IEEE 275-1992. However, this procedure (use of the lowest activation energy) does not demonstrate the materials' thermal compatibility. Thermal compatibility is integral to the IEEE 117-1974 or IEEE

275-1992 methods. Additional information regarding these two approaches is contained in [1].

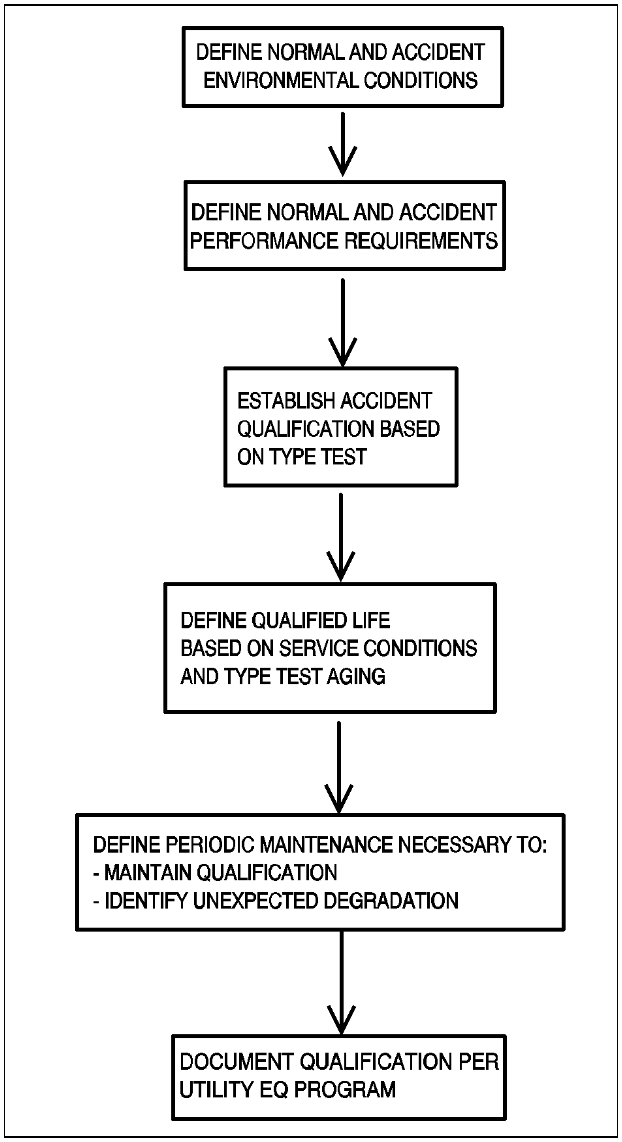

Figure 5.1
Flow Chart for Establishing Qualification for Inside Containment LOCA Applications

Mechanical Aging: Some form of mechanical vibration should follow thermal aging in order to simulate the stresses placed on windings during starting and operation. IEEE 334 suggests 1 hour of vibration at 1.5g and 60 Hz. Other alternative methods are also acceptable. For example, a number of start-stop cycles or plug-reversals subject the motor to simultaneous thermal and vibratory stresses. Seismic testing prior to the LOCA exposure may also be used, in part, to simulate mechanical aging. Although the collective duration of the various seismic tests (e.g., resonance search, sine beat/sweeps, or random motion OBE and SSE) may be relatively short, the accelerations and associated stresses are typically several times the suggested 1.5g mechanical aging test.

***Voltage Stress*:** IEEE 334-1994 recommends as a voltage stress test, a one minute AC high potential test at 0.67(2x rated voltage + 1000), that was not contained in IEEE 334-1974. While this test provides some measure of voltage stress to the windings, it is not considered a critical component of the aging simulation for the low-voltage and medium-voltage (<7 kV) motors addressed in this guideline. As noted in Section 4, this test was added to the 1994 standard, in part, to represent typical in-service voltage tests used by many utilities. The test was not intended to simulate voltage aging. As discussed in Section 4, when insulating system vpm stresses are substantially below 100 vpm, voltage endurance aging is not significant for medium voltage motors. In the low voltage applications that account for virtually all in-containment safety-related motor applications, long term voltage endurance is not a significant aging mechanism for the insulating system components.

5.2.1.2 Accident Simulation. Both IEEE 323 and IEEE 334-1994 suggest that the DBA simulation include either two environmental transients or else additional margin should be added to the first transient. Consequently, the motor accident test need not include a double transient. Several other factors affecting the applicability of qualification tests are described below.

Motor Load Profile: During high-pressure, high-temperature LOCA steam conditions, motor internal and external temperatures can rise rapidly, reaching test chamber saturated steam conditions within 30 minutes or less.[1] For energized and unloaded motors, this represents peak insulating system temperature. Subsequent motor energization and operation will increase winding temperature beyond test chamber temperatures. However, the temperature increase will proceed at a slower rate similar to the rate occurring during operation under normal conditions (e.g., 2 to 3 hour time

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1 As described in Section 6, the temperature of deenergized insulating systems should not exceed saturation temperature due to the minimal additional heating effects of superheated steam and the thermal mass of the winding, stator, motor enclosure configuration.

constant). This additional heat up is related to both the test chamber's actual temperature (instead of saturation temperature) and the amount of motor load. For motors with substantial load during the initial LOCA transient, winding temperatures will rapidly increase to test chamber saturated conditions and then continue to increase at the slower rate. For example, if the LOCA peak temperature conditions exist for an extended period (e.g., peak BWR conditions of 340°F - 320°F may be postulated for 3 to 6 hours), then the winding temperature of a fully loaded Class B heat rise motor could reach 420°F (215°C).[2] As discussed in Section 4.3.3, although thermal conditions are more severe for a loaded motor, steam / moisture-related degradation should be more severe for deenergized motors. It is difficult for a single test program to address both conditions. IEEE 334-1994 suggests different test protocols depending on the motor's status (*idle* or *in-service)* at the initiation of the DBA.

If qualification testing is performed with the motor idle or unloaded during LOCA peak temperature conditions, the qualification testing may be acceptable for loaded applications based on one or more of the following considerations:

1. Motor operation during the peak conditions is not required.
2. The duration of required loading is relatively short and would not result in significant heat up of the windings. This could apply to valve actuator and other intermittent duty motors.
3. The test temperatures envelope required LOCA temperatures, during periods of required motor operability, by an amount sufficient to account for internal motor heat rise. The heat rise of energized but unloaded motors is often assumed to be roughly 20% - 25% of the full load heat rise [2]. As a rule-of-thumb, the winding heat rise of an unloaded, Class B, rise motor is approximately 10°C - 15°C. A very conservative estimate can be made if the qualification test report contains motor current information during the LOCA simulation. Comparing this no-load or partial load current with the motor's published full load current data would permit an estimate of heat rise and winding temperature during the LOCA simulation.
4. If the test profile achieves prolonged exposure to accident temperatures exceeding the required qualification temperature, then analysis may be used to demonstrate that the test winding temperature exceeds the required winding temperature. The evaluation would estimate winding temperature during the required LOCA profile using a winding thermal lag analysis and anticipated motor heat rise at the required load.

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2 For simplicity, this neglects the effect of increased winding resistance at higher temperatures.

5. Periodic operation of the motor during the LOCA test subjects the winding to transient thermal, mechanical, and electrical stresses that provide confidence in motor operation under loaded conditions.
6. Prolonged operation at no load or lightly loaded conditions subjects the winding to thermal, mechanical, and electrical stresses that provide confidence in motor operation for shorter durations under more heavily loaded conditions.
7. Estimated winding temperature, based on combining LOCA and heat rise temperatures, is lower than the thermal classification of the insulating system or materials. For example, Class H systems are designed for prolonged operation at 180°C (356°F).

Similar heat rise questions arise when addressing the use of an insulating system qualified for continuous-duty for motors rated for intermittent-duty (e.g., MOV) or vise versa. Limitorque MOV motors are generally rated as 15 minute duty cycle motors with a Class B temperature rise. These motors will achieve their Class B rise when operated for 15 minutes at approximately 20% of their nominal torque rating. In valve applications, motors can experience high loads during the short-time seating / unseating operations but loads during the remainder of the valve travel are generally only 20% - 30% of seating loads. Under accident conditions most plant valves achieve full stroke within 15 seconds to 2 minutes. The short operating time of these motors, when compared to their duty cycle (15 minutes), suggests that they experience relatively minor temperature increases.[3] Consequently, stator temperatures for Limitorque MOV motors during typical valve operations are significantly below the motor's rated Class B operating limit.[4] Based on this discussion, it may be difficult to qualify for continuous duty applications those systems originally qualified for intermittent duty operation in Limitorque MOVs . In this case the suggestions provided above, regarding the use of test results for motors energized but unloaded during LOCA simulations, might be used.

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3 A very rough estimate of heat rise during MOV operation can be developed as follows:
1. The stator temperature of a Class B 15 minute duty cycle motor increases approximately 5.3° C / minute (i.e., 80°C / 15 minute). A 2 minute stroke time would increase stator temperature by roughly 11°C.
2. Near locked rotor currents during valve seating and unseating would provide additional heating. Limitorque typically limits locked rotor times to 10 - 15 seconds but MOVs typically only see seating loads for less than 1 second. Assuming a stator rise of roughly 8°C / second (i.e., 80°C / 10 seconds), seating / unseating times of 1 second would increase stator temperature an additional 16°C.
3. A total temperature rise for the MOV motor of 27°C (11 + 16) is substantially less than the Class B allowable 80°C average heat rise.

4 Although Limitorque motors are rated with a Class B rise, the LOCA qualified insulating systems (RH and LR) are both rated as Class H systems.

Conversely, from a thermal perspective, qualification of loaded continuous-duty motor insulating systems can be conservatively applied to MOV applications. Even unloaded but energized motors could be thermally justified for MOV applications since the Limitorque motors do not have a significant stator heat rise during operation. However, since MOV motors are not continuously energized, their cooler windings may be more susceptible to moisture related degradation during the intervals between operations. In addition, periodically cycling a motor during the LOCA simulation tends to draw the external steam-laden air into the motor housing. This potential degradation mechanism can be addressed if during qualification testing the motor specimen was periodically deenergized and permitted to cooldown.

Enclosure Type: The principal question regarding enclosure type is whether the motor enclosure type used during the LOCA test provides greater protection to the winding than the type of enclosure used for the rewound motor. During LOCA tests, the following types of winding enclosures typically are used:

- Totally enclosed (e.g., TEFC)
- Open construction (e.g., open dripproof)
- Unprotected (motorette or formette coils directly exposed to test conditions).

Inside containment motors generally use TEFC, TEAO, TENV, or TEWAC enclosures which are all categorized as totally enclosed designs. The totally enclosed constructions provide superior protection to windings. Consequently, LOCA testing with either an open type enclosure or without an enclosure is conservative when qualifying windings for totally enclosed constructions. Additional analysis is necessary to determine the qualification adequacy of a winding tested in a totally enclosed construction but used in a rewound motor with an open type construction. Such an analysis would attempt to demonstrate that the steam, spray, and temperature conditions experienced by the test winding exceed those experienced by the rewound winding during the required LOCA profile. For example, it would be reasonable to assume that during prolonged exposure to peak test conditions, a totally enclosed winding experiences temperature and humidity stresses that exceed those experienced by a winding in an open drip-proof enclosure. This assumption should be supported by some type of heat transfer and thermal lag analysis, unless the conclusion is intuitively obvious due to the difference in test and required conditions. However, it may be more difficult to evaluate the impact of spray conditions since the external environment is drawn into open type enclosures by the cooling fan but is effectively excluded from totally enclosed type enclosures.[5]

5 Different types of open enclosures (e.g., drip-proof vs. Type II weather-protected) provide different levels of environmental protection.

Voltage: Most random-wound, in containment motors have a 460 V rating and are operated on 480 V systems. However, some utilities use 575 V motors on 600 V systems. Per IEEE 323, test voltages should envelop the required voltage with margin (e.g., +10%), but in many type tests motors have been operated at rated voltage without margin. For AC induction motors, operation at slightly higher voltages (for margin) is not necessarily conservative. Although the windings are subjected to higher voltage stresses, winding current and heat rise might decrease slightly. Consequently, it has become accepted practice to test induction motors at representative voltages. IEEE 334-1994, Section 6.3.6, *Design basis accident environment simulation (DBA)*, suggests that test motors be operated "at full load and rated voltage" during the LOCA simulation. Some voltage margin can be established by recognizing that prolonged motor operation during the LOCA test demonstrates the inherent voltage tolerance of the winding design. Further, voltage surges occurring during test motor start/stop cycles provide some additional voltage stress. Voltage margin can also be established if the vpm values of the tested motor contain margin when compared to the values for installed motors.

It may be difficult to argue the acceptability of 480 V motor testing for 600 V applications. Fortunately, for motor rewinds it is possible to modify the insulating material thicknesses to produce vpm stresses on the 600 V rewind that are less than those occurring in the 480 V test motor. In random-wound motors the turn insulation thickness need not be varied to account for system voltage changes. Since phase-to-phase and phase-to-ground voltages increase, the slot liner, phase, and slot separator thicknesses may be increased. For example, increasing the slot liner thickness from 15 mil (the *as tested* thickness @ 480 V) to 20 mil provides an improved vpm value for the 600 V insulating system.

Chemical Spray: In TEFC motors, the external spray environment can only enter the motor through the endbell drains (typically two 1/8" holes) and along the motor shaft. Since the spray is generally initiated after the initial pressure transient, an enclosure pressure differential is not available to force spray into the motor. This suggests that chemical spray during the LOCA test might not be critical to establishing qualification for TEFC type motors. However, it is possible that periodic motor operation during spray conditions might promote spray entry into the motor as the external environment is drawn into the motor during the thermal cycles . It is also possible that the chemical spray may accumulate in the motor terminal box and adversely impact performance of the motor lead wires. Containment spray can provide a cooling effect for energized motors, since evaporation of the spray from the motor enclosure surface aids motor cooling. This effect was observed during one random wound motor test for TVA [3] where *pre-spray* stator core temperatures were roughly 20°C higher than chamber temperature but were less than 10°C higher after containment spray was initiated.

5.2.2 Fabricating LOCA Qualified Systems

Section 4.4 describes general considerations associated with fabricating harsh environment qualified rewind insulating systems. Since LOCAs generally produce the most severe harsh conditions, one can conclude that LOCA qualified insulating systems might be susceptible to variations in fabrication methods. The radiation resistance of a system is related more to materials than fabrication techniques. Experience and qualification testing have demonstrated that moisture resistance is a critical factor during steam conditions. Further, variations in fabrication methods can affect a winding's moisture resistance under both new and aged conditions. Consequently, special care must be exercised during those processes that directly affect the winding's moisture resistance. There is general agreement that a critical factor affecting moisture resistance is the quality of winding resin treatment. Poor penetration, inadequate curing, or insufficient build on end-turns can cause failures where windings are exposed to high moisture conditions. The insulation and resin treatment of winding and lead wire connections is particularly critical, since these connections are vulnerable to moisture penetration and moisture related failures.

For VPI systems, problem sealing areas are at connections and in the coil area where the leads exit the winding. For VPI systems, the development of an essentially-void-free winding, sealing in the coil lead and connection areas, and adequate resin build are critical to performance during LOCA type conditions. Several measures can provide additional confidence that the rewind shop is adequately addressing these critical factors. VPIed windings are often designed as sealed systems. If the VPI winding has been designed as a sealed system, immersion high potential and IR tests can be used to verify the quality of system construction. Immersion tests performed on a sample winding could be used to demonstrate the shop's capability. Alternatively, the immersion testing could be done on each fabricated winding as a post-production test. There are differing views regarding possible degrading effects of post-production immersion tests. An additional method of verifying an essentially-void-free construction is through selective testing and dissection of sample coils constructed and processed with each motor rewind. A Navy document on motor repairs [5] provides guidance on the construction and inspection of sample coils.

5.2.3 Material Procurement and Acceptance

When insulating systems are qualified by type testing, it is recommended that identical materials be used whenever possible. The procurement and acceptance processes are intended to insure that, when specified, identical materials are supplied and used. When materials with the same manufacturer and descriptive information are ordered, these efforts should be focused on: 1) determining that the manufacturer has not implemented design or material changes that are not reflected in a material designation or specification revision and 2) verifying that the received material possess characteristics consistent with the material specification.

CGI Method 2, *Commercial Grade Survey* and Method 3, *Source Verification* are the best methods of determining that no unidentified design or material changes have occurred. Even when these methods are not part of formalized acceptance, discussions with the material manufacturer should provide information supporting other methods of acceptance. Although Method 1, *Special Tests and Acceptance,* can be used to accept most material characteristics, it is very difficult to identify material or design changes that would not affect the material's published characteristics. If such changes are identified, then a technical evaluation of the substitute material should be performed using the guidance provided in Section 4.3.6.

Table 4.15 lists recommended critical characteristics for acceptance of insulating system materials for mild environment motor applications [1]. These characteristics are equally applicable to materials used in LOCA / HELB systems that are type test qualified.

5.3 Evaluation of Systems Made Available to EPRI

5.3.1 Random-Wound

TVA's qualification testing of two, 5 HP and 50 HP, 1800 rpm, 460 Vac, TEFC random-wound motors is documented in [4]. Table 5.1 is a summary of the relevant test conditions. The LOCA simulation test profile is provided as Figure 5.2. The motors operated successfully during each of five operability tests (unspecified duration) during the LOCA simulation with operating currents equivalent to the pre-LOCA values. During subsequent functional tests, after motor removal from the test chamber, smoke emanated from the 5 HP motor leads where they exited the motor housing and the IR on both specimens was below 0.5×10^6 ohms @ 500 Vdc. Upon disassembly, water, found to have accumulated inside the enclosures, was suspected to be the cause of the low IR readings. The damaged lead area on the 5 HP motor was repaired and both motors were successfully operated under normal conditions for 36 hours with acceptable post-operation IR measurements (9×10^6 ohms - 50 HP, 500×10^6 ohms - 5 HP). The motors then successfully completed a 100 day post-LOCA operability test under normal conditions (i.e., motors located outside the test vessel). The motors were partially loaded during the 100 day test. TVA concluded that the design was qualified based on acceptable performance of the 50 HP motor and an analysis that concluded the lead wire damage was caused during shipping between test phases and not by the qualification test conditions. The thermal aging time was based on an activation energy of 1.07eV for the insulating varnish based on a product data sheet. The TVA qualification test report, applicable material specifications, and TVA fabrication procedures and controls are available by contacting EPRI PSE and requesting report TR-104872, Supplement 1.

Since the TVA motors were periodically operated unloaded during the LOCA simulation, the test results must be carefully evaluated for applicability. Periodic current measurements were made on both motors prior to and during the LOCA simulation. Pre-LOCA and LOCA currents were virtually identical for both motors. The current values were in the range of 5.4 - 5.7 amps for the 5 HP motor and 14.3-15.7 amps for the 50 HP motor. Unfortunately, the test report does not identify the duration of each motor's operability test. Consequently, one must assume that the heat-rise during energization was insignificant. Since LOCA temperatures in excess of 380°F existed for over 20 minutes, we may conclude that the windings reached 380°F. This suggests that other Class B motors operating at full load (i.e., average winding heat rise of 80°C) could be exposed to LOCA transient temperatures of roughly 113°C (236°F) and not exceed the test motors' peak winding temperatures during LOCA. If the motor to be qualified was not fully loaded, higher LOCA temperatures could be justified. Thermal lag analysis might also be used to justify qualification to higher, short time LOCA temperatures. However, as the amount of analysis and extrapolation grows, confidence and regulatory acceptability tend to weaken. This brief discussion illustrates the difficulty in using unloaded motor qualification to support continuously loaded motors. The TVA qualification could be used for intermittent duty applications, particularly for Limitorque MOVs, where periodic motor operation does not involve significant motor heat rise.

The random-wound test motors were fabricated at the TVA Power Service Shop using the materials identified in Table 5.2. The insulation system uses a blend of IMI 708/709 solventless polyester resins. The coil extensions, connections, and leads are fully taped with 1/2 lap layers of fiberglass tape to aid in resin retention during VPI processing and curing. The system also uses a Type 424, saturable calendered grade of DuPont Nomex paper that is no longer in production. Although other types of Nomex paper are available, they do not have the saturable characteristics of the Type 424. Use of other Nomex papers could affect resin penetration and the development of an essentially-void free VPI structure in the windings. In addition to the winding materials listed in the table, the motor antifriction bearings were lubricated with Chevron SRI-2 grease. The grease was exposed to the full qualification sequence.

Table 5.1
Summary Test Conditions - Wyle Report No. 17521-1

Test	Type	Summary Conditions
1.	Radiation	$2x10^8$ rad @ approximately $9.8x10^5$ rad / hr
2.	Thermal Aging	1674 hours @ 200ºC = 40 years @ 130ºC
3.	Vibration Aging	1 hour, 1.5g @ 60 Hz
4.	Seismic	Sine sweep - sine-beat (4.5g H, 3g V) - Triax random (5 OBE, 1 SSE) - 10g peak, 5% damping for SSE
5a.	LOCA Temp.	400ºF peak
5b.	LOCA Press.	50 psig peak
5c.	LOCA Spray	Chemical Spray, 30 min.
5d.	LOCA Humidity	100%
5e.	LOCA Duration	58.5 hours
5f.	LOCA Operation	Periodically energized, unloaded
6.	Post-LOCA	100 day, partially loaded, outside vessel (ambient conditions)

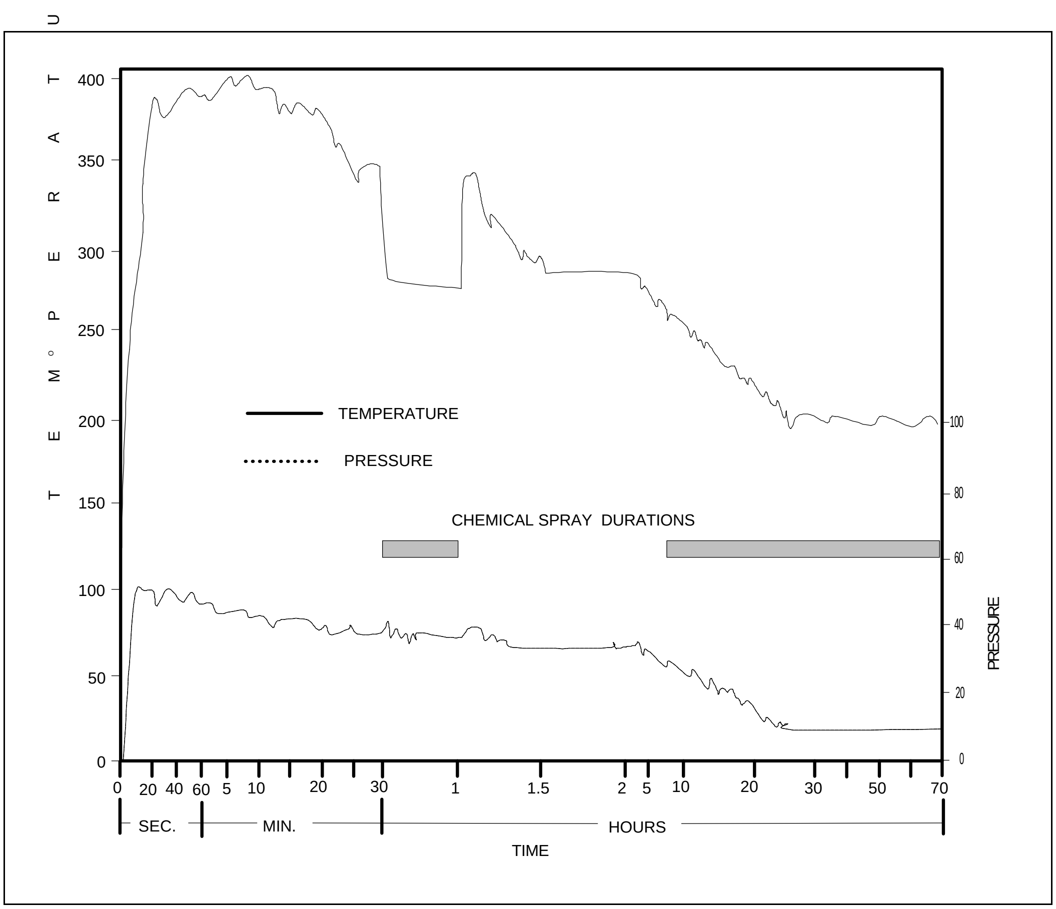

Figure 5.2
LOCA Test Profile - Wyle Report No. 17521-1

Table 5.2
Summary Materials List - Wyle Report No. 17521-1

Component	Material
Magnet Wire	Heavy Polyimide (MW 16C) Phelps Dodge
Slot Liner	Nomex 424 - 15 mils (saturable grade), DuPont
Wedge	Nomex 410, curved wedge
Tie tape	Nomex, Western Filament NFB-1X
Connection & Lead Tape	Heat cleaned glass, Mutual C-150, 1 half-lap layer
End-turn Tape	Heat cleaned glass, Mutual C-150, 1 half-lap layer
Coil Resin	180°C solventless polyester, slightly thixotropic, 50% IMI 708, 50% IMI709
Motor Lead	Belden silicone insulated - glass braided hookup wire
Lead Sealant	Dow Corning 732 silicone rubber sealant
Lead Blocking	Nomex felt
Filler Strips	Nomex 410 Paper
Slot Separator	Nomex 410 Paper
Phase Separator	Nomex 424 - 15 mils (saturable grade)

5.3.2 Form-Wound

EPRI was not provided with qualification information for inside containment form-wound motors. Most plants do not have form-wound motors inside containment requiring qualification to LOCA accident condition. However, certain plants do use specialized water-cooled (TEWAC) form-wound motor designs for containment cooler fan applications.

5.4 References

1. EPRI TR-103585, *Guidelines for the Selection, Procurement, and Acceptance of Nuclear Safety-Related Mild Environment Motor Insulation for Rewinds*, July 1994
2. Nailen, Richard L., *The Plant Engineer's Guide to Industrial Electric Motors*, Barks Publications, Inc., Chicago, IL
3. Wyle Test No. 18070-1, *Nuclear Environmental Qualification Test Program on Random-Wound and Form-Wound Motor Insulation Systems and Other Motor Components*, January 13, 1993
4. Wyle Report No. 17521-1, *Test Report on Motor Insulation Systems Used Inside Containment Class 1E Safety Systems for use in Various Nuclear Plants*, June 3, 1985

5. S2629-AC-GYD-010 / Ships, *Refurbishment Inspection Guide for Motor-Generator Sets Submarine Service*, Department of the Navy, 1983

6.0

HELB OUTSIDE CONTAINMENT QUALIFIED SYSTEMS - DETAILED GUIDANCE

This section discusses the qualification methodologies, guidance, and related considerations specific to HELB Outside Containment qualified motor applications.

6.1 Technical Approach and Justification

As noted in Section 4.0, qualification can be based on testing, analysis, operating experience, or an appropriate combination of these methods. This section recognizes two principal methods of establishing qualification for HELB outside containment harsh motor insulating systems:

1. Type testing, per IEEE 323 and IEEE 334-1994, which simulates the effects of aging and the HELB accident conditions.
2. Analysis coupled with partial test data which demonstrates the inherent protection provided by the totally enclosed motor enclosures. The partial tests include accelerated aging tests, per UL 1446 and several IEEE standards (e.g., IEEE 117, IEEE 275, etc.), which subject insulating system models to prolonged high temperature and 100% relative humidity, condensing conditions after the systems have been exposed to thermal and mechanical aging).

Other methods of qualifying motor insulating systems for HELB conditions exist (e.g., operating experience). However, this guide emphasizes these two methods since they can be used to cost effectively qualify many HELB motor applications. A third possible method, not addressed by this guide, could establish qualification based on passing "sealed" system immersion tests. Figure 6.1 presents, in flow chart form, the qualification methodologies discussed in this section. Qualification by type testing is recommended for all motors exposed to high pressure HELB events and for motors not of the totally enclosed design. For totally enclosed motors exposed to a low pressure HELB, this guideline encourages the use of analysis coupled with partial test data as a qualification basis. At the present time the NRC prefers type testing for demonstrating qualification of insulating systems for all harsh environment applications. The NRC has not reviewed the specific information and conclusions contained in this guideline. However, utilities are encouraged to apply the suggested analysis plus partial test data method.

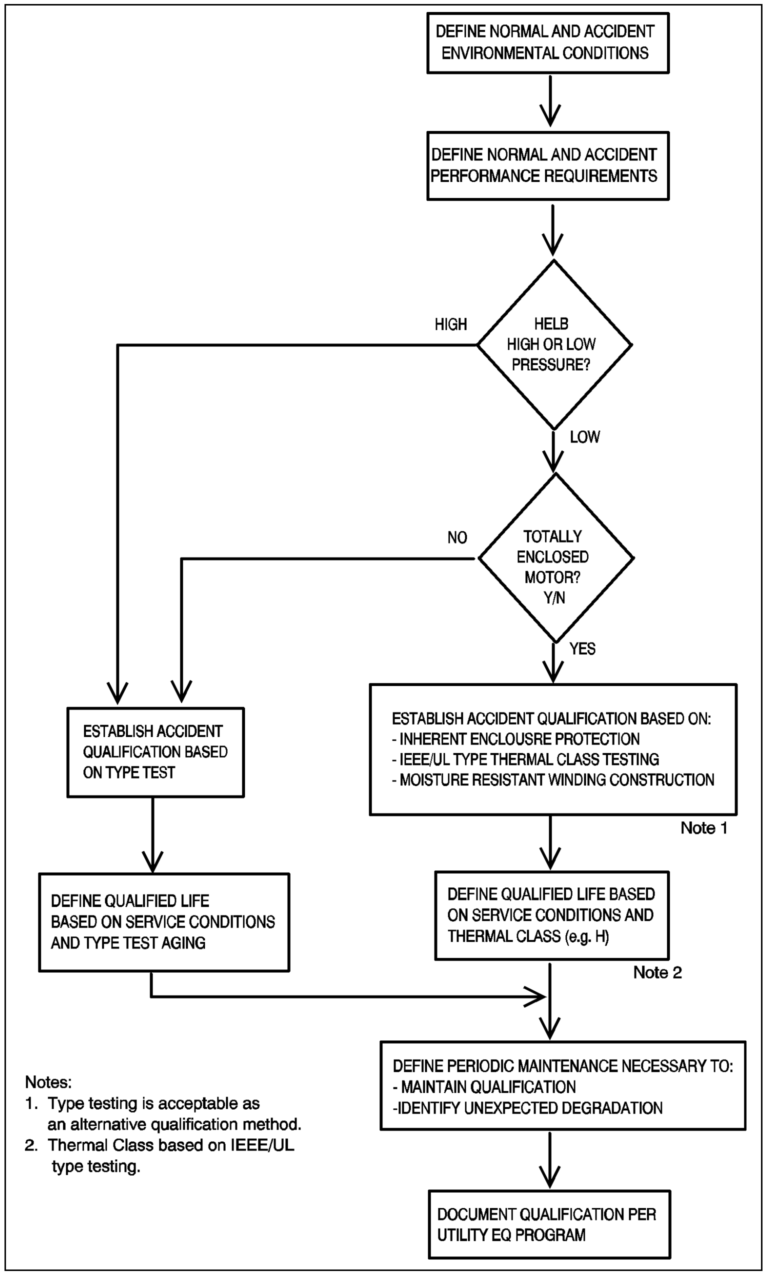

Figure 6.1
Qualification Flow Chart for Motors Exposed to Outside Containment HELB Conditions

Current motor rewind technology can create both random-wound and form-wound systems that are classified as *sealed* systems. These fabricated systems can be totally immersed in water and subjected to a variety of electrical tests demonstrating that they are impervious to moisture intrusion even when submerged for extended periods of time (e.g., 150 hours). The commercial and military standards which address sealed systems and underwater proof tests are identified in Table 6.1 The military requirements were developed to ensure that certain ship motors (e.g., bilge pumps) would continue to operate even when the motor is totally submerged in sea water. Reason suggests that insulating systems with this capability should be more than capable of adequate performance during transient steam conditions associated with low-pressure HELBs (e.g., saturation temperatures of approximately 212°F - 222°F). The sealed nature of these systems strongly suggests that a generic qualification basis could be established for the use of such systems in open type enclosures during low-pressure HELBs. Insufficient information currently exists concerning the generic effects of aging on the sealed nature of these systems or their capability to remained sealed at high ambient steam temperatures.

Table 6.1
Commercial and Military Standards on Sealed Insulating Systems

Standard	Section	Comments
MG-1	1-20.48	Submerged stator post-production test: • 10 minute dielectric absorption • 1 minute AC high-pot @ 1.15 rated voltage • 500 Vdc insulation resistance
IEEE 429-1994	4.6	Qualification test on prototype statorettes • 30 minute immersion during each test cycle • 1 minute AC high-pot @ 1.15 rated voltage while submerged
IEEE 429-1972	4.0	Post-production immersion test: • 10 minute dielectric absorption • 1 minute AC high-pot @ 1.15 rated voltage • 500 Vdc insulation resistance
MIL-M-17060E	4.3.4.20	Post-production immersion test per IEEE-429
MIL-M-17060E	Appendix A	Qualification Test on prototype motor test specimens: • 24 hrs at 155°C -- IR > 2 Megohm @ 155°C • 168 hrs at 100% humidity -- IR > 1000 Megohm • 200 hrs submerged -- IR > 2 Megohm

6.2 Detailed Guidance

6.2.1 Establishing EQ for HELB Outside Containment Qualified Systems

HELBs are due to the hypothesized rupture of high pressure steam and water piping. The most severe environmental conditions result for steam system ruptures. For water system breaks, vaporization of the discharged fluid must occur in order to produce pressurization and high humidity/steam conditions in various plant areas. However, since only a fraction of the released water will vaporize, the atmospheric temperature and pressurization effects are much less severe than those caused by steam line breaks. During typical large steam line HELBs, rooms typically reach their peak temperature in less than 10 - 30 seconds. Peak transient pressures (of a few seconds duration) only occur during the initial pressurization and drop to near atmospheric levels within a few minutes. Break detection and isolation generally occur within several minutes. After isolation, ambient temperatures decay rapidly to near pre-break conditions.

If small size steam breaks should occur, little if any pressurization will result; however, break detection and isolation may require significantly longer periods of time. Peak temperature conditions resulting from these breaks are also significantly lower than those occurring from the larger size breaks. EQ criteria regarding these smaller size steam breaks vary among plants. However, some utilities assume that certain small breaks might go undetected for several hours.

The significance and impact of HELB conditions on motors are different for open and enclosed motors. The enclosure in *totally enclosed* motors provides a significant barrier limiting the thermal and moisture effects on the winding system. However, in open type motors little or no such barrier exists. The HELB environmental stressors with the potential to impact motor operability are pressure, humidity/steam, and temperature.

6.2.1.1 Pressurization Effect. Pressure *alone* is of no significance to motor performance unless the motor enclosure is unvented and sealed. If the motor enclosure were fully sealed, pressure equalization could only occur through the shaft bearings. This might cause bearing grease to be extruded into the motor. However, under the relatively low pressures associated with HELB conditions, grease extrusion has never been identified as a problem. The significance of pressure as a stressor for motors is related to intrusion of the external steam-air environment into the motor enclosure. Pressurization compresses the internal air volume and forces the external environment into the enclosure. When the external environment is a high temperature steam-air mixture, this can directly expose the motor internals to the external environment. A rough estimate of the relative volume of external environment which enters the motor can be developed by dividing pre-HELB pressure (i.e., roughly 15 psia) by HELB pressure. The resulting ratio roughly represents the fractional internal volume occupied by the compressed internal air. The remaining volume fraction is the external environment. For example, for a 3 psig (18 psia) HELB pressurization, roughly 17% (i.e., (3 ÷ (14.7 + 3)) based on the ideal gas laws) of the internal motor air space is from the external environment and the remaining 83% is the compressed pre-pressurization air volume. As described below, the low pressurization during HELBs minimizes external environment intrusion into totally enclosed motors, thus protecting the winding system from significant moisture and temperature effects.

6.2.1.2 HELB Moisture Intrusion Into TEFC Enclosures. The internals of TEFC and other types of totally enclosed motors are effectively isolated from the external steam-air environment by the enclosure design. In TEFC enclosures the only openings where steam can penetrate the enclosure are along the shaft between shaft and seal and via the enclosure drains on the endbells. Other possible intrusion paths are sealed with O-rings and gaskets or they are potted (e.g., enclosure lead wire entrance). The following discussion is focused on TEFC enclosures; however, the information can be readily applied to other types of totally enclosed designs.

Steam penetration during HELBs into these totally enclosed enclosures is limited to; 1) transient flow due to initial pipe-break pressurization and 2) long-term steam diffusion. For most TEFC motors exposed to HELB conditions, steam intrusion due to pressurization is limited by several factors. First, most HELBs are low pressure events, with peak pressures generally below 3 psig. The majority of HELB analyses result in sustained pressures below 1 psig. Sustained higher pressures are rare since blow-out panels, doors, roofs, or hatches will open at very low differential pressures.[1] Consequently, HELB peak pressures only occur for a few seconds. Secondly, motors are rarely in the immediate vicinity of the pipe-break. When the initial pressurization occurs, the external environment at the motor remains essentially steam-free. Consequently, only air flows into the motor during the few seconds of pressure equalization. Even when the external environment is assumed to be a steam-air mixture, relatively little of the external environment will enter the motor during low pressure events. The external environment will only enter a TEFC motor via shaft-seal clearances (through the motor bearing and grease), and drains. In both cases, the openings are small, effectively limiting flow and providing ample cooler surfaces for steam condensation before reaching the insulating system.

As a limiting case example, assume the pre-HELB environment is at 25ºC (77ºF) at a high relative humidity (RH) of 80%. Further, assume the HELB external environment at the motor is all steam at roughly 100ºC and 1 psig. This is a very conservative

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1 For example, a 1 psi pressure differential exerts over 3,000 lb. of force on a standard 3'x7' door.

assumption since the actual external environment during the initial pressurization would be generally all air. Even if the motor were near the assumed pipe-break, the environment would be a steam-air mixture with a significant percentage being air. Using the ideal gas law and a conservative assumption of no internal motor temperature increase, the internal dew point will increase from approximately 21ºC (the saturation temperature for water vapor with a RH of 80% at 25ºC) to 45ºC (113ºF). This analysis assumes an initial water vapor pressure of 0.36 psia (i.e., roughly 2.4% of the internal gas volume is water vapor). After the pressurization at 1 psig, an additional volume of water vapor (steam) is charged into the enclosure that increases the water vapor percentage to roughly 8.7% and vapor pressure to 1.4 psia. The saturation temperature (dew point) at 1.4 psia is approximately 45ºC. Under a more realistic assumption that the external environment is a 50% steam- 50% air mixture, the internal dew point would rise to roughly 38ºC (100ºF). Assuming a worst case, long-term pressurization with a 3 psig, 100ºC, 50% steam- 50% air mixture, the internal dew point would rise to roughly 50ºC (123ºF). These limited analyses suggest some small amount of condensation *might* occur inside an *idle* motor if it were in the steam path during pressure equalization. However, this relatively small amount of moisture would have an insignificant effect on motor operation. The modest amount of moisture hypothetically formed under these worst case conditions can be visualized by recognizing that similar condensation would occur when a room temperature object is placed for a few minutes inside a steam bath at 100ºF - 120ºF. These modest amounts of moisture will not prevent motor operation. Although some minor amount of moisture might condense on the cold windings of an idle motor under these conditions, if the motor were energized and operating, the higher winding temperature would prevent condensation formation.

Although this analysis helps characterize moisture intrusion due to pressurization, moisture could continue to enter the motor enclosure via diffusion. Fortunately, diffusion is a relatively slow process driven by concentration differences and is not expected to significantly affect the amount of moisture inside the enclosure. Information on diffusion of gases into TEFC motor enclosures is presented in [1]. In this study to estimate gas diffusion rates for purposes of determining combustible concentrations, several tests were performed to determine the diffusion rate of oxygen into a 40 hp, 3600 rpm, TEFC motor, with 1/8" NPT drain holes in each endbell and shaft seals.[2] The oxygen data should be representative of water vapor. With the motor idle, the time constant (τ) for the exponential relationship of internal concentration and

2 The motor was of heavy duty construction intended to meet the guidelines of IEEE 841 [8].

time was 13.3 hours.[3] With the drain holes plugged (i.e., diffusion only along the shaft), τ increased to 44 hours. This testing demonstrates that insignificant water vapor intrusion will occur via diffusion into an idle motor.

This testing also identified another method of moisture intrusion for operating TEFC motors. In similar tests with an *operating* motor, τ decreased to 30 minutes. According to the report, the significant difference in time constants is due to the slight negative pressure, at the opposite drive-end shaft seal, produced by the external TEFC fan. This negative pressure was sufficient to cause a gas outflow at the bearing and an inflow at the drains and drive-end bearing. However, the I^2R heating occurring during motor operation is sufficient to raise internal motor temperatures above saturation temperature and prevent condensation.

Importantly, condensation effects will only occur when surface temperatures are at or below saturation temperature (i.e., dew point). Surface temperatures only 2ºC above the dew point will effectively prevent condensation since relative humidity at the warmer surface would be below 90%.

The above analysis indicates that the conditions inside the TEFC enclosure during HELB events are significantly different than the external steam-air environment. For motors located in areas where enclosure pressure equalization will occur prior to the arrival of steam, moisture intrusion will only occur via diffusion. The external environment will return to essentially pre-HELB conditions long before any significant diffusion driven moisture intrusion. For other motors, an external steam-air environment might exist almost instantaneously. In these cases, pressurization will drive some of the steam-air mixture into the motor with the amount directly related to HELB pressures. Due to the relatively low HELB pressures; however, the internal environment will not be steam but simply high humidity air at a slightly elevated temperature. While some condensation might occur on internal surfaces, it would be limited to a light film that will not affect operability or insulation system integrity. The light moisture film may even evaporate as motor temperature increases due to heat flow into the TEFC enclosure from the external steam-air environment. As described above, subsequent diffusion effects are insignificant.

For motors that are operating during the HELB conditions, the internal heat rise effectively prevents the formation of moisture. Although some small amount of the

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3 The testing demonstrates that the relationship between internal and external concentrations of a particular gas can be expressed as $P_i(t) = P_e\,(1\text{-}e^{-t/\tau}) - P_{io}$; where $P_i(t)$ is the internal concentration at any time t, P_{io} is the initial internal concentration, P_e is the external concentration, and τ is the time constant.

external steam-air mixture may be drawn into the enclosure due to fan pressurization effects, the internal temperature rise, due to operation and external HELB heating, will prevent condensation on the internal surfaces.

This description of the moisture response of a TEFC motor subjected to HELB conditions is supported by testing and analyses conducted by several utilities to determine HELB moisture intrusion effects for devices, other than motors, protected by unsealed enclosures. In one such effort [2] a series of HELB tests was performed on vented junction boxes. The vented boxes contained terminal blocks or were connected with short sections of conduit to unsealed devices (limit switch, electronic transmitter). Three junction boxes, whose sizes ranged from roughly 1/2 to 1 ft^3, communicated with the test chamber environment through short sections of open conduit and 3/8" drain holes at the bottom of the enclosures. The enclosures and connected instruments were subjected sequentially to two HELB tests whose conditions are summarized in Table 6.2. Visual inspection immediately after the second exposure found a *light moisture film* on some internal surfaces of two enclosures and the electronic transmitter. Also a small water mark was found centered on the bottom-inside-surface of two enclosures. Since interconnecting cables entered the boxes (vertically from above) directly over the marks through the conduits, it was evident the marks were due to a small amount of moisture that had accumulated on the cables and dripped onto the box. No rusting or any other evidence of moisture accumulation was found inside the enclosure or devices. Terminal block leakage currents were monitored during the test. Except for one problem traced to the detection circuit, leakage currents were *below the limits of detection* (50 microamps @ 140 Vac).[4] Equivalent results were obtained in a third test of two similar enclosures with a HELB profile similar to Table 6.2 HELB Test No. 2. The lack of any significant moisture inside the enclosure, coupled with the excellent condition and visual appearance of the box components, confirms the lack of any significant moisture intrusion during low-pressure HELB conditions.

6.2.1.3 HELB Temperature Effect. The second HELB environment stressor which can potentially impact motor operability is temperature. During HELBs, external temperatures can rapidly rise to values over 200°F. Temperatures in excess of 400°F have been hypothesized in small rooms with large steam breaks. Given enough time, motor temperatures will ultimately reach these high temperatures. For most HELBs; however, the peak temperature conditions only exist for relatively short periods of time. After detection and isolation of break flow, environmental temperatures will rapidly decay.

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4 Several Sandia test programs [9] have demonstrated that terminal block leakage currents will occur when condensation forms on terminal block surfaces.

Table 6.2
Summary Test Conditions for Test Report No. 48365-01

Duration	Temperature (°F)	Pressure (psig)
HELB Test No. 1		
0 - 70 sec	195 - 215	0
70 sec - 3 min	205	1.4
3 min - 5 min	200	1.4
5 min - 3 hrs	200 declining to 145	0.2
3 hrs - 16 hrs	145	0.2
HELB Test No. 2		
0 - 3 min	270	0 - 4.4 (varies)
3 min - 5 min	270 declining to 215	3 declining to 0.4
5 min - 3 hrs 30 min	215 declining to 150	0 - 1 (varies)
3 hrs 30 min - 16 hrs	145	0.4

As discussed in Section 4.0, it normally takes several hours for motors to achieve thermal equilibrium under normal (e.g., non-steam environment) operating conditions. More rapid heating occurs in steam environments due to the relatively high heat transfer rate of condensing steam when compared to hot air. The heating impact of the HELB steam environment is critically dependent on several factors, including:

- Motor Enclosure type
- Pressurization
- Saturation Temperature of the steam-air environment
- Molecular ratio of the steam- air mixture
- Motor Operation

Because of the relatively low pressure occurring during most outside containment HELBs, saturation temperature of the external steam-air environment remains in the range of 212°F - 222°F.[5] The high temperatures predicted for many HELB events (e.g., 300 °F) means that the environment is a mixture of superheated steam and air. It is widely accepted that heat transfer from such a superheated mixture to colder objects (i.e., objects with temperatures below saturation temperature) is more appropriately modeled by using the temperature difference between the object and saturation temperature and not

5 Saturation temperature for pure steam at 3 psig is approximately 222°F.

between the object and the higher superheat temperature.[6] This indicates that although HELB analyses might predict high ambient temperatures, the heat-up rate of devices, like motors, is driven by the much lower saturation temperatures. The effect is illustrated by Figure 6.2, which reproduces temperature data from [3] for LOCA tests of NEMA type (e.g., NEMA 12) thin sheet metal enclosures containing a variety of electrical and electromechanical components. The internal temperatures of the larger enclosure quickly rose to saturation temperature (300°F) within 10 seconds, yet essentially remained at this temperature until the chamber temperature reduced to this value at approximately 26 minutes. A less rapid response occurred for the smaller enclosure which may have been due to the drop in chamber temperature during the initial transient. After this time both chamber and enclosure temperatures decreased. At no time during the first three hours did internal temperatures exceed saturation temperatures. Motor enclosures, with much larger mass-to-surface area ratios, will heat up much more slowly but, like the sheet metal panels, internal temperatures will not increase beyond saturation temperatures for unenergized motors. Based on these considerations, it is reasonable to conclude, for the purpose of addressing temperature effects on motors, that the maximum *effective* ambient temperature during outside containment, low pressure HELBs is roughly 100°C.

Unless a motor is exposed directly to a jet of steam emanating from a HELB, the ambient environment surrounding the motor during the HELB is composed of a mixture of steam and air. The heat transfer characteristics of this mixture are strongly dependent on the ratio of condensable (i.e. steam) to non condensable (air) gases. Table 6.3 from [4] summarizes this effect. The heat transfer coefficient, which may be higher than 1000 BTU / hr-ft.^{2}-°F for high quality saturated steam, will drop to much lower values as the percentage of air increases. As a basis for comparison, the heat transfer coefficient for natural convective heating in air without steam is roughly 2 Btu / hr-ft^2-°F. The lowering of the heat transfer coefficient due the air-steam mixture minimizes heat transfer from HELB environments to the motor.

6 See for example the discussion on equipment temperature modeling provided in NUREG-0588, Appendix B, *Model for Environmental Qualification for Loss-of-Coolant Accident and Main Steam Line Break Inside PWR and BWR Dry Type of Containment*.

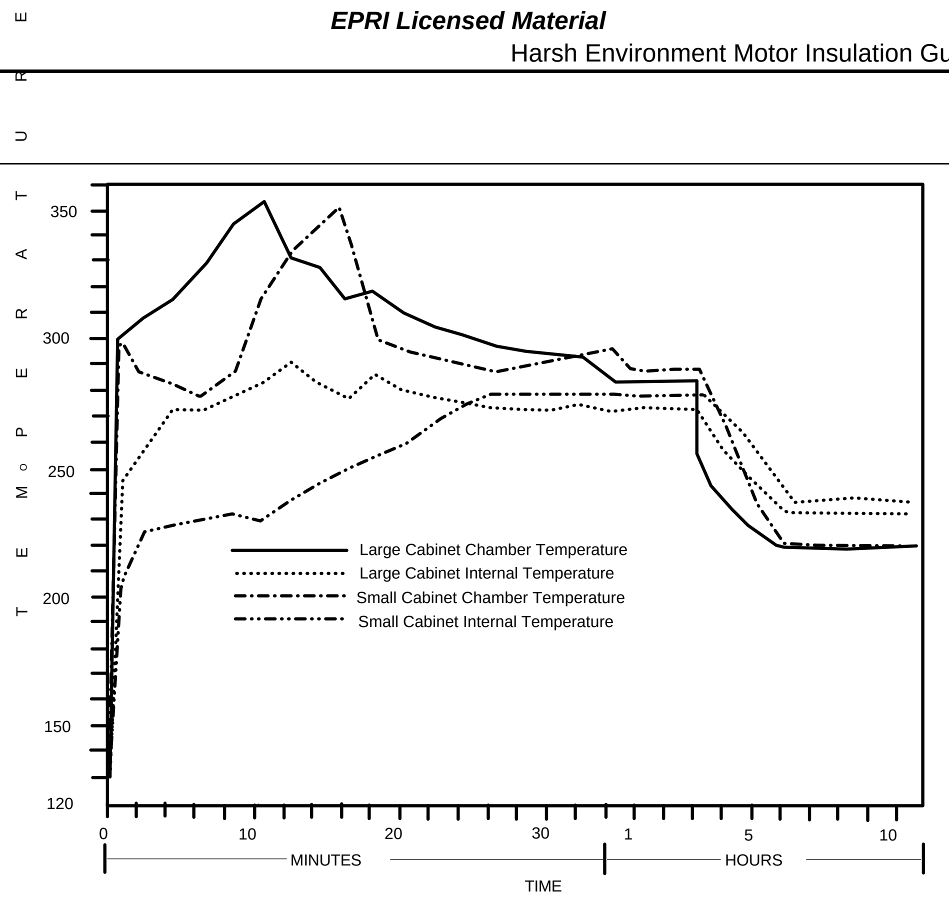

Figure 6.2
Thermal Response of Enclosures to LOCA Superheat Conditions

Table 6.3
Non Condensable Gas Effects on Steam Heat Transfer

Mass Ratio (lb air/lb steam)	Heat Transfer Coefficient (Btu/hr-ft^2-°F)
0.1	280
0.5	140
0.8	98
1.3	63
3	29
10	14
20	8
50	2

As described above under *Humidity Effects,* very little of the external environment penetrates totally enclosed enclosures during HELB events. Consequently, the only motor surfaces contributing to motor heat transfer during the HELB are those directly exposed to the external environment. Unfortunately, the same situation does not exist for certain open type enclosures which provide relatively unobstructed paths for penetration of the external environment into the motor interior.

Taken collectively, these considerations suggest the likely thermal response of motors to the HELB steam conditions. These are:

- Motors of the TEFC type, or other totally enclosed designs which effectively isolated the internals from the external steam environment, will only experience heat up from their external surfaces
- The relatively low driving temperature (e.g., 100°C) during HELBs will not cause a rapid temperature rise for the relatively massive stator structure (i.e., winding and core)

Several motor tests demonstrate that totally enclosed enclosures provide considerable protection for internal motor components, including the insulation system, during HELB conditions. Figure 6.3 extracted from a test sponsored by TVA [5] presents temperature measurements made on a deenergized 40 HP Limitorque MOV motor during a HELB simulation. The superheated steam test included a rapid temperature increase from the initial 140ºF to 325ºF with peak temperatures near 450ºF. The external environment could enter the test motor through the unsealed motor lead wireway. In order to achieve the high temperature conditions, a number of short pressurizations, not representative of actual HELB conditions, occurred. These pressurizations, by helping force the external environment into the motor, make the test results very conservative. The two internal temperatures are rotor / stator air gap and average winding temperatures. The two temperatures are virtually identical. The average winding temperature, determined based on resistance, represents the average temperature of the copper winding. Since the winding and air gap temperatures are very similar, with slightly lower gap temperatures, internal heating principally occurred via heat transfer through the enclosure and stator assembly and not via introduction of hot moist air into the motor. The slow thermal response of the stator winding indicates that transient low pressure HELB conditions do not significantly change winding temperatures.

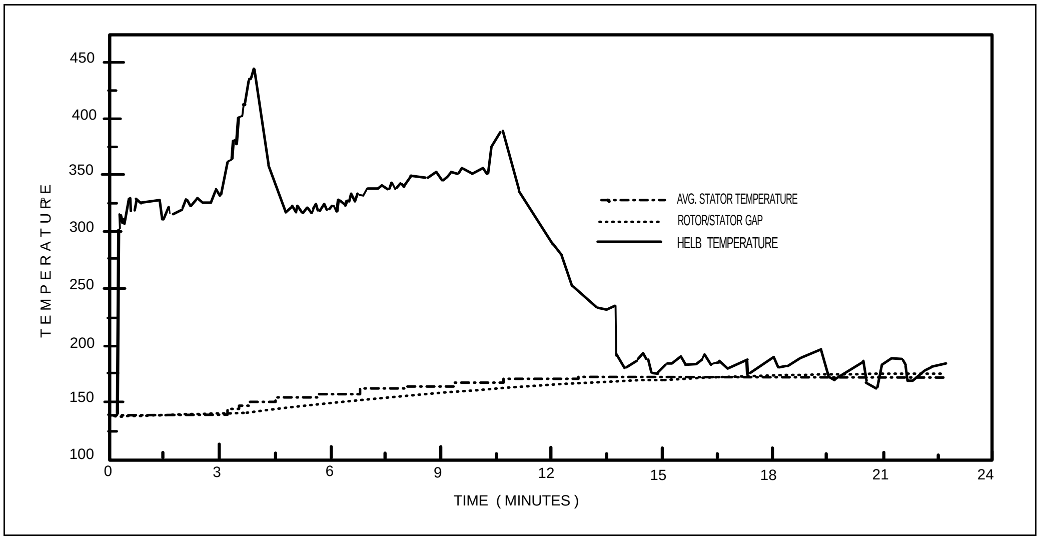

Figure 6.3
Thermal Response of 40 HP Motor During HELB Simulation
(If Motor was Running or Shutdown)

Insight into the differences between low-pressure HELB and LOCA steam conditions is dramatically provided by comparing these motor temperature curves with those in Figure 6.4 that were developed in a TVA LOCA test [6]. Curves for chamber pressure and the temperature of the chamber, motor terminal box, and stator core during the LOCA test are provided in Figure 6.4. The LOCA test specimen was a random-wound 20 hp, 1775 rpm, TEFC motor. Interestingly, the chamber temperatures in both the HELB test (Figure 6.3) and the LOCA test (Figure 6.4) are similar for the initial 10 minutes. Still, there are dramatic differences in the motor thermal responses. During the LOCA test, motor temperatures rapidly increase from 115ºF to over 300ºF in less than 10 minutes; while during the HELB test, temperatures rise very slowly and only reach roughly 170ºF (a 30ºF rise) after 10 minutes. The dramatic differences in the motor thermal responses are principally due to pressurization and the heat transfer differences between saturated and superheated steam. In the LOCA exposure, with pressures near 60 psig, saturation temperatures will exceed 300ºF. During the HELB simulation, with significantly lower pressures, saturation temperature varies between 212ºF and roughly 230ºF. Since heat transfer is dominated by condensation, a significantly lower thermal difference exists for the HELB situation. Secondly, during LOCA, steam is driven into the motor enclosure by the high pressures. Under these steam pressure conditions, over 80% of the internal air volume may be occupied by steam.[7] As this steam condenses and heats the motor internals, additional steam is drawn into the motor to continue the heating process. During the LOCA test, heat-up may have been lowered by motor operation, which increased both internal and external air velocity through the action of the shaft fans. This contrasts with the HELB situation, where little steam / moisture was forced into the motor. Consequently, in the HELB case virtually all the heating occurs from the external enclosure surfaces. This data demonstrates the level of thermal protection and thermal lag provided by the TEFC motor enclosure during low-pressure HELB conditions.

Similar supporting data on form-wound motor thermal response during HELBs is also provided in [6]. This test involved formettes assembled into a stator core inside a vented enclosure. The initial transient involved a rapid temperature increase from 105ºF to 245ºF followed by several minutes with temperatures in the vicinity of 200ºF. After approximately 24 hours, with chamber temperature roughly 120ºF, the temperature was quickly increased to 175ºF. During the second temperature transition, terminal box and core temperatures slowly increased, taking hours to reach equilibrium temperatures.

6.2.1.4 Generic Qualification Basis for Totally Enclosed Motors. The previous discussion characterizes the types of environmental conditions that motor windings are exposed to during typical HELBs. It demonstrates that the inherent protection provided by TEFC and other totally enclosed designs significantly limits the thermal and humidity conditions experienced by the winding during HELBs. Less information is provided for the open type enclosure constructions, since the conditions at the winding could vary considerably, based on the specific type of enclosure and the severity of the HELB conditions.

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7 Initial pressure is 15 psia but quickly rises to 75 psia during the 60 psig steam admission into the chamber. Using the ideal gas law to provide a rough approximation (60 / 75 = 0.8), 80% of the internal free volume would be occupied by steam.

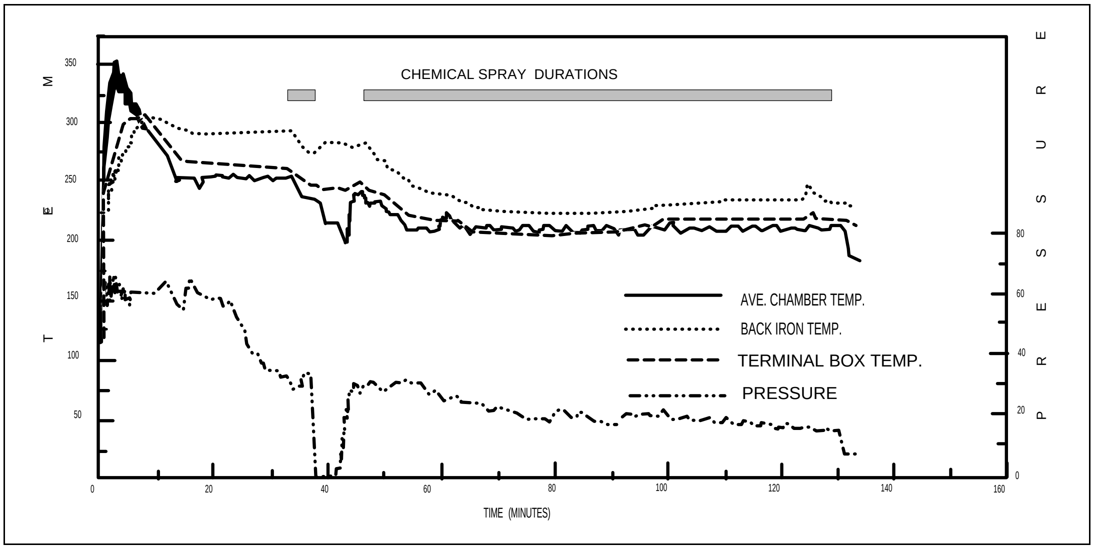

Figure 6.4
Thermal Response of 20 HP Motor During LOCA Simulation
(If Motor was Running or Shutdown)

The following discussion provides technical information supporting the HELB qualification of rated insulation systems used in TEFC motors. The principal testing basis for this qualification is the thermal life testing performed on the insulating system per the requirements of UL 1446 or the IEEE thermal life standards (e.g., IEEE 275). This testing is considered adequate to demonstrate qualification for HELB conditions because it: 1) incorporates both thermal and vibration aging, 2) subjects the winding system to temperatures substantially greater than those likely to be experienced during HELB conditions, and 3) subjects the winding to prolonged high humidity, condensing conditions while being subjected to voltages greater than those experienced during operation. Section 4.2.2 of this guideline and Section 3 of a companion EPRI report [7] contain additional information on these UL and IEEE standards and the testing methods used to establish system thermal ratings.

Several topics regarding the acceptability of this UL and IEEE life testing as a qualification basis for HELB exposed systems should be clarified. The first involves winding and motor lead connections. The second relates to peak winding temperatures during HELBs and winding temperatures during the UL and IEEE testing.

Connections: Many motorette and formette tests do not include lead wire and coil connections as part of the test specimens. Further, these connections could be susceptible to tracking and possible failure if high humidity conditions produce significant condensation on the connections. Several considerations indicate that moisture related failures of appropriately formed and insulated connections are not a qualification concern. First, based on the analysis and partial testing previously discussed, little, if any, condensation will occur within a TEFC motor during low-pressure HELB conditions. No condensation should exist in operating TEFC motors due to their heat rise. Secondly, resin treatments (both Dip & Bake and VPI) apply protective resin films over the connections. These treatments effectively protect and insulate the connections from moisture effects. The connections in properly fabricated VPI windings and other windings designed as "sealed systems" will tolerate full submergence without failure at operating and high potential test voltages. Although Dip & Bake (D&B) treatments may not provide the same level of protection, the use of multiple D&B cycles adequately isolates the connections from minor moisture contamination. Finally, operating experience (as discussed further in Section 6.2.1.5) indicates that properly insulated and resin treated connections remain functional during high humidity conditions.

Winding Temperatures: For the high quality random-wound motor rewinds being used in safety-related applications, virtually all the materials used to construct the system have Class H (180°C) or better thermal ratings. Similarly, the thermal classification of the composite system is generally Class H or better. Since these systems are designed and rated for continuous operation at 180°C, transient temperatures during HELB conditions at or below the system thermal rating should not be of concern. Section 6.2.1.3 demonstrates that heat transfer considerations and the thermal response of TEFC motors during HELBs will limit the *effective* ambient temperature to values below 100°C. The sum of the effective ambient temperature and motor temperature rise establishes the insulating system's peak operating temperature during HELBs.

For the Class B temperature rise motors typically used in nuclear power plants, the maximum allowable *average* temperature rise during operation is 80°C. In reality, actual temperature rises under design conditions for Class B motors can be considerably less than 80°C. Further, most motors are not continuously operated at their maximum horsepower rating. Using an effective ambient temperature of 100° C and an average heat rise of 80°C results in an estimated winding temperature of 180°C. This limited but bounding analysis indicates that random-wound motors with Class H insulating systems are designed for continuous operation in the thermal environments occurring during most HELB events. The qualification is based on the thermal classification of the insulating system and the associated testing, per IEEE or UL standards, used to establish the system's thermal rating. Similar conclusions can be drawn for form-wound Class H systems.

Even if winding temperatures should exceeded 180°C during HELBs, qualification to the short time, higher operating temperature is achieved based on the accelerated thermal aging temperatures used during thermal life testing per UL and IEEE standards.[8] In order for a system thermal rating to be developed to these standards, insulating systems must be operated for extended periods of time at temperatures substantially higher than their rated operating temperature.

The preceding discussion suggests that operating temperatures of TEFC motor insulating systems during HELB conditions should be at or below 180°C. For Class H rated systems such short-term temperature exposures are insignificant. These temperatures are considerably above the maximum continuous operating temperature of Class F systems. These Class F systems are often used in form-wound applications. Acceptable operation of Class F systems in the range of 180°C can be established by using the thermal aging data developed to establish the system's thermal classification. For example, IEEE 275-1992 suggests accelerated aging temperatures in excess of 210°C - 220°C for durations exceeding several days for Class F insulating systems.

6.2.1.5 Relevant Standards and Operating Experience. The following discussion provides additional information relevant to qualifying motors to low-pressure HELB conditions. Since high ambient temperatures and high humidity conditions are encountered in non-power plant applications, experience with the performance of motors in these environments can be used to check the adequacy of the qualification methods being proposed for motors.

A variety of industries, including petrochemical, pharmaceutical, food processing, pulp and paper, and steel, subject motors to high temperature or high humidity conditions. While standard NEMA commercial grade motors can function in these rather hostile environments, experience has shown that motors with special design features provide better performance and substantially longer life. Motor manufacturers have responded by offering specially designed motors under a variety of designations such as "severe duty", "extra tough", "washdown duty", "hostile environment duty", etc. Collaboration among manufacturers and users has produced an IEEE standard [8]. The standard applies to motors "*indoor or outdoor severe duty applications, such as humid, chemical (corrosive), or salty atmospheres*". Provisions of the standard applicable to insulating systems include:

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8 Section 4.2.2 contains additional information on typical temperatures used during thermal aging tests per UL and IEEE standards.

- The system shall be non-hygroscopic, chemical- and humidity-resistant
- The system thermal rating shall be Class F or better
- 2.3 and 4 kV systems shall be VPI form-wound *sealed* systems per NEMA MG-1
- Phase insulation, in addition to varnish, shall be used between phase coils of random wound windings
- Average temperature rise at rated load shall not exceed 80°C

Additional provisions concerning other motor components include:

- Exposed internal stator, rotor, and shaft surfaces shall be protected against moisture and corrosion by a suitable protective coating
- Corrosion-resistant automatic drainage fittings shall be provided at low points
- A moisture-resistant barrier shall be provided between the terminal box and motor cavity
- Fans shall be non-sparking bronze alloy or conductive plastic
- Frames, endshields, and fan covers shall be cast iron
- Direct-coupled motor bearing temperatures at rated load shall not exceed 45 - 50°C temperature rise.

A survey of manufacturer literature for random-wound "severe duty" motors indicates most provide "double" or "multiple" Dip & Bake insulating systems with Class F or better thermal ratings. Discussions with the motor manufacturers indicate they have little concern for the capability of the Dip & Bake insulating systems for these severe applications. Most of their efforts have focused on bearings / greases, bearing seal systems, and coatings to minimize corrosion.

Feedback regarding moisture and low-pressure steam resistance was also requested through the Electric Apparatus Service Association (EASA) from motor manufacturers and repair shops. The following summarizes the feedback provided from most of the respondents:

- Totally enclosed enclosures are effective in limiting moisture intrusion provided steam is not directed onto the motor
- Moisture related failures occur during prolonged moisture exposure when moisture penetrates cracks and defects
- Sealed VPI systems are preferred to Dip & Bake. Multiple Dip & Bake cycles are needed to minimize moisture intrusion effects.
- Connections should be designed to promote absorption and retention of resin
- Materials which hydrolytically degrade (e.g., Mylar) should not be used

- Resins with some flexibility should be used to minimize crack development and growth
- Flexible coatings can be applied to the windings after resin treatment to minimize the impact of resin cracking and increase moisture resistance
- Additional turn insulation (e.g., quad build enamel) should be considered to minimize moisture induced tracking between turns

This feedback supports our general conclusions regarding totally enclosed type enclosures and indicates that winding designs and treatments that minimize moisture intrusion are preferred. Based on this feedback and as added conservatism, the following are recommended design considerations for low-pressure HELB qualified rewind systems used in totally enclosed type enclosures:

- Sealed systems are preferred
- Where sealed systems are not used, multiple resin treatments should be applied
- Measures should be taken to ensure that the lead connections and fabrication promote resin absorption / retention and minimizes moisture intrusion

6.2.2 Fabricating HELB Qualified Systems

The material presented in this section demonstrates that analysis and partial test data can form an adequate qualification basis for the insulating systems in totally enclosed motors exposed to low-pressure HELB conditions. No specialized fabrication techniques, other than those used to produce a high quality, safety-related, mild environment motor rewind, are needed when fabricating windings for totally enclosed motors exposed to low-pressure HELB conditions. Consequently, no additional fabrication guidance and requirements, beyond those used for mild environment motor applications, are necessary. Guidance on the procedures, controls, and documentation needed to demonstrate the acceptability of such motor repairs are contained in EPRI NP-6407 [10].

For motor insulating systems which have been type test qualified for use in open type enclosure designs, the fabrication guidance contained in Section 5.2.2 for LOCA qualified systems can be applied. The Section 5.2.2 guidance should also be applied to type test qualified windings for higher pressure HELB events.

6.2.3 Material Procurement and Acceptance

As discussed above in Section 6.2.2, no special techniques, other than those used to produce a high-quality, safety-related mild environment motor rewind, are needed when totally enclosed motors are qualified for low-pressure HELB conditions using the analysis and partial test data contained in this section. Since tolerance to these HELB conditions is based principally on enclosure design, the procurement and acceptance processes for the insulating system materials need only insure that the specified material was supplied. Consequently, the general guidance contained in EPRI TR-103585 [7] applies to materials used in these motors. Additional material controls or verifications, beyond those used to accept materials for mild environment safety-related motor repairs, should not be necessary. When a motor insulating system, particularly those used in open type motors, is type test qualified for HELB conditions, then the controls described in Section 5.2.3 for LOCA qualified motors should be considered.

6.3 Evaluation of Systems Made Available to EPRI

The following discussion describes several form-wound VPI systems that have been made available to EPRI and are qualified for typical low-pressure outside containment HELB conditions using type testing. No random-wound systems specifically tested for HELB conditions were provided to EPRI. However, LOCA qualified systems can be used for HELB applications. LOCA qualified systems are generally exposed to significantly more severe accident conditions than those encountered during outside containment HELBs. Additional conservatism exists in LOCA tests since the radiation exposure during LOCA qualification produces insulation degradation that is not encountered during HELB conditions. It is possible that certain outside containment high temperature HELB profiles are not fully enveloped by LOCA test temperatures. However, even under these conditions the LOCA testing should be considered as an acceptable qualification basis for HELB applications. This conclusion relies on the difference in motor heat-up rates under LOCA high pressure steam conditions when compared to low-pressure outside containment HELB steam conditions. In cases where HELB peak temperatures exceed LOCA test temperatures, a more quantitative basis can be developed by modeling motor thermal response under both LOCA and HELB conditions.

Systems qualified using LOCA or HELB type tests should be used for open type enclosures and in cases where the HELB profile contains significant pressurization and cannot be categorized as a low-pressure HELB.

6.3.1 Random-Wound

EPRI was not provided with qualification information for random-wound motors exposed to HELB outside containment conditions. Section 5.3 identifies a random-wound VPI motor insulating system that has been type test qualified to LOCA conditions. This system could be used for random-wound motors installed in HELB harsh environments.

6.3.2 Form-Wound

TVA recently completed a qualification test program on a three phase stator containing three independent insulating system designs. The testing is documented in [6]. A summary of the relevant test conditions is provided in Table 6.4. The test temperature and pressure profiles are presented in Figure 6.5. The insulating systems successfully operated during the functional tests conducted after all test phases and the post-simulation electrical tests. The formettes were energized at rated phase-to-phase and phase-to-ground voltage during the HELB simulation. Circulating currents were applied during the simulation to produce a representative heat rise. Although the formettes were not constructed to simulate conductor-to-conductor voltages, these voltages are relatively small (e.g., <50 Vac) in most applications. The thermal aging time was based on an activation energy of 1.2 eV for the insulating resin based on product data provided by the manufacturer. The TVA qualification test report, applicable material specifications, and TVA fabrication procedures and controls are available by contacting EPRI PSE and requesting EPRI Report TR-104872, Supplement 2.

Table 6.4
Summary Test Conditions Formettes - Wyle Report No. 18070-1

Test	Type	Summary Conditions
1.	Normal Radiation	$3.6x10^6$ rad @ approximately $2.22x10^5$ rad / hr
2.	Thermal Aging	2107 hours @ 200ºC = 40 years @ 130ºC
3.	Vibration Aging	1 hour, 1.5g @ 60 Hz
4.	Seismic	Sine sweep - sine-beat (3.3g H, 2.2g V) - Triaxial random (5 OBE, 1 SSE) - 10g peak, 5% damping SSE
5.	Accident Radiation	$1.14x10^7$ rad @ approximately $5.9x10^5$ rad / hr
6a.	HELB Temp.	235ºF peak
6b.	HELB Press.	2 psig peak, 13 psig spike
6c.	HELB Humidity	100 %
6d.	HELB Duration	11.2 days
6e.	HELB Operation	Energized and current loaded during most of test

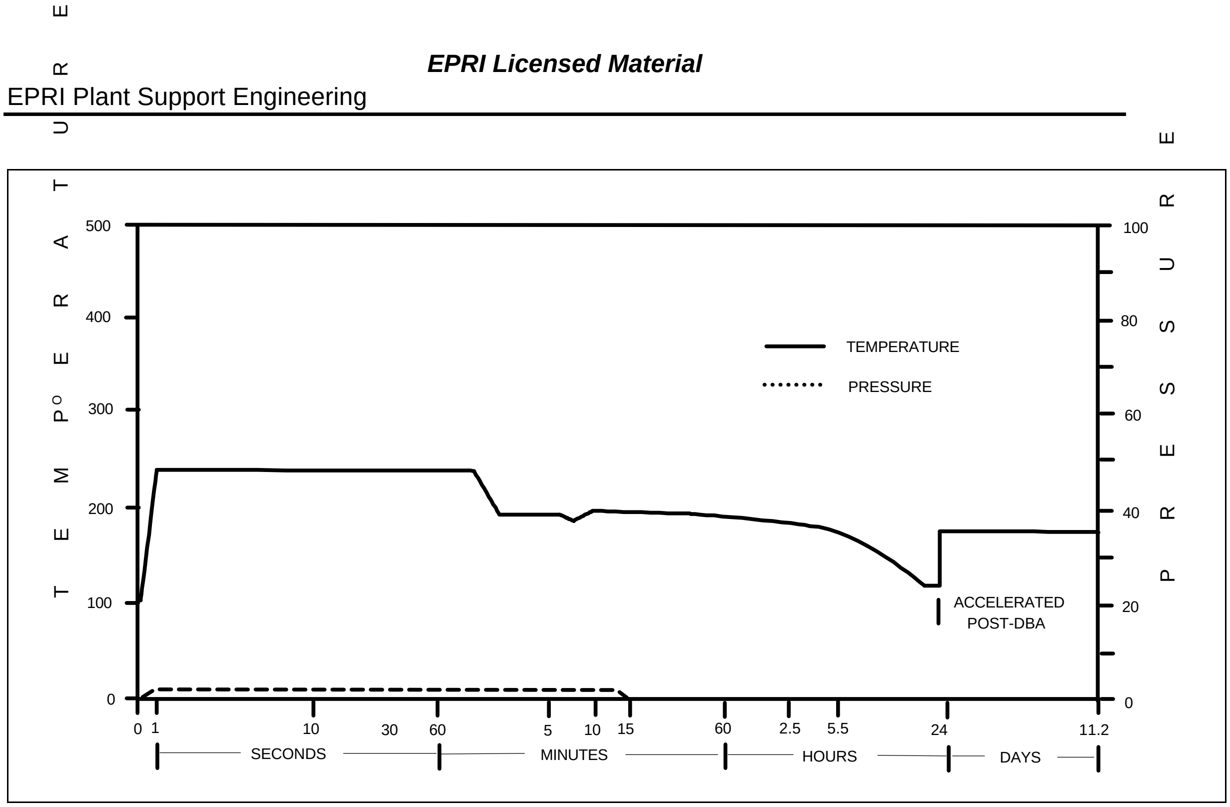

Figure 6.5
Formette Temperature and Pressure Profile - Wyle Report No. 18070-1

The formettes were fabricated at the TVA Power Service Shop using the materials identified in Table 6.5. TVA's stated order of preference for these systems is B, C, A. This preference is based on the amount and durability of turn insulation available in the systems. System B contains a double Daglas (DDG) fibrous covering over a heavy polyimide film. System C contains the same polyimide film but uses a shop-applied butt-lapped layer of Dacron tape in lieu of the DDG. Since the C construction is somewhat thinner, it might be used in motors where slot space is at a premium. System A uses DDG without a film layer.

Table 6.5
Formette Materials - Wyle Report No. 18070-1

Component	System A	System B	System C
Magnet Wire	DDG (silicone binder)	DDG (silicone binder) over heavy polyimide	heavy polyimide, 1 butt-lapped layer 5 mil Dacron tape
Mica Tape	Class F, glass backed, US Samica 4601	Class F, glass backed with polyester mat, US Samica 4373	Class F, glass backed with polyester mat, IMI 77986
Wedge	Glastic 6090577	Glastic 6090577	Westinghouse Micarta H-17825
Tie tape	Nomex, Western Filament NFB-1X	polyester, Carolina Narrow Fabric K5050	Nomex, Western Filament NFB-1X
Connection Sleeve	N/A	N/A	Bently Harris ACRYL Overbraid VPI
Armor Tape	heat cleaned glass, Mutual C-150		
Coil Resin	180°C solventless polyester, slightly thixotropic, 50% IMI 707, 50% IMI711		
Motor Lead	EPDM insulated, Belden 37506		
Lead Sleeve	Bently Harris 1151 superwall (applied post-VPI treatment)		
Filler Strips	Nomex 410 Paper		
Felt Strips	Nomex felt, Southern Mills S/14		

6.4 References

1. Buschart, R.J. et al, *Safe Application of Totally Enclosed Motors In Hazardous Class I, Division 2 Locations*, IEEE Paper No. PCIC-93-35, 1993
2. Wyle Test Report No. 48365-01, *Qualification Test Program on Terminal Blocks, Namco Limit Switch and Instrumentation Sealing Compound for the Washington Public Power Supply System for use in the WNP-2 (outside Containment)*, September 8, 1986
3. Wyle Report No. 44439-2, *Accident (LOCA) Test and Analysis of Five (5) Equipment Enclosure types for Public Service Gas and Electric Company (PSE&G)*, August 15, 1979
4. NRC Branch Technical Position CSB 6-1, *Minimum Containment Pressure Model for PWR ECCS Performance Evaluation*
5. Wyle Test Report No. 17242-1, *Temperature Lag Test Report*, December 7, 1992

6. Wyle Report No. 18070-1, *Nuclear Environmental Qualification Test Program on Random-Wound and Form-Wound Motor Insulation Systems and Other Motor Components*, January 13, 1993

7. EPRI TR-103585, *Guidelines for the Selection, Procurement, and Acceptance of Nuclear Safety-Related Mild Environment Motor Insulation for Rewinds*, July 1994

8. IEEE 841-1994, *IEEE Standard for Petroleum and Chemical Industry - Severe Duty Totally Enclosed Fan-cooled (TEFC) Squirrel Cage Induction Motors - Up to and Including 500 hp*

9. Craft, C.M., *An Assessment of Terminal Blocks in the Nuclear Power Industry*, NUREG / CR-3691, September 1984

10. EPRI NP-6407, *Guidelines for the Repair of Nuclear Power Plant Safety-Related Motors*, March 1990

7.0

RADIATION-ONLY HARSH QUALIFIED SYSTEMS - DETAILED GUIDANCE

This section discusses the qualification methodologies, guidance, and related considerations specific to radiation-only harsh environment motor applications. Radiation-only harsh is defined as an accident environment where radiation is the only environmental condition substantially different from those normally occurring. All other environmental conditions, pressure, temperature, humidity, etc. are assumed to remain within the plant area's normal design envelope. Radiation-only harsh environments occur in outside containment areas whenever a LOCA occurs inside containment.

7.1 Technical Approach and Justification

As noted in Section 4.0, qualification can be based on testing, analysis, operating experience, or an appropriate combination of these methods. More specifically, the EQ rule recognizes four qualification methods:

1. Testing of an identical item under identical conditions or under similar conditions with a supporting analysis
2. Testing of a similar item with a supporting analysis
3. Experience with identical or similar equipment under similar conditions with a supporting analysis
4. Analysis in combination with partial test data that supports analytical assumptions and conclusions.

This section recognizes two principal methods of establishing qualification for radiation-only harsh motor insulating systems:

1. Type testing per IEEE 323 and IEEE 334-1994 which simulates the effects of aging and the radiation-only accident conditions.
2. Analyses of the effects of radiation and aging on the insulating system and materials, combined with material/system radiation test data and thermal effects test data (i.e., partial test data), that conservatively support the analysis assumptions and conclusions.

Other methods of qualifying motor insulating systems for radiation-only harsh conditions exist (e.g., operating experience). However, this guide emphasizes these two methods since they can be used to evaluate virtually all radiation-only harsh motor insulating system applications.

Figure 7.1 presents a flow chart of the suggested approaches for establishing qualification for motors in radiation-only harsh applications. Qualification by type testing is recommended for all motors exposed to radiation dose levels in excess of established system or material radiation service limits. This radiation dose service limit data may be either material specific or generic to a material class (e.g., silicone rubber).[1] Below these service limits, this section maintains that the conservative application of material radiation and thermal aging test data combined with analysis is an adequate qualification basis for motor insulating systems exposed to radiation-only environments. At the present time the NRC prefers type testing for demonstrating qualification of insulating systems for <u>all</u> harsh environment applications, including radiation-only harsh applications. The NRC has not reviewed the specific information and conclusions contained in this guideline. However, utilities are encouraged to apply the suggested analysis plus partial test data method as a qualification basis.

The qualification by type test methodology described in Section 5 for inside containment motor rewinds is applicable to the motors installed in radiation-only areas. Even motor type test qualification programs that were unable to fully qualify motors to LOCA steam conditions can be used to support type test qualification in radiation-only harsh areas, if the motor or specific insulation material demonstrated acceptable performance after the radiation exposure but prior to the LOCA steam simulation. Section 7.3.1 contains information on one such random-wound system.

While type testing, per the NRC, is the preferred qualification method for all harsh EQ applications, the major focus of this section is the use of partial testing combined with analysis as the qualification basis for motor rewinds in radiation-only environments. Specifically, the use of insulating material radiation test data, combined with system thermal/compatibility testing and an overall qualification analysis, is proposed. IEEE 334-1994 supports the use of partial test data and analysis to establish qualification for radiation-only applications. Section 6.3 of that document states that *motor applications in harsh environments containing only one environmental parameter threat (e.g., radiation-*

1 The conservative service limit radiation doses suggested in this section need not be used if other more appropriate radiation data can be applied to the insulating systems or materials under evaluation.

only) may be addressed adequately through an analytical technique. The standard also states that if radiation tests and analyses of

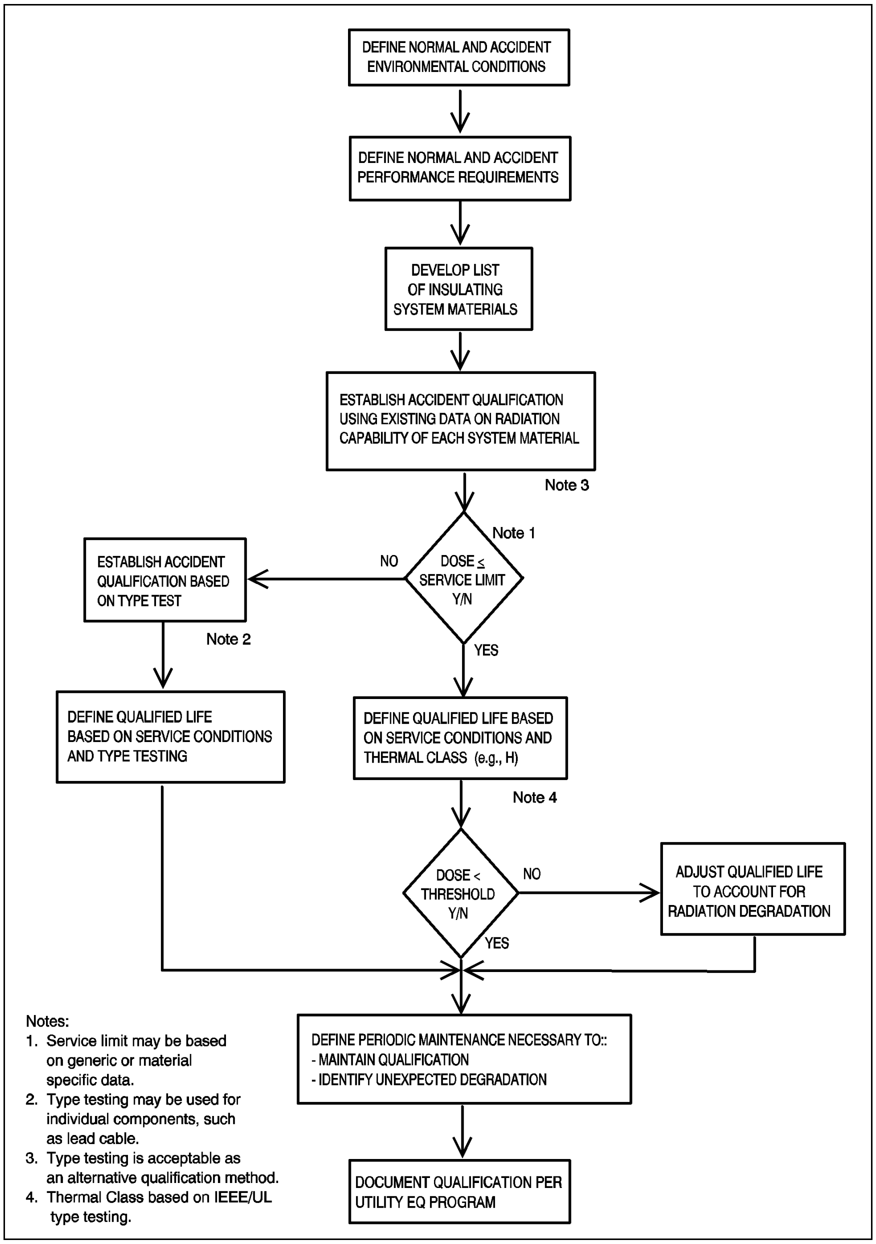

Figure 7.1
Qualification Flow Chart for Motors Exposed to Radiation-Only Harsh Conditions

the various materials used in the motor show that direct damage to any materials or the evolution of radiation produced substances (e.g., gases) are negligible, then type testing of the motor is not necessary. IEEE 323-1983 permits the exclusion of radiation from type testing if it can be shown that radiation will not adversely affect equipment functions and there are no adverse aging effects.

Radiation-only harsh environments are those where the radiation dose rate and total integrated dose occurring during accidents are significantly greater than those occurring during normal operation. Under this definition, which is fully consistent with 10 CFR 50.49, motors subjected to 10^7 rad of radiation during normal operation and 10^6 rad during a design basis accident are not in a harsh environment (i.e., they do not require qualification to 10 CFR 50.49). However, motors subjected to 10^6 rad of radiation during normal operation and 10^7 rad during a design basis accident are in a harsh environment and require such qualification. The basis for this distinction rests in the recognition that an appropriate design (i.e., one with acceptable radiation tolerance), coupled with normal operation, maintenance, and surveillance activities, will identify and address the degrading effects of radiation and other aging stressors during normal operation. Further, since the accident radiation levels are not significantly greater than those occurring normally, these normal activities would adequately address the accident radiation. This section conservatively assumes that all the radiation exposure occurs during accident conditions but considers the issue of dose rate effects should some of the radiation occur as an aging dose. A specific methodology is proposed that addresses issues of relevance to this method, including the effects of aging and the need to establish (possibly significant) margins to address radiation tolerance uncertainties for some material classes.

7.2 Detailed Guidance

7.2.1 Establishing EQ

Radiation can affect physical (e.g., color), mechanical, electrical, and chemical characteristics of insulating materials. Extensive material testing has established that mechanical properties (e.g., elongation, bond strength, flexure strength) degrade prior to significant changes in electrical properties (e.g., dielectric strength, insulation resistance, dissipation factor) [1,17]. Consequently, mechanical properties are used to evaluate the radiation resistance of insulating system materials. The use of mechanical properties is supported further by recognizing that the vast majority of motor winding failures are initiated by mechanical degradation of the insulating materials resulting in cracks, holes or other damage to the integrity of the insulating boundary. After this initial mechanical degradation, moisture, contaminants, or continued mechanical degradation results in electrical failure. The initial degrading effects of radiation on motor insulating system materials are: *increased brittleness and hardness, shrinkage and weight loss, and decreased flexibility*.

The information presented in this section indicates that most of the materials used in premium motor insulation systems are not significantly degraded by the radiation conditions occurring in radiation-only applications. Based on utility surveys, the maximum accident radiation dose for outside containment equipment is generally below $5x10^7$ rad ($5x10^5$ Gy)[2]. This required dose is below the threshold damage dose for virtually all the insulating materials used in premium rewind systems containing materials with high thermal ratings (e.g., Class F or H). Based on this guide's detailed evaluation of the insulating materials, motor lead wire insulation is typically the most radiation sensitive material in the insulating system.

7.2.1.1 Threshold and Service Limits.

Threshold: EPRI [2] provides the following definition of a material radiation damage threshold: *The lowest radiation dose which induces permanent changes in a measured property(s) of a material; also, the first detectable change in a property of a material due to the effect of radiation.* This section uses a slightly modified view of the radiation damage threshold. First, the detectable change should be in a material property that is relevant to a particular application. As discussed below, this guideline uses selected mechanical properties to determine radiation resistance of insulating materials. Secondly, small changes in a property can be embraced by the threshold concept. In the subsequent material evaluations, property changes of less than 10% are consider to be threshold effects. When a material is exposed to radiation levels at or below its threshold dose, the radiation exposure produces insignificant differences in the material's performance or capability as part of the motor insulating system. If the motor insulating system is exposed to radiation levels that are below the threshold limits of the insulating system materials, then the motor is essentially in a mild environment.[3]

It could be argued that at or below these doses, radiation qualification and a qualified life need not be established since radiation is neither a significant aging or accident environmental stress mechanism. Since such motors still require qualification per 10 CFR 50.49, age related degradation must be considered. Under

[2] 1 Gy = 100 rad

[3] In a radiation-only environment, radiation is the only environmental stressor significantly different than normal. If the radiation level is below the threshold damage level for the insulating materials, then it has an insignificant effect on performance.

these conditions, radiation would not influence ultimate capabilities and performance limits would be based on other operational and aging stressors (e.g., thermal life). A thermally-based qualified life should be established based on the system's thermal rating and service conditions. A well supported maintenance/surveillance program in conjunction with a good preventive maintenance program would suffice to insure the motor remains qualified throughout its installed life for the installed conditions. Such a program should include periodic motor evaluations to insure that unexpected degradation has not occurred. EPRI in [3] provides utilities with guidance for establishing an effective motor maintenance program through planned motor maintenance efforts.

Service Limit: A material's *Service Limit* is more difficult to define since it is generally based on application and final use. Most publications summarize material radiation tolerance by identifying two or three regions of radiation effects. Table 7.1 identifies several ways of categorizing these radiation effects regimes.

Table 7.1
Three Methods of Describing Radiation Degradation Categories

Method	Least Damage	More Damage	Most Damage
A	Incipient to mild	Mild to moderate	Moderate to severe
B	Nearly always usable	Often satisfactory	Not recommended
C	threshold - 25% property change	25% - 50% property change	> 50% property change

For qualification purposes, these rather vague categories can be difficult to apply. The initial inclination may be to exclude any materials that may experience more than 50% property damage. Yet extensive LOCA qualification testing of various types of electrical equipment, particularly cables, has demonstrated that materials with severe thermal and radiation damage have performed well during subsequent LOCA steam simulations. Sandia in [4] successfully LOCA steam tested cables which had little or no remaining flexibility (i.e., elongation-at-break was degraded by more than 90%) prior to the LOCA simulation due to thermal and radiation exposures.

In an effort to define meaningful radiation service limits for motor insulating system materials, this guide defines service limits in two ways. The first method of defining a service limit is based on a 50% reduction in those physical properties most meaningful to the application. This is a broadly applied, conservative, end-point criterion used by ASTM, IEEE, UL, IEC, and other standard writing bodies.

For example, elongation-at-break is recognized as the most appropriate physical property for determining thermal and radiation service limits for low-voltage cable insulating materials. Many cable publications, standards, and other documents establish 50% absolute elongation or 50% relative elongation (i.e., e/e_o=50%) as an arbitrary but conservative end-of-useful life criterion for cable insulating materials.

A second method establishes radiation service limits based on degradation or property end point criteria that are consistent with those used to establish thermal classifications. For example, an appropriate limit for resins could be developed by considering the criteria used to define resin thermal classes and the impact of thermal aging on resin properties. The two most common test methods used to establish the thermal class of a resin are the twisted pair dielectric strength test (ASTM 3251) and the helical coil bond strength test (ASTM D3145). The dielectric strength test uses a voltage of approximately 300 V/mil for the wire insulation - resin composite. However, since the wire enamel provides much of the samples' dielectric strength, this test is not as meaningful as the bond strength test. The end point criterion for the bond strength test is a break strength of 5 lb. or less at ambient temperatures. Typical bond strengths for unaged samples of polyester and epoxy resins range from 30 - 55 lb. The initial bond strength of an often used silicone resin (Dow Corning 997) ranges from 9 to 25 lb., based on cure cycle. For these resins, the ASTM D3145 end point criterion for thermal classification (5 lb) represents a *relative* bond strength range of 9% - 17% of the unaged resin's strength. This suggests that a conservative end point criterion for radiation resistance of *unaged* resins could be established as 20% of either initial bond strength or some other resin strength property.

7.2.1.2 Thermal Aging Considerations. Neither of the service limit approaches described above considers the impact of non-radiation aging mechanisms (principally thermal aging) on the material's capabilities. Thermal aging and radiation have similar, but not identical, effects on insulating materials. Because of these similar effects, most materials after significant thermal aging are less tolerant of radiation. Similarly, after significant radiation, materials are less tolerant of extended thermal exposures. Thermal aging must be considered when radiation service limits are established. The following approaches are proposed to address thermal aging when radiation-only harsh qualification is based on analysis and partial test data.

To illustrate, it is assumed that the rewind insulation system has a Class H (180°C) or better thermal rating. The average extrapolated life of a Class H system is at least 20,000 hours at the rated temperature. Using a conservative Arrhenius activation energy of 1.0 eV, this extrapolates to almost 55 years at the Class B operating temperature limit of 130°C. An activation energy of 0.9 eV lowers the projected thermal life at 130°C to 40 years (350,400 hours).[4] This indicates that a 40 year extrapolated thermal life, including margin, can be easily justified when any system with a Class H or better thermal rating is applied to a continuously operating Class B rated motor. A 40 year life might also be justified for systems with a Class F rating if the motor was not continuously operated at Class B thermal limits or operated at a lower temperature.

For motors not normally operating (e.g., MOVs and continuous duty motors normally in standby), the insulating system temperature is ambient temperature (e.g., 40°C) for the vast majority of its installed life. These motors only experience operating temperatures for a relatively small percentage of time. This guideline maintains that such motors are exposed to insignificant thermal aging during their installed life and, consequently, radiation service limits need not consider the effects of thermal aging. For the purposes of this guideline, any motor with a total operating time of less than 100 hours per year is considered to experience insignificant thermal aging during its installed life. The basis for this conclusion is as follows. Thermal aging at 130°C (Class B operating temperature) occurs 1700 to 4000 times more quickly than at 40°C, based on the Arrhenius relationship and activation energies of 0.9 eV and 1.0 eV. This suggests that any motor with a total operating time per year in excess of 2 - 5 hours will experience most of its thermal degradation during operation. Motors with operating times less than 2 - 5 hours per year will experience most of their thermal degradation when in standby. The relative amount of thermal aging during standby becomes insignificant as operating times extend beyond 2 - 5 hours.[5] If a motor operates 100 hours per year at Class B thermal limits then its extrapolated thermal life would be in excess of 3500 years.[6] Using Arrhenius and based on these extrapolations, 40 years of thermal aging is insignificant. For these motors conservatively selected radiation service limits can be applied without considering the possible effect of thermal aging on radiation resistance.

For motors with operating times in excess of 100 hours per year, the effects of thermal aging should be considered when establishing radiation service limits. In

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4 The less conservative 10°C rule would predict a life of 73 years.

5 Hypothetically, the extrapolated thermal life of a Class H insulated motor operating for 5 hours per year at 130°C and exposed to 40°C ambient conditions is over 30,000 years using an activation energy of 0.9 eV.

6 When the extrapolated life at 130°C is 350,400 hours and the operating time is 100 hours per year then the life is 3500 years (i.e., 350,400 / 100).

cases where the insulating system materials are exposed to radiation dose levels below their stated thresholds, then radiation degradation is insignificant and service life can be based on the system thermal aging data (e.g., at least 40 years at 130°C for Class H systems). In cases where material radiation testing included simulation of appropriate levels of thermal aging, the service limit from the radiation testing data can be directly used.[7] In other cases, radiation-only harsh qualification using analysis should take into consideration anticipated levels of thermal aging.

The following process is suggested for evaluating the thermal aging of materials exposed to doses above their threshold values. The overall qualification process for radiation-only qualification is illustrated in Figure 7.1. The process steps involved in establishing a qualified life are performed after determining that the materials are suitable at the required radiation dose level. These steps are:

1. Define Qualified Life based on Service Conditions and Thermal Class. This step determines the system's thermal classification based on existing life test data. EPRI Report No. TR-103585 [54] contains an extensive discussion on system thermal classifications and the use of existing data to determine the system class. Based on motor design and environments, develop an *initial* extrapolated thermal life (qualified life) for the system. This involves determining normal ambient conditions, estimating motor operating time, average load, and heat rise at anticipated load. Arrhenius type calculations are typically used to extrapolate thermal life from the system thermal classification data.
2. Determine if the insulating materials are subjected to doses above or below each material's threshold radiation damage dose. For doses at or below the threshold, the extrapolated thermal life can be defined as the system's qualified life.
3. For required doses above a material's threshold dose level, adjust the material or system thermal qualified life value to account for degradation occurring due to radiation beyond the threshold dose.
4. Document the analysis, including the qualified life estimate and data sources, and establish a maintenance/surveillance program to address unanticipated in service degradation using [5].

7 For example, certain motor lead wires may have been included as part of a insulating system qualified for both aging and LOCA accident conditions.

The following example describes how resin qualified life might be adjusted using the helical coil bond strength test (ASTM D3145) criteria. It was noted earlier that a reasonable end point criterion for thermal or radiation aging of resins could be established as 20% of either initial bond strength or some other resin strength property. Figure 7.2 illustrates that the change in bond strength with *thermal* exposure for several types of resins is reasonably represented by a straight line [6]. Similar data is presented in [7].

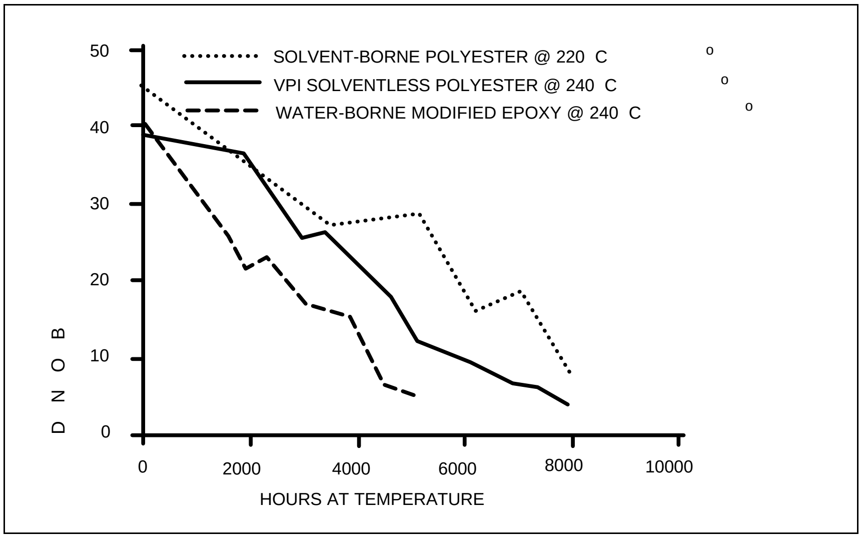


Figure 7.2
Bond Strength vs. Time for Several Types of Motor Resins

Many of the solventless, and solvent / water based polyester and epoxy resins in current use have thermal ratings of 180ºC or higher. Dow Corning 997 (a silicone resin) has a thermal classification of 220ºC. We can assume for plant rewinds that these resins are used in Class B systems with operating temperatures below 130ºC. Using Arrhenius and an activation energy of 1 eV, a Class H resin would be qualified for roughly 55 years at a 130ºC continuous operating temperature. Since bond strength decreases linearly with time and 20% retention is the end-of-life point, the bond strength must decrease roughly 1.5% per year to reach the end-of-life point in 55 years. For motors operated only 50% of the time, this would suggest a bond strength decrease of roughly 30% due to thermal aging over a 40 year period (0.75% / yr x 40 yr). The resin's bond strength would still exceed the 20% end-of-life point if accident radiation did not degrade resin bond strength an additional 50%. Figures 7.3 and 7.4 indicate that linear reductions in resin strength typically occur when plotted against the log of radiation. Although the degrading effects of radiation after thermal aging may differ from those experienced by unaged resins, given the other conservatisms in the evaluation, it can be reasonably assumed that the dose at 50% strength retention adequately addresses thermal aging effects for this periodically operated motor. If the motor operated continuously for 40 years at the Class B temperature limit, the allowable bond strength degradation due to radiation would be limited to roughly 20%. For this motor's insulating materials, the dose at 80% strength retention could be used as the service limit.

This discussion illustrated how existing thermal and radiation data can be used to estimate an insulating system's qualified life. In addition to this life estimate, periodic maintenance and inspection activities should be implemented to confirm lack of significant insulation degradation during the motor's installed life.

7.2.2 Insulating Material Radiation Damage Evaluations

Table 7.2 summarizes the threshold and service limits described in the material-specific evaluations which follow. The threshold limits include some mild damage data (i.e., less than 10% loss in relevant property). Unless otherwise noted, the service limit doses are based on at least 50% retention of a relevant mechanical property. Materials can experience significantly greater losses in mechanical properties and still function adequately. However, the 50% retention criterion is selected to maintain consistency with other guidance (e.g., IEC 544) and to provide conservatism when addressing possible differences in materials within a generic class. The table indicates that cable lead wire materials are the most susceptible to radiation degradation. Except for these lead wires and possibly Dacron / Mylar, the other listed insulating materials are virtually unaffected by radiation levels of $5x10^7$ rad.

The threshold and service limits defined in Table 7.2 were selected, using existing radiation test data, to conservatively represent lower limits for materials within a given class. The actual radiation capabilities of the specific materials used in motor rewinds can be significantly better. For example, the vast majority of epoxy resin formulations have a dose threshold of roughly 10^9 rad, yet, $5x10^7$ rad is proposed in Table 7.2 to encompass the test data for a few atypical resin formulations. Similarly, a service limit of $5x10^7$ rad is suggested for silicone lead wire even though several motor qualification tests have demonstrated the suitability of Belden silicone lead wire after thermal aging, $2x10^8$ rad, and a LOCA steam exposure.

Table 7.2
Threshold and Service Limits for Typical Motor Insulating System Materials

Material	Threshold (rad)	Service Limit (rad)
Epoxy resin	$5x10^7$	$2 - 5x10^8$
Polyester resin	$5x10^7$	$2 - 5x10^8$
Silicone resin	$2x10^8$	not established*
Silicone lead wire	10^6	$2-5x10^7$
EPR / EPDM lead wire	$5x10^6$	$5x10^7$
XPLE lead wire	$5x10^6$	$5x10^7$
Magnet wire - fibrous	$5x10^7$	10^8
Magnet wire - polyimide film	10^9	not established*
Magnet wire - modified polyesters**	10^9	not established*
Nomex papers and fibers	$2 - 4x10^8$	$1.6x10^9$
Mica paper tapes***	$>10^8$	not established*
Fiberglass fibers	$>10^9$	not established*
Dacron fibers	$2x10^7$	$5x10^7$
Mylar film	$3x10^7$	10^8
Kapton film	$2x10^8$	$>10^9$
PSA tapes (assembly aid)	not defined	10^8****
Sleeving (rubber coated)	based on coating	based on coating
Sleeving (uncoated fiberglass)	see fiberglass fibers	see fiberglass fibers

Notes: * Service limits were not established for materials with high threshold doses.
** Includes polyester-imide, polyamide-imide, polyester amide imide, with / without topcoats
*** Based on resin and backing materials, higher thresholds may exist. See text.
**** Adhesive limit only. Backing material values should be based on relevant material.

7.2.2.1 Gas Evolution. IEEE 334-1994 suggests that analysis of material radiation data should consider the impact of radiation induced gas evolution in insulating materials. Data on radiation-induced gas evolution are not as extensive as data on mechanical or electrical effects. Information on gas evolution is typically expressed using a G value, with one G defined as the number of chemical changes produced when 100 eV of energy is absorbed by a polymer. The gas composition and amounts will vary based on the irradiated polymers. In [8] G values are reported for a range of different epoxy resins and curing agents (hardeners). The major evolved gases are hydrogen, carbon dioxide, carbon monoxide, ethane, and methane. The combined G values for a particular formulation ranged from roughly 0.1 to 0.6. Table 7.3 extracted from [9] presents similar G data for a range of other polymers. Those with relatively high G values, such as polyethylene, nylon, and polyvinyl alcohol, are not generally used in motor coil insulating systems.

Table 7.3
Relative G Values for Gases Produced During Polymer Irradiation

Polymer	G Value	Gas Composition
Polyethylene	2.1	H_2 (95.5%); C_3H_8 (3.4%)
Polystyrene	0.03	H_2 (100%)
Polyacrylonitrile	0.4	H_2 (24%), NH_3 (8%), C_2N_2 (67.5%)
Polyvinyl chloride (PVC)	0.3	HCl
Polyvinyl alcohol	1.7	H_2 (95%), CO (4.3%)
Polybutadiene	0.2	$H_2 + CH_4$ (100%)
Polymethyl methacrylate (PMMA)	1.3	H_2 (18%), CH_4 (15%), CO (36%), CO_2 (25%), C_3H_8 (5.3%)
Polyisobutylene	0.87	$H_2 + CH_4$ (95.5%), $CO_2 + C_3H_8$ (4.5%)
Polytetrafluoroethylene (Teflon PTFE)	0.03	$CO + CO_2$
Polyethylene terephthalate (Mylar, PETP)	0.15	
Polyamide (Nylon)	1.1	
Styrene butadiene (SBR)	0.15	
Polyurethane rubber (PUR)	0.7	
Polysiloxane (silicone)	0.6	
Polychloroprene (Neoprene)	0.1	

G-value = number of product molecules formed or reactant molecules consumed per 100 eV of energy absorbed by the polymer. The G-values listed here are for the production of all gases listed.

Gas evolution has the greatest potential for degrading insulating systems when gas production rates within the insulation system exceed the gas diffusion rates out of the insulation. Should this occur, gas accumulation could produce internal pressures that may crack or rupture the insulation. Gas production rates are proportional to radiation dose rates. Peak gamma dose rates for outside containment equipment exposed to LOCA recirculation fluids should remain well below 10^6 rad / hr during most of the accident. These accident dose rates are substantially below the dose rates used during virtually all the material radiation testing. For example, CERN conducts much of its material testing at dose rates of 10^7 rad / hr and higher.[8] This suggests that the lower LOCA dose rates should not result in gas related degradation. However, the impact of gas evolution on fabricated coils may not be fully represented by comparatively small, thinner material test samples. Fortunately, magnet coil operating experience at facilities

8 CERN is a European organization for nuclear research located outside Geneva.

like CERN, Fermilab and the industry's motor qualification testing experience indicates that gas evolution is not a concern for coil insulating systems at the accident doses and dose rates experienced in radiation-only harsh plant areas. Additional supporting information is provided in [8] where discussions focus on the impact of sudden gas formation in epoxy resin systems during heat-up to ambient temperatures from cryogenic temperatures.[9] That report notes that the sudden release of gas formed after cryogenic irradiation could cause degradation, but the same volume of gas gradually diffuses out of the material without causing significant damage during ambient temperature irradiation. Although the report concludes that existing data do not fully resolve gas related concerns for epoxy resin coil systems at cryogenic temperatures, it does not identify such a concern for irradiation at ambient or higher temperatures. Finally, no reference to gas-related coil degradation was identified in any of the motor qualification reports reviewed during development of this guideline.

7.2.2.2 Dip & Bake and VPI Resins. The post-winding Dip & Bake and Vacuum Pressure Impregnation (VPI) resin treatments provide increased structural and dielectric strength to the winding and increase its resistance to external environmental contaminants, including moisture. The vast majority of the resins used for these treatments is classified as polyester, epoxy, or silicone. These resins are considered thermosets and exhibit a high degree of crosslinking that is achieved during oven curing. However, these resins are also used as a constituent in other insulating system components. The fibrous coverings used on rectangular wires, fiberglass, woven polyester, or combinations (e.g., Daglas) are typically treated with polyester, epoxy, or silicone resins to help bind the coverings to the conductor. Similarly, all mica and mica paper products contain a resin binder. Many insulating tapes and banding products contain significant amounts of B-stage (partially cured) resins. Finally, resins are elements of the rigid laminates that are used as wedges/top sticks and phase separators in many form-wound motors. The following radiation resistance discussion focuses on post-winding treatment resins. However, the general discussion has applicability to the polyester, epoxy, and silicone resins used as constituents in other insulating system components.

There is virtually universal agreement that radiation affects physical/mechanical properties of resins and other organic materials long before there are significant electrical effects. A review of the relevant literature confirms that physical/mechanical properties should be used to establish the radiation resistance of resin products. The following discussions focus on properties such as elongation

9 Fusion system magnets must operate at cryogenic temperatures but will periodically warm-up to near ambient conditions.

at break, flexure, tensile, and bond strengths. Since these thermosetting resins do not exhibit the flexibility of elastomers, the strength categories (e.g., bond strength and flexure strength) are widely used to classify radiation effects.

The radiation resistance literature on resins describes both reinforced (laminates or composites) and non reinforced (neat) resins. The physical properties of composites is a function of the resin, reinforcing material, and the bond between them. Generally, the radiation resistance of the composites is superior to that of the non reinforced resin.

Epoxy Resins: Extensive data has been developed describing the radiation resistance of epoxy resins at high levels of radiation. The principal work has been done in support of constructing reliable magnet systems for high-energy particle accelerators such as those used at CERN and Fermilab. Other data has been developed by organizations involved in the development of magnet systems for fusion reactors. An extensive summary of existing data on the radiation resistance of epoxy and polyimide resin systems has recently been published in support of next generation fusion device toroidal field magnets [8]. While this document is extensively referenced in this discussion of epoxies, it should be recognized that it reviews and evaluates the data from over 130 other publications which report on the radiation stability of epoxy resins.

The radiation resistance of epoxy resins can vary based in part on the chemical structure of the base epoxy polymer and the composition and amount of hardener, accelerator, dilutent, and other additives. The most commonly studied epoxy polymer systems have included Diglycidyl Ether of Bisphenol A (DGEBA), Polyglycidyl Ether of Phenol Formaldehyde Novolac (EPN or Novolac), Tetraglycidyl Diaminodiphenyl Methane (TGDM), and Cycloaliphatic resins.

Simon in [8], conducted an extensive review of gamma, beta (electron), and neutron radiation exposures conducted at both ambient and cryogenic temperatures. The data for cryogenic exposure and property tests are excluded from this review since these conditions are not representative of power plant motor applications. Similarly, the neutron and beta exposure data were excluded from the review, since gamma is the only significant radiation for outside containment radiation-only harsh conditions. Further excluded was much of the mixed gamma/neutron exposure data, particularly when the neutron percentage exceeded approximately 5% of the total radiation. These data are excluded, based on the data presented in [8], since damage at cryogenic temperatures and from neutron radiation tends to be more severe when compared to room temperature gamma exposures. Even with these exclusions, [8] contains extensive data for the DGEBA epoxies which are typically used for motor coil treatment. The literature reviewed in [8] contains information on the relative differences in the radiation resistance of neat and reinforced (principally with fiberglass) resins. Data are also presented for the radiation resistance of mica paper products impregnated with epoxy resins. Some of the data even compares the impact on radiation resistance due to different fiberglass surface treatments (e.g., heat cleaned, caramelized, and silane coupling agents). The following summarizes general conclusions.

Table 7.4
Relative Radiation Resistance of Epoxy Resin Polymers

↑ increasing radiation resistance	
	TGDM
	EPN
	CYCLOALIPHATIC
	TGPAP
	DGEBA

Based on the literature review, the general order of radiation resistance of resins fabricated from different types of epoxies is presented in Table 7.4. Although the DGEBA resins are generally considered to be inferior to most other resin types studied, DGEBA is the base polymer for virtually all solvent-based, water-based, and solventless epoxy resins used for commercial motor coil treatments. Consequently, the remaining discussion focuses on the radiation resistance of DGEBA based resins. Since the radiation resistance of DGEBA systems is generally inferior to the other resin systems that were studied, the following data should conservatively apply to these other epoxy resin systems. Variations in radiation resistance of different types of epoxies, curing agents, and dilutents tend to follow the rules listed in Table 7.5:

Variations in the type and amount of hardener (curing agent) affects both the thermal and radiation resistance of the base epoxy polymer. The most important classes of hardeners used for curing coil treatment epoxy resins are the cycloaliphatic amines, aromatic amines, acid anhydrides, Lewis acids and imidazoles. The acid anhydrides are considered the most popular. The Lewis acids and imidazoles (e.g., BF3MEA) are generally used as accelerators. Often mixtures of selective hardeners are used to develop desirable processing and cured resin characteristics. Like the base epoxy polymers, hardeners containing ring structures generally create cured epoxies with improved thermal and radiation resistance. For example, aromatic amine hardeners (e.g., DDS, MPD, and DDM) are significantly superior to aliphatic amines (e.g., TETA). Importantly, the same hardeners tend to increase both thermal and radiation resistance. Consequently, the higher temperature class (e.g., Class H) epoxy resins should generally exhibit better radiation resistance when compared to lower class (e.g., Class B) resins. Different types of hardener have varying effectiveness based on the type of base epoxy resin.

Table 7-5
Effect of Polymer Structure on Relative Radiation Resistance

1.	Aromatic compounds are more stable than aliphatics, because the resonating ring structures serve as an energy sink. The radiation's excitation energy can be slowly dissipated to thermal energy without rupture of bonds.
2.	Substituted aromatics are more stable than unsubstituted compounds, because the side chains provide an easier way for the energy to flow into the aromatic ring.
3.	Branched chains are less stable than straight chains. If the polymer contains two side chains bound to one carbon atom, its degradation will increase under irradiation, due to the presence of the quaternary C atom.
4.	Small molecules are more stable than large molecules, because a small volume per molecule means less energy absorption per molecule under radiation.
5.	Saturated molecules are more stable than unsaturated ones and terminal unsaturation is less stable than an internal one.
6.	The general order of decreasing radiation stability for compounds is as follows: aromatics, aliphatics, ethers, alcohols, esters, and ketones.
7.	Acidic compounds are less stable than basic ones since acids contain the -C-O- linkage which is particularly susceptible to radiation damage.
8.	Very rigid molecular structures are more stable; flexibility in the main or side chains decreases radiation resistance.

Data for unreinforced (neat) DGEBA resins with various hardeners are presented in Figure 7.3. Figure 7.3a is particularly relevant to VPI solventless epoxy resins, since DGEBA with anhydride hardeners is the most popular resin system for VPI motor winding processing. Except for the TETA hardener, the flexure strengths are virtually unaffected for doses up to 10^9 rad.[10] TETA is a room temperature aliphatic amine hardener not used for motor coil epoxy resins.[11] Figure 7.4 illustrates the radiation resistance of fiberglass reinforced (FGR) DGEBA resins and several hardeners. Although differences exist based on hardener, the flexure strength of these DGEBA epoxies is virtually unaffected for doses up to 10^9 rad. The only exceptions are the MD and AEP hardeners. Like TETA, the MD and AEP hardeners are aliphatic amines and are not used in coil treatment epoxy resins. However, even resins utilizing these hardeners will remain serviceable at doses below 10^8 rad. Superimposed on each of the Figure 7.3 and 7.4 graphs are the threshold ($5x10^7$ rad) and service limit ($2 - 5x10^8$ rad) doses proposed for epoxy resins.

10 In these figures, radiation is expressed in Gray (Gy).. The conversion used is: 1 Gy = 100 rad.

11 The aliphatic amine hardeners produce resins with relative poor high temperature (e.g., > 120°C) properties. Consequently, they are not used in Class F or higher epoxy resin systems.

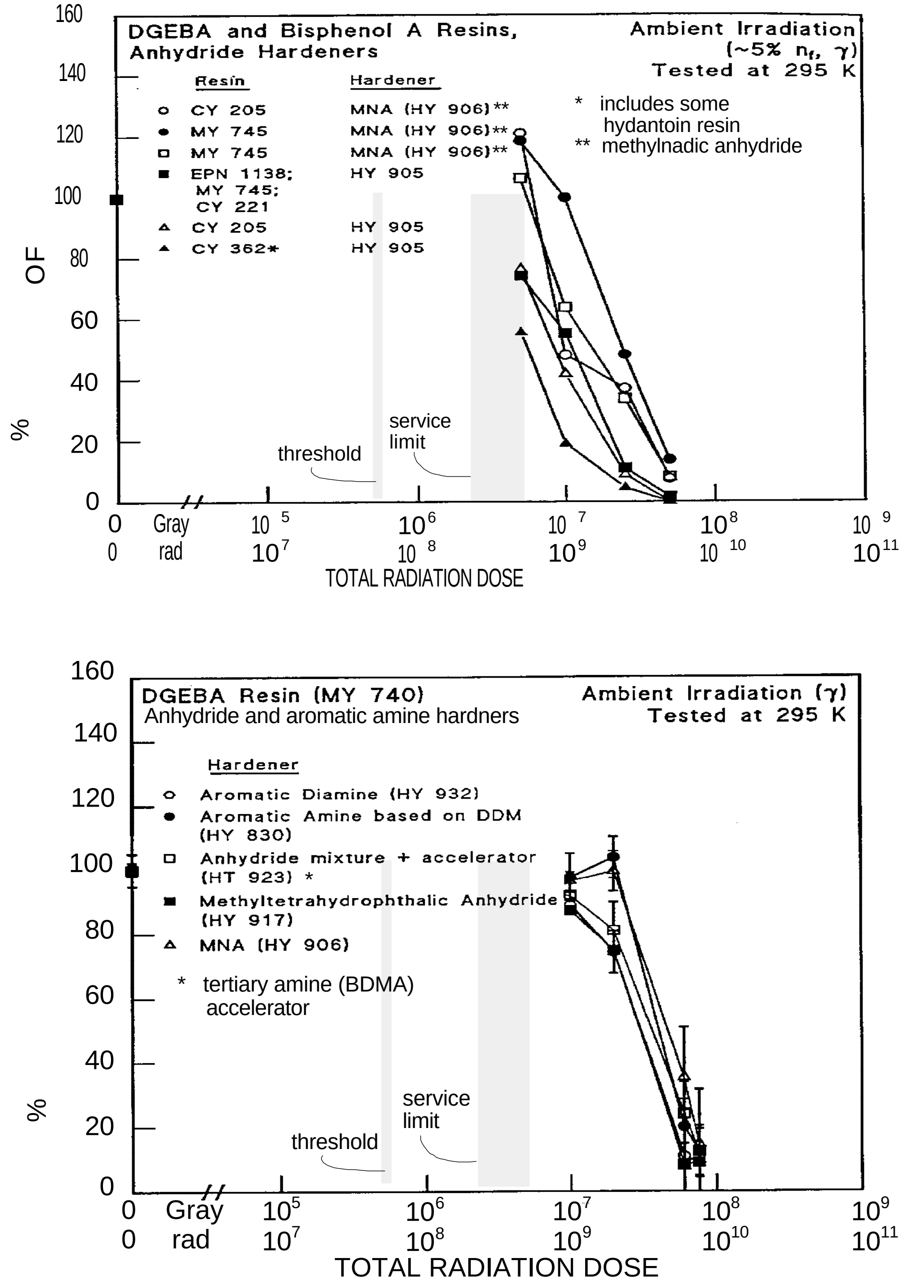


Figure 7.3a & 7.3b
Effect of Hardener on Radiation Resistance on DGEBA Resins

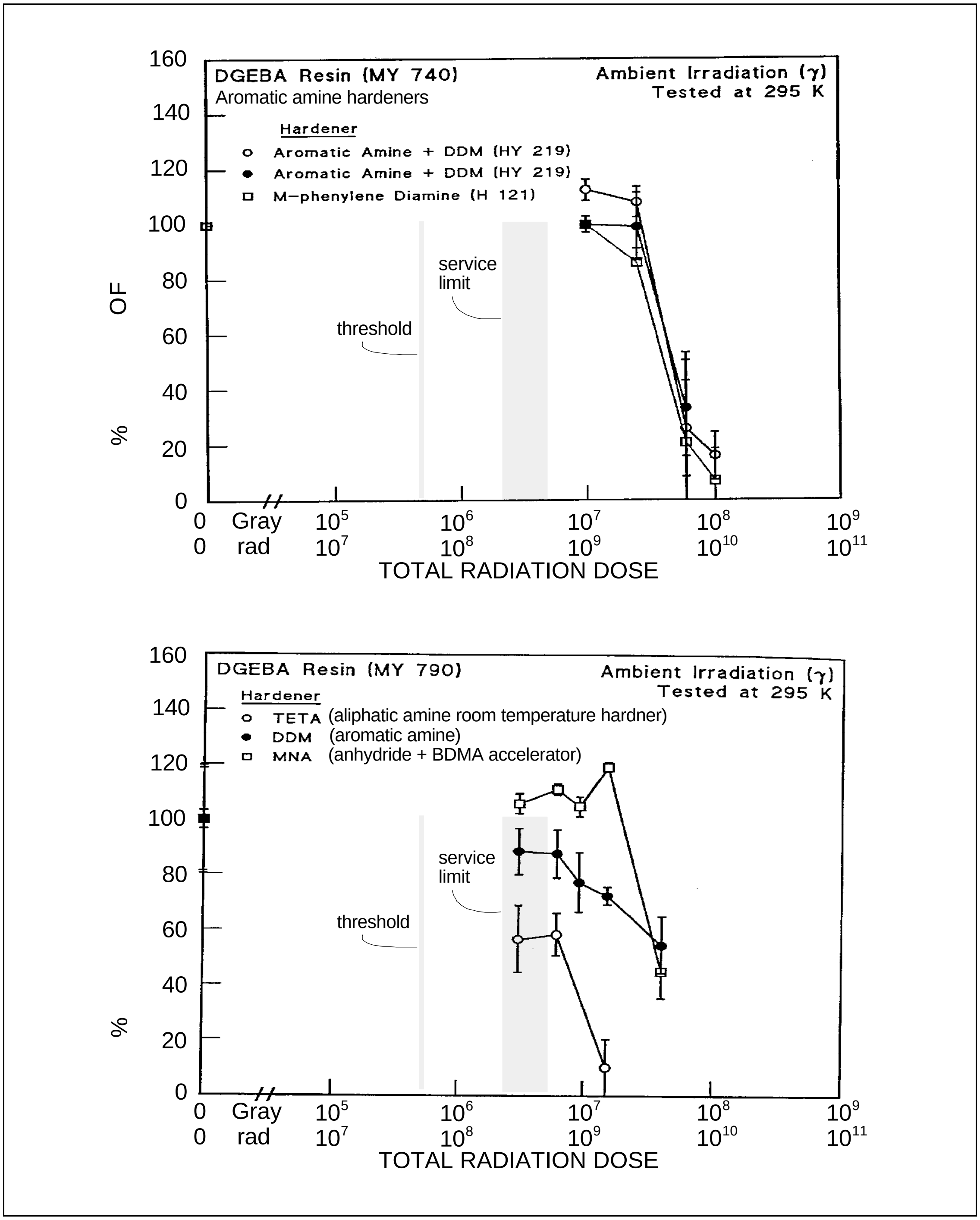
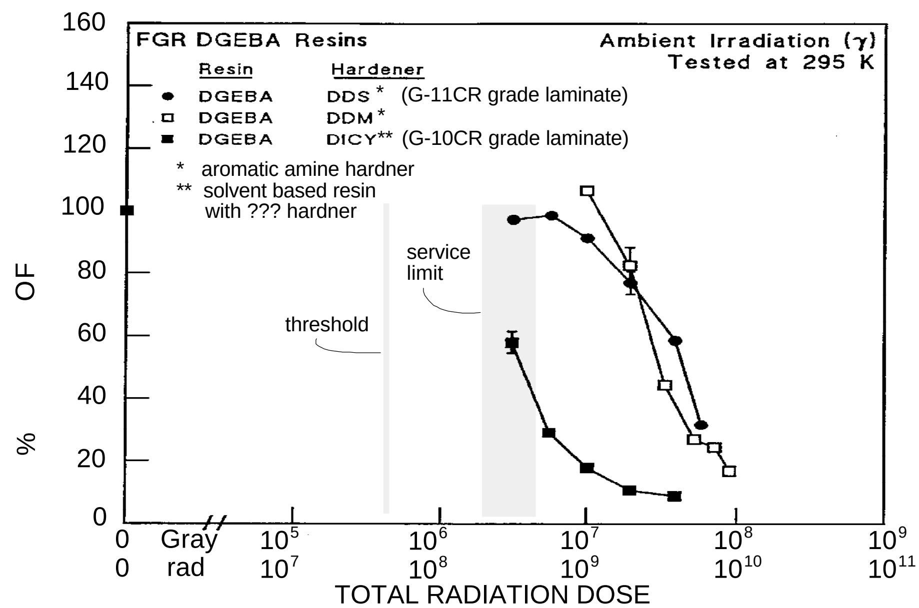


Figure 7.3c & 7.3d
Effect of Hardener on Radiation Resistance on DGEBA Resins



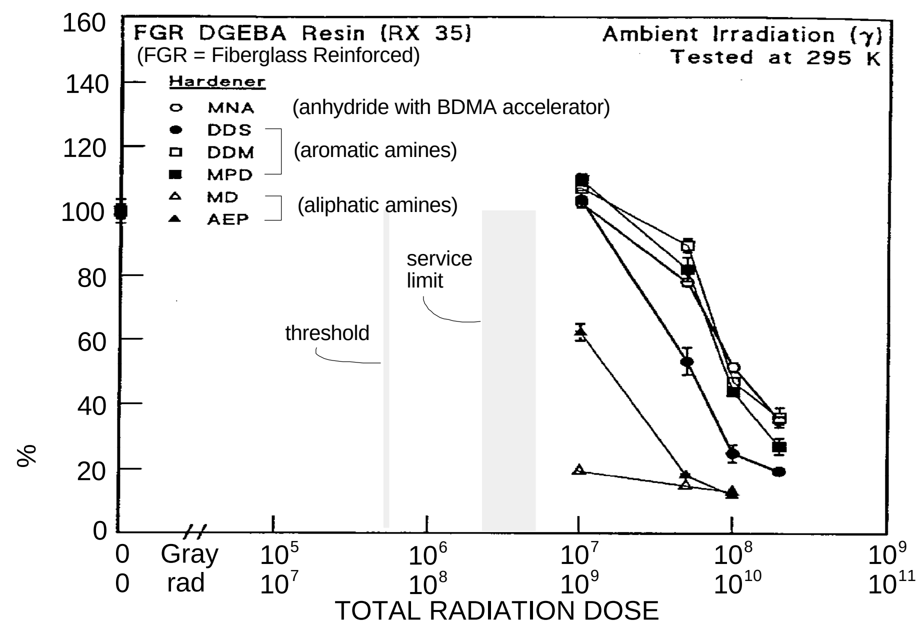


Figure 7.4a & 7.4b
Effect of Hardener on Radiation Resistance on Fiberglass Reinforced (FGR) DGEBA Resins

The epoxy formulations addressed by Simon are all apparently solventless epoxies. However, other data sources suggest that the radiation resistance of solvent and water-borne epoxy resins should be similar to the values cited above for solventless resins. In [10] one manufacturer examined the radiation resistance of their epoxy, polyester, and silicone resins, varnishes, and compounds. The total gamma dose was $3.6x10^8$ rad at an exposure rate of 10^7 rad / hr with temperatures below 200°F. Different properties (e.g., hardness, elongation, tensile strength, helical coil bond strength, weight loss, dielectric constant, power factor and volume resistance) were measured based on the type of specimen. The electrical properties and hardness for all the specimens were largely unaffected by the exposure. Three solvent-borne Bisphenol A epoxies (one air-dried and two varnishes) were included in the test program. The tensile strength and elongation of the air dried epoxy improved after irradiation. The helical coil bond strength of the two varnishes, on several types of magnet wire enamel, remained within 75% of the original values. With one exception (on an ML enamel wire) all helical coil bond strengths were within 85% of original values.[12] No water-borne epoxy varnishes were tested. However, as outlined below under polyesters, two polyester water-borne varnishes were tested with excellent results. These data strongly suggest that the radiation resistance of solventless epoxies can be reasonably applied to solvent and water-borne epoxies.

In [11] the results of long-term natural irradiation at the CERN high-energy particle accelerators is compared with the accelerated high-dose rate tests for selected reinforced and unreinforced epoxy resins. The long-term natural radiation reached doses up to $5x10^8$ rad at dose rates varying between 0.1 to 65 Krad / hr. The report concludes that the dose rate effects observed for some thermoplastic and elastomeric materials do not exist for the thermosetting resins used for the CERN magnets. For the samples tested, the worst case flexural strength only decreased to approximately 75% of the pure resin's initial value. Similar results were obtained in [12] which compared two sets of samples. The first was irradiated at high dose rates excluding oxygen; the second involved a low dose rate (1.4 Krad / hr) in air. For the epoxy samples, there was no dose rate influence up to the maximum tested dose of 10^8 rad. Based on this information, dose rate effects are not significant for epoxy resins used in motor insulation systems.

The data presented in [8] also included several rigid epoxy laminates, particularly the G-10 and G-11 laminate grades. Figure 7.4 presents typical data for two rigid laminates (G-11CR and G-10CR) which indicates capabilities similar to the DGEBA resins presented in other figures.[13]

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[12] The bond strengths for the epoxy varnishes on the ML wire were 75% - 84% of the original values and may have been due to solvent degradation of the magnet wire enamel..

[13] The DICY hardener used in the G-10CR laminate is a solvent-based aliphatic amine.

Based on this information, a very conservative threshold gamma radiation dose value of $5x10^7$ rad is established for solventless, solvent-borne, and water-borne epoxy resins. Similarly, conservative service limits of 2 - $5x10^8$ rad are established based on retention of at least 50% tensile, bond, or flexural strength.

Polyester Resins: Information provided by one resin manufacturer contains electrical and bond strength data for several epoxy and four polyester VPI resins after samples were subjected to $1.4x10^8$ rad [13]. All the polyester resins were catalyzed with peroxide but used three different viscosity reducers, T-Butyl Styrene, Vinyl Toluene, and Diallyl Phthalate. One was thixotropic. Dissipation factor was provided for all the resins; helical bond strength data and dielectric strength data only existed for two of the polyesters. The dissipation factor data for cured disks, tabulated for various temperatures from room temperature up to 170ºC, indicates insignificant changes for all the polyester resins at the tested dose of $1.4x10^8$ rad. The bond strength and dielectric strength data are presented in Table 7.6. The data indicate insignificant changes in mechanical and electrical properties after the $1.4x10^8$ rad exposure. Room temperature bond strength and dielectric strength at $1.4x10^8$ rad remained with $\pm$10% of the pre-exposure values. Interestingly, the 155ºC bond strength values actually improved.

Table 7.6
Effects of Radiation Exposure on Two Polyester VPI Resins

Resin Type	Exposure (rad)	Helical Coil Bond Strength (lb.)		Twisted Pair Dielectric (kV)
		Room Temp.	155ºC	
Polyester A	None	32.4	5.8	9.5
	$1.4x10^8$	31.0	7.0	10.5
Polyester B	None	30.4	6.5	10.7
	$1.4x10^8$	27.6	8.3	9.6

Polyester A: T-Butyl Styrene viscosity reducer, thixotropic
Polyester B: Vinyl Toluene viscosity reducer, non thixotropic

Helical coil bond strength, dissipation factor (solventless only), and dielectric strength data on both a solvent-borne oil-modified and a solventless polyester resin are reported in [14] after exposure to $1.2x10^8$ rad. Dielectric and bond strength data are presented in Table 7.7. The strength data were virtually unchanged by the exposure. The solventless resin's dissipation factor data, measured using both cured disks and fabricated form-wound coils, were virtually unaffected by the exposure.

Table 7.7
Effects of Radiation Exposure on Two Polyester VPI Resins

Resin Type	Exposure (rad)	Helical Coil Bond Strength (lb.)			Twisted Pair Dielectric (kV)
		25ºC	105ºC	155ºC	
Solvent borne	None	41.2	2.2	1.0	14.6
	$1.2x10^8$	47.2	1.9	1.8	13.8
Solventless	None	32.4	17.2	5.8	9.5
	$1.2x10^8$	31.0	17.0	7.0	10.5

Similar supporting data on several polyester resins are presented in [10] where samples were subjected to a radiation level of $3.6x10^8$ rad with subsequent mechanical and electrical tests. Helical coil bond strength values, based on tests with four types of magnet wire enamel, for the two water-based and three solvent-based polyesters (two phenolic-modified and one unmodified), were virtually unaffected by the radiation. In fact, most of the bond strengths improved after irradiation.

Based on this information, a conservative threshold gamma radiation dose value of $5x10^7$ rad is established for solventless, solvent-borne, and water-borne high temperature (i.e., Class F or better) polyester resins. Similarly, conservative service dose limits of 2 - $5x10^8$ rad are established based on retention of at least 50% tensile, bond, or flexural strength.

Silicone resins: The physical characteristics and radiation resistance of silicone based thermosetting resins are substantially different from the silicone elastomers used as wire insulating materials. The silicone resins are highly crosslinked, physically stronger, exhibit lower elasticity, and have greatly improved radiation resistance when compared to silicone elastomers. The higher temperature rated silicone resins typically used for motor insulating systems are based generally on methylphenylsiloxane. Elasticity and temperature resistance both increase with the content of the phenyl group. Although solventless silicone resins are often used in traction motor designs, their high cost and availability have limited their use in other commercial motor designs. Solvent-borne silicone resins for motor windings are supplied by several manufacturers including Dow Corning and General Electric Silicones. In literature on its silicone resins [15], GE indicates there are "minimal effects by gamma radiation to 10^9 rad". Similar data is reported in [16] for several types of Dow Corning silicone resins with inorganic fillers, including cloth-coating, laminating, and solventless resins and a molding compound. It indicates there was no evidence of physical or electrical effects on the solventless resin up to a dose of $1x10^9$ rad. Further, the only salient physical effects of these radiation exposures for the tested resins were: 1) a decrease in flexibility of the glass cloth - resin composite and 2) noticeable darkening of the solventless resin color at doses above $5x10^8$ rad. Similar data are reported in [17] for fiberglass reinforced specimens using either solvent-based or solventless silicone resins. For both resin types, the measured physical properties, including flexure strength, remained virtually unaffected by the maximum reported exposure of $5x10^9$ rad. Finally, CERN in [17] citing three references, establishes incipient-to-mild dose limits of $1x10^9$ rad for glass or mineral-filled silicone resins and $2x10^8$ rad for unfilled silicone resins. Interestingly, EPRI [2] citing many similar references, including a CERN report [18], identifies a threshold of 10^6 rad for unfilled silicone resins. However, the EPRI report inadvertently includes data on the less radiation tolerant silicone cable insulations (i.e., silicone elastomer or silicone rubber) in its review of silicone resins. The EPRI radiation information which is clearly related to resins is more consistent with prior citations. In particular, EPRI NP-2129 [2] reports minor changes in a silicone-asbestos laminate at $6x10^8$ rad, 50% retention of flexure strength after $8.3x10^8$ rad <u>and two hours in boiling water for a second laminate</u>, and retention of 70% tensile strength after exposure to $8.3x10^7$ rad at "500°C" for a silicone-glass fabric laminate.

Additional silicone resin data is provided in [10] where samples were subjected to a radiation level of $3.6x10^8$ rad with subsequent mechanical and electrical tests. The post-irradiation helical coil bond strength values, for a solvent-based modified silicone varnish over four types of wire enamel, were either unaffected or improved. Finally, a threshold dose of $2\ x10^9$ rad is cited in [19] for a silicone-resin glass composite.

Silicone resins have been used in several proprietary motor qualification tests sponsored by equipment manufacturers. Random-wound intermittent-duty motors, manufactured by Reliance Electric and using silicone insulating resins (i.e., Reliance RH Class insulation) were successfully qualified for inside containment LOCA conditions, including radiation exposures up to $2x10^8$ rad, by Limitorque [20,21]. Reliance Electric and GE have also qualified both form-wound and random-wound motors with silicone resins.

Silicone resins possess extremely high thermal tolerance with thermal class ratings of 200ºC and higher. When operated at Class B operating temperatures (i.e., 130ºC), the silicone resins should exhibit little if any significant thermal aging. Consequently, the radiation dose limits cited above should be representative of the capabilities of the silicone resins after prolonged exposure to Class B motor operating temperatures.

Based on this information, a conservative threshold gamma radiation dose value of $2x10^8$ rad is established for solventless and solvent-borne silicone resins. It must be emphasized that this threshold dose applies to silicone thermosetting resins and is <u>not</u> applicable to silicone rubber or elastomeric compounds.

7.2.2.3 Lead Wire Insulation. The lead wire insulation materials most commonly used for safety-related motor repairs are silicone rubber and EPDM (including EPR). We also include data on crosslinked polyethylene due to the availability of several higher temperature grades (e.g., 150ºC). In general, the elastomeric materials used for cable insulation are less radiation resistant than the other motor insulating systems materials. This suggests that motor lead cables may be the weak-link material for radiation-only harsh qualification purposes. The impact of thermal aging on the radiation resistance of motor lead wires varies with material. However, lead wires may also be the thermal weak link material in many rewind insulating systems. For example, silicone lead-wire is typically thermally rated at 150ºC or 200ºC; however, silicone thermoset insulating resins have thermal ratings in excess of 200ºC.[14] Fortunately, the lead wires are exposed to operating temperatures substantially below average winding temperatures.

A significant amount of information has been developed regarding dose rate effects for elastomeric materials. For example, Sandia in [22,23,24] has demonstrated that most elastomeric cable insulating materials exhibit oxygen diffusion dose rate effects with greater degradation occurring at lower dose rates. The following radiation information and lead wire dose limits assume that essentially all of the lead wire radiation results from a relatively high dose rate (e.g., 10^6 rad / hr), accident exposure. Consequently, the published radiation test data generically apply. If a significant percentage of the radiation occurs during normal operation,(e.g., <10 rad / hr), consideration should be given to lowering this guideline's stated dose limits by a factor of 5 to 10.

Silicone Insulation: Silicone elastomers are produced by introducing substantial amounts of inorganic fillers into high molecular weight silicone rubbers (polysiloxanes) and then vulcanizing (crosslinking) the polymer. Silicone rubber insulation is noted for its retention of physical and dielectric properties after prolonged high or low temperature exposures. In addition to filler variations, silicones can be classified based on the molecular groups, (i.e., methyls, phenyls, and vinyls) attached to the silicone backbone. Theoretically, variations in the composition of these groups should effect the radiation resistance of the silicone rubber. Per [16] increasing the percentage of phenyl groups in silicone *liquids* increases their radiation resistance when compared to methyl based silicones. However, the same source indicates phenyls provide little if any increased radiation resistance for silicone *elastomers*. Table 7.8 extracted from [25] presents radiation resistance data for methylvinyl (on of the more prevalent silicone for general purpose insulation) and methylphenylvinyl silicone rubbers. The table suggests that while the absolute elongation may vary among compounds, the change in relative elongation (i.e., e / e_o) with dose is similar for both materials.

14 According to Belden, identical silicone compounds are used in the 150ºC and 200ºC styles; however, UL only accepts the lower thermal class for finer stranded wires.

Table 7.8
Radiation Resistance of Different Silicone Rubber Compounds

Dosage (rad)	Elongation Absolute (relative) %	
	Methyl-Vinyl	Methyl-Phenyl-Vinyl
None	200 (100)	600 (100)
$5x10^6$	130 (65)	450 (75)
$5x10^7$	50 (25)	225 (38)
$1x10^8$	20 (10)	75 (13)

In [26] CERN tested eight different European samples of commercially available silicone rubber insulated cables. Figure 7.5 represents their results. As the figure illustrates, all the materials exhibited excellent resistance up to $5x10^7$ rad but evidence a rapid loss of elongation at higher doses. By 10^8 rad all the samples have less than 50% remaining elongation and all *broke* by $5x10^8$ rad. CERN recommended a dose limit of $5x10^7$ rad based on retention of 50% absolute elongation. Similar results are reported in other CERN reports for three additional silicone insulations in [27] and one insulation in [28]. However, the absolute elongation values were somewhat lower (28% - 104%) at $5x10^7$ rad.

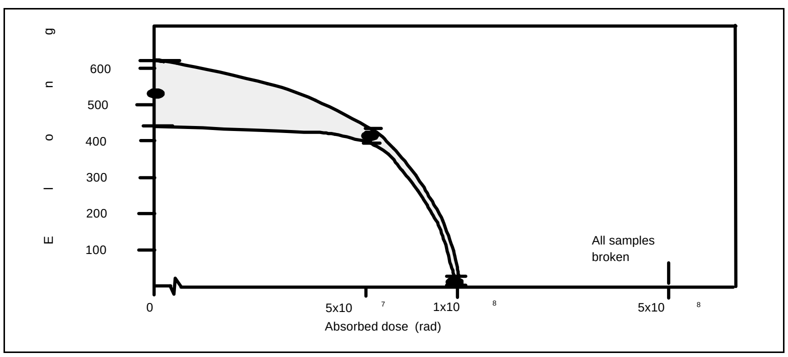

Figure 7.5
CERN Radiation Data for 8 Commercial Silicone Rubber Insulations

In [30] a dimethyl cable insulating material retained 34% elongation after $5x10^7$ rad. EPRI, in [2], suggests a silicon rubber radiation *threshold* of $5x10^5$ rad based on oxidation resistance; however, the relevant citation is not identified. One reference cited by EPRI identifies 10^6 rad as the threshold level for silicone rubber. Dow Corning provides general information on the radiation resistance of Silastic silicone rubbers and establishes 50% retention of elongation as an arbitrary material end point [31]. That publication indicates this end point is reached for doses in excess of $5.5x10^7$ rad at 23ºC and less than $1x10^7$ rad at 200ºC (based on cobalt-60 gamma source exposures) for typical Silastic silicone rubbers. The Sandia and Dow Corning data suggest decreasing radiation resistance at higher temperatures when compared to room temperature data.

The effects of varying dose rate, oxygen concentration, and exposure temperature on silicone rubber are addressed in [32] . Figure 7.6 illustrates little differences in the elongation vs. dose curves due to changing exposure conditions. Assuming an initial elongation of 400% - 600%, absolute elongation would be roughly 100% at $5x10^7$ rad and decreasing to roughly 20 - 30% by $1.5x10^8$ rad. Similar data at 10^8 rad is reported in [33] where commercial silicone rubber cable insulation was irradiated using different types of radiation sources and dose rates. The cable insulation degraded to roughly 20% - 40% absolute elongation after $1x10^8$ rad exposure to gamma sources. Additional CERN data which also address dose rate effects are presented in [34]. At high dose rates ($1.8x10^7$ rad / hr) the material retained 54% absolute elongation at $5x10^7$ rad and 15% elongation at 10^8 rad. At lower dose rates ($2.1x10^7$ rad / hr) the elongation actually improved to 27% at 10^8 rad. Sandia in [35] exposed a Rockbestos nuclear qualified cable to simultaneous thermal (90ºC) and low-dose rate radiation exposures. After $1x10^7$ rad the samples had roughly 90% elongation which decreased to less than 5% at $1.8x10^7$ rad. Yet, the same material has been qualified for inside containment LOCA applications, after being subjected to extensive thermal aging and a radiation dose of $2x10^8$ rad [36]. Finally, Sandia reported the results of dose rate effects in [24] for several silicone materials. Minor dose rate effects were predicted by Sandia for one silicone material whose absolute elongation would decrease to 100% at $3x10^7$ rad (for a dose rate of approximately 10^5 rad / hr) and at 10^7 rad (when the dose rate fell to 10^2 rad / hr). For three other formulations, when dose rates increased from 10^2 rad / hr to 10^6 rad / hr, the 50% relative elongation dose increased from $4x10^6$ rad to slightly less than $2x10^7$ rad. At dose rates representative of accident conditions (i.e., 10^5 rad / hr - 10^6 rad / hr) the 50% relative elongation doses were unchanged (i.e., slightly less than $2x10^7$ rad).

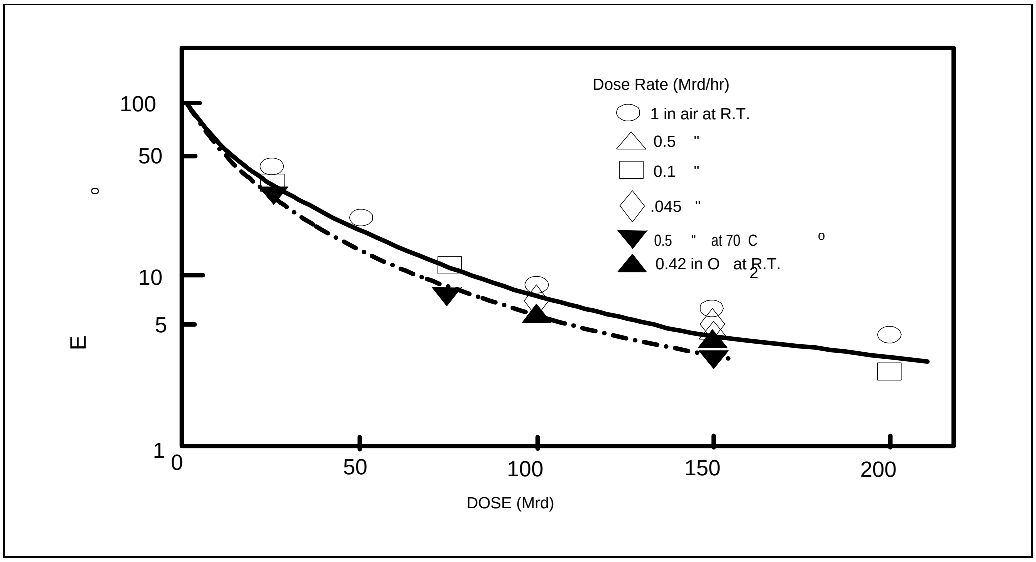

Figure 7.6
Effects of Dose Rate, Oxygen Concentration, and Temperature on Silicone Rubber Radiation Resistance

Silicone rubber motor leads have been included in a number of motor qualification test programs. In several motor qualification tests for TVA, random-wound motors with silicone lead wires were successfully subjected to thermal aging, radiation, and vibration testing, including post-radiation electrical and operability tests. In [37] two random-wound motor stators (5 hp & 50 hp) with Belden silicone insulated glass braid lead wires, were sequentially subjected to $2x10^8$ rad, accelerated thermal aging at 200ºC for 1674 hours, and vibration aging at 1.5g for 1 hour. The motors were also successfully subjected to subsequent seismic (random motion biaxial) and LOCA simulations.[15] In [38] a random-wound motor with Belden silicone insulated lead wires was subjected to two radiation exposures as part of the test sequence. The motor was sequentially exposed to $6x10^7$ rad aging radiation, thermal aging at 200ºC for 2295 hours, vibration aging, seismic testing, $1.54x10^8$ rad accident radiation, and a LOCA simulation. Although the motor was not qualified for the LOCA steam exposure, the problems were not related to the silicone lead wires. Silicone lead wires have also been subjected to LOCA qualification tests, including radiation exposures of $2x10^8$ rad, during testing of other devices, such as solenoid operated valves (SOV). For example, ASCO

15 One lead wire exhibited damage which was related to shipping and not the aging or accident stresses.

successfully qualified its NP series SOVs with silicone lead wires to such conditions in several reports, including [39,40].

In summary, the following silicone rubber dose limits are proposed. A conservative threshold dose of 10^6 rad has been selected based on numerous references. A dose of 2 - $5x10^7$ rad, based on 50% retention of relative elongation or 100% absolute elongation, appears to be a conservative, generic lower service dose limit for silicone rubber wire insulation. At this dose, silicone rubber insulation remains flexible and would not exhibit radiation induced cracks. Due to the high thermal capability of silicone insulation, this service dose limit should be relatively unaffected by the degree of thermal aging experienced by silicone lead wires used in Class B heat rise motors. Based on the two referenced TVA tests, Belden silicone insulated glass braid lead wire is considered qualified to $2x10^8$ rad and includes consideration of thermal aging effects.

Ethylene Propylene Rubber: Radiation data for Ethylene Propylene Rubber insulations may exist under two material categories, EPR or EPDM (Ethylene Propylene Diene Monomer). Since EPR is often used to describe both types of insulating materials, radiation resistance data for both EPR and EPDM is presented here. Figure 7.7 presents summary information extracted from [26] for 10 EPR based insulating materials. The figure indicates that all materials retained at least 100% elongation at doses up to 10^8 rad. Per the report, specially formulated EPRs can be used at doses up to 10^9 rad. It suggests $2x10^8$ rad as the usable limit for EPRs. Two other CERN reports [27] and [28] contain data for 26 EPDM and over 50 EPR commercial insulating materials. At 10^8rad all but 2 EPDM materials had in excess of 50% elongation.[16] Except for 10 compounds, all the EPR based materials had elongations in excess of 50% at 10^8 rad. CERN 89-12 suggests threshold to mild effects for EPR/EPDM at doses of roughly $2x10^7$ rad and below.

16 These 2 EPDM materials are not representative of typical motor lead wires since they had <u>initial</u> elongations of only 170% and 50%.

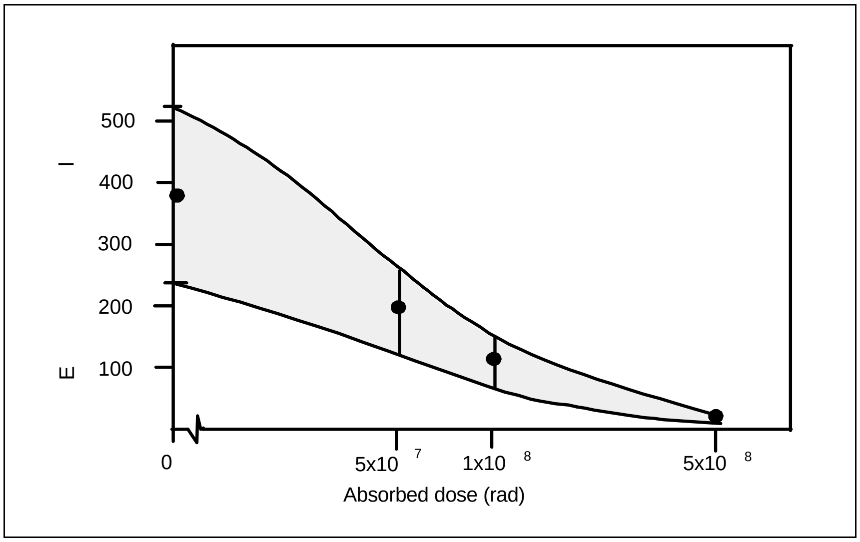

Figure 7.7
CERN Radiation Resistance Data for 10 Commercial EPR Insulations

In [30] elongation of EPDM insulation was not significantly changed after 5x10^6 rad, reduced to 48% relative elongation after 5x10^7 rad, and 37% after 10^8 rad. The tested EPR formulation retained 81% relative elongation after 5x10^6 rad, 41% after 5x10^7 rad, and 26% after 10^8 rad. This data is consistent with and extends the CERN data to lower doses and suggests both threshold (5x10^6 rad) and service limit (5x10^7 rad) dose values. EPRI in [2] cites a threshold dose of 10^6 rad based on compression set (e.g., O-rings) but reports higher threshold-to-minor damage values for cable materials.

There has been extensive LOCA qualification testing of EPR and EPDM cable compounds that demonstrate the tolerance of these materials up to doses of 2x10^8 rad after being subjected to accelerated thermal aging conditions. Although some of these materials have not performed as well as others during the LOCA steam exposures, all have survived and have exhibited functionality after extensive thermal aging representing 90°C continuous operating temperatures for 40 years and gamma radiation exposures in the range of 2x10^8 rad.

In [41] several types of US and French EPR and EPDM cable materials were exposed to thermal aging and radiation conditions. The materials received total doses up to roughly 8x10^7 rad and had ultimate elongations identified in Table 7.9. The 5.5x10^7 rad data are for unaged samples exposed to an accident dose. The data for 8x10^7 rad represent the data for samples subjected to either a sequence of thermal aging followed by radiation or a simultaneous temperature and radiation exposure. The lowest US $8x10^7$ rad values represent simultaneous exposure to radiation and 120ºC for approximately 380 hours. According to a companion report [42], after roughly the initial $6.5x10^7$ rad, neither US material's elongation had been *reduced* more than 25% from initial values. The French $8x10^7$ rad data represent samples subjected to aging sequences of radiation and thermal aging exposures at 140ºC for approximately 240 hours and then LOCA radiation ($5.5x10^7$ rad) .

Table 7.9
NUREG/CR-4091 US EPR & French EPDM Elongation Data

Test Condition	Remaining Ultimate Elongation				
	US EPR 1	US EPR 2	FR EPDM 1	FR EPDM 2	FR EPR
New	419%	223%	240%	245%	174%
55 Mrad	96% - 138%	61% - 83%	65% - 76%	63% - 67%	97% - 103%
80 Mrad*	55% - 90%**	30% - 71%**	49% - 57%***	51% - 61%***	53% - 62%***

Notes: * Includes data for both simultaneous and thermal-then-radiation sequences
** Includes 16 days thermal aging at 120°C
*** Includes 10 days thermal aging at 140°C.

In [43] Japanese data on the typical degradation behavior of EPRs show *relative* elongation (i.e., e/e_o) reductions to roughly 30% at $5x10^7$ rad and 10% at $1.5x10^8$ rad. The 30% relative elongation data at $5x10^7$ rad are reasonably consistent with the Table 7.9 values.

Sandia reports the results of dose rate effect studies on two EPR/EPDM formulations in [22]. For one formulation the doses at 100% absolute elongation increased from 10^7 rad to $5x10^7$ rad as the dose rate increased from $5x10^3$ rad/hr to $5x10^5$ rad/hr. The total dose at 100% elongation increased similarly for the other formulation from $2x10^7$rad to $8x10^7$ rad. The higher dose rate numbers are applicable to accident conditions.

In a form-wound stator qualification test for TVA [38], Belden EPDM lead wires rated at 150ºC and 7.5 kV were tested successfully as part of the three formette test specimens. The specimens were sequentially exposed to $0.36x10^7$ rad aging radiation, thermal aging at 200ºC for 2295 hours, vibration aging, seismic testing, $1.1x10^7$ rad accident radiation, and a LOCA simulation. Based on the TVA test, the Belden EPDM lead wire is considered qualified to $1.46x10^7$ rad which includes the effects of thermal aging under Class B heat rise conditions.

The following radiation capabilities are considered generically applicable to EPR and EPDM insulating materials. A threshold damage dose of $5x10^6$ rad dose is justified based on several cited references. Based on service limits of roughly 50% retention-of-elongation and 100% absolute elongation, a dose of $5x10^7$ rad conservatively reflects the results of the references.

Crosslinked Polyethylene: Figure 7.8 presents summary information extracted from [26] for 40 polyethylene based materials. The figure contains information for crosslinked polyethylene (XPLE), low-density polyethylene, and high-density polyethylene.[17] It notes that the XPLE materials are the most radiation resistant of these three types. Non-crosslinked polyethylene exhibits greater radiation degradation at higher temperatures. The figure data is very similar to the EPR/EPDM data in Figure 7.6. Two other CERN reports [27] and [28] contain data for 27 additional XLPE materials. At $1x10^8$ rad all the tested materials retained in excess of 60% elongation. Two materials exhibited somewhat lower elongation levels (40% - 55%) when exposed at a lower dose rate (0.4 $x10^6$ rad/hr). One of the reports [28] suggests threshold to mild effects for XLPEs (and other crosslinked polyolefins) for doses of roughly $1x10^7$ rad and below.

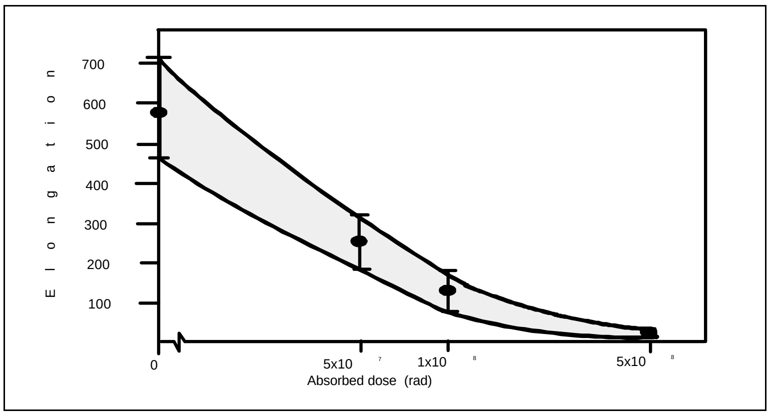

Figure 7.8
CERN Radiation Resistance Data for 40 Commercial XLPE Insulations

17 The abbreviation XLPE is used in this guide to denote both crosslinked polyethylene and crosslinked polyolefin materials.

There has been extensive LOCA qualification testing of XLPE cable compounds that demonstrates the tolerance of these materials up to doses of $2x10^8$ rad after being subjected to accelerated thermal aging conditions. Although some of these materials have not performed as well as others during the LOCA steam exposures, all have survived and have exhibited functionality after extensive thermal aging representing 90ºC continuous operating temperatures for 40 years and gamma radiation exposures in the range of $2x10^8$ rad.

In [44] several types of US and French XLPE cable materials were exposed to thermal aging and radiation conditions. The materials received total doses up to roughly $8x10^7$ rad and had ultimate elongations as identified in Table 7.10. The $5.5x10^7$ rad data are for unaged samples exposed to an accident dose. The data for $8x10^7$ rad represent the data for samples subjected to either a sequence of thermal aging followed by radiation or a simultaneous temperature and radiation exposure. The lowest US $8x10^7$ rad values represent simultaneous exposure to radiation and 120ºC for approximately 380 hours. According to a companion report [42], after roughly the initial $6.5x10^7$ rad, neither US material's elongation had been *reduced* more than 20% from initial values. The French $8x10^7$ rad data represent samples subjected to sequences of radiation and thermal aging exposures at 140ºC for approximately 240 hours and then the LOCA accident radiation ($5.5x10^7$ rad). The US XPLE 2 unaged samples exhibited an unusually wide range (19% - 140%) of elongation values after the $5.5x10^7$ rad radiation exposure. The 140% value resulted when the irradiation was performed at 70°C, while the 19% value occurred when irradiation was performed at 28°C. The elongation values actually improved (e.g., 107% - 113%) when similar samples were subsequently exposed to LOCA steam conditions. Sandia has recently proposed an explanation for such unusual XLPE results in [45] that involves an annealing effect when temperatures are increased above approximately 60°C. Since motor lead wires will be exposed to operating temperatures during motor operation, the unannealed data (i.e., 19%) does not fully apply to motor lead wire insulation.

Table 7.10
NUREG/CR-4091 US XPLE Elongation Data

Test Condition	Remaining Ultimate Elongation		
	US XPLE 1	US XPLE 2	FR XPLE
New	389%	336%	370%
55 Mrad	129% - 253%	19% - 140%	185% - 240%
80 Mrad*	66% - 157%**	40% - 77%**	27% - 58%***

Notes: * Includes data for both simultaneous and thermal-then-radiation sequences
** Includes 16 days thermal aging at 120°C
*** Includes 10 days thermal aging at 140°C.

Sandia reports the results of dose rate effect studies on three XLPE formulations in [22]. The doses at 100% absolute elongation increased from 2-4x10^7 rad to 7-10x10^7 rad as the dose rates increased from roughly 2-5x10^3 rad / hr to 2-5x10^5 rad / hr. Similar results were reported in [24] for another XLPE whose dose at 100% elongation similarly increased from 7x10^7 rad to 10^8 rad as the dose rate increased from 10^4 rad / hr to 10^6 rad / hr. The higher dose rate numbers are applicable to accident conditions. Finally, dose rate results are reported for another XLPE in [23]. For that material, the total dose, 5x10^7 rad, at roughly 50% relative elongation remained essentially unchanged for dose rates ranging from 2x10^4 rad / hr to almost 10^6 rad / hr.

Based on these extensive references, the following radiation capabilities are considered generically applicable to XLPE insulating materials. A threshold damage dose of 5x10^6 rad is justified based on several cited references. Based on service limits of 50% retention-of-elongation and 100% absolute elongation, a dose of 5x10^7 rad conservatively reflects the test data.

7.2.2.4 Magnet Wire. Magnet wire insulations can be divided into the enameled and fibrous (e.g., Daglas) categories. For the round wires used in random-wound motors, enameled coatings are almost universally used. For the square and rectangular wires found in form-wound motors, woven fibrous coverings, generally a polyester-fiberglass mixture (i.e., Daglas), are most common. In most of these wire designs, an epoxy, polyester, or silicone resin is used as a binder to help consolidate the conductor-insulation composite.[18] It is not uncommon to find both enamel and fibrous coverings (e.g., double Daglas over film) used on form-wound magnet wires.

Fibrous: Specific radiation resistance data for fibrous covered magnet wire were not identified. It is reasonable to conclude; however, that the overall resistance can be represented by data for the individual materials (i.e., fiberglass, Dacron, and binding resins) that comprise the covering.[19] The weak-link material from a radiation perspective is the Dacron fiber which comprises approximately 50% of the fabric weave. As noted in Section 7.2.2.8, Dacron Fabrics, this material has a threshold-to-mild dose of 2x10^7 rad and a service limit dose of 5x10^7 rad. In form-wound VPI applications; however, the wire's fibrous covering provides little post-VPI treatment

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18 It is also possible to create adhesion between the conductor and fibrous coverings containing woven polyester (Dacron) by a heat treatment that partially melts the woven covering. In this method a binder resin is not necessary. However, such specialized magnet wire insulations are only available on special order.

19 These radiation data are based on Daglas coverings. The radiation resistance of Nomex paper covered magnet wire should be equivalent to the separately described Nomex data.

mechanical strength. When film is used, the Daglas provides a secondary dielectric function. Consequently, dose limits based solely on the Dacron fiber would be overly conservative. In fact, arguments could be made that significant degradation of the Dacron portion of the wire covering could occur without significantly affecting coil performance. However, based on both Dacron and Mylar data, a threshold dose of $5x10^7$ rad and a service limit dose of 10^8 rad are proposed for use. If the covering does not contain Dacron, the dose limits should be based on the covering material (e.g., fiberglass or Nomex).

Film: A wide variety of wire insulating enamels are available, each with its own NEMA magnet wire classification (e.g., MW35C). For safety-related motor repairs, only the high temperature modified polyester and polyimide enamels (e.g., MW16C, 35C, 36C, 76C) are recommended. In [46], a wider variety of film-insulated wire products were subjected to a range of electrical, physical, mechanical, and chemical tests subsequent to gamma irradiation. The wire samples were subjected to total gamma doses ranging from 10^7 rad to 10^{10} rad. The post-irradiation tests, based on the methods contained in the NEMA magnet wire standard [47], were:

- Film Build
- Flexibility and Adhesion
- Scrape Abrasion
- Thermoplastic flow (Cut-through)
- Solvent Resistance
- Breakdown Voltage
- Infrared Absorption

Table 7.11 identifies the film types described in [46] and the equivalent commercial designations used today. The last column identifies the relative ranking of radiation resistance defined in the paper, with 1 being the most radiation resistant material. As expected, polyimide (e.g., Kapton or ML) is the most radiation resistant enamel followed by the modified polyesters, including polyester 200. Additional supporting data for the radiation resistance of polyimides can be found in the section on Kapton. Polyester 200, a theic polyester, is representative of modern higher temperature (180° C) polyester enamels. In addition, modern topcoats for these high temperature theic polyester enamels are composed of polyamide imides rather than liner polyester. The polyamide imides are considered superior to the linear polyesters in thermal rating, moisture resistance, and radiation tolerance. For harsh EQ motor rewind applications, either a high temperature polyester with polyamide imide topcoat (e.g., MW-30) or polyimide (e.g., MW-16) should be used.

Table 7.11
Enamel Wire Constructions Tested in [46]

As Described in Paper	Typical MW Class	Thermal Class	Radiation Ranking
Polyimide	MW-16	220°C	1
Polyester 200	MW-30	180°C	2
Polyester 200 with linear polyester topcoat **	MW-30	180°C	3
Polyester, isocyanurate modified *	MW-5	155°C	4
Polyester, isocyanurate modified basecoat with linear polyester topcoat *	MW-5	155°C	5
Polyvinyl acetal-polyurethane (hermetic)	MW-15	105°C	6
Polyester, unmodified	MW-5	155°C	7
Polyester, unmodified basecoat with linear polyester topcoat *	MW-5	155°C	8
Polyvinyl acetal (regular)	MW-15	105°C	9
Polyurethane, solderable, polyvinyl acetal modified	MW-75	130°C	10
Nylon (Type 66)	MW-6	105°C	11
Epoxy	MW-9	130°C	12

Note: * Obsolete construction not generally offered as a standard wire enamel
** Polyamide imides have replaced linear polyester in modern MW-30 constructions

The following discussion is limited to the results for the five top-ranked compounds (shaded in table). No significant changes in breakdown voltage were observed until 5×10^9 rad. However, consistent with other information, mechanical properties are expected to exhibit more significant deterioration at lower doses than electrical properties. Several types of Flexibility and Adhesion tests were performed including a mandrel bend test with examination for cracks and the NEMA MW1000 rapid snap test. In both these tests, the performance of the top five enamels was virtually unaffected to doses up to 10^9 rad. At 5×10^9 rad all the samples failed the rapid snap test. Similarly, the samples failed the mandrel bend diameter test (i.e., cracks were evident at bends greater than 5 times the bare wire diameter) at 5×10^9 rad, while the results at 10^9 rad were identical to those in the unirradiated condition. Thermoplastic Flow (cut-through temperature) results varied widely among the enamels with the polyimide exhibiting the best results (i.e., >450ºC). However, for all the enamels little change in cut-through temperature was evident until 5×10^9 rad.

Three wire enamels -- polyester-imide, modified polyamide-imide with topcoat, and Mylar with a nylon overcoat -- were examined for changes in elasticity and hardness due to radiation exposures up to a maximum dose of 10^9 rad in [9]. Hardness measurements were unaffected by the maximum dose (10^9 rad). Insignificant changes in elasticity were observed at 10^9 rad for the polyester-imide and Mylar with nylon overcoat samples. However, the polyamide-imide with topcoat, which was unaffected at $5x10^8$ rad, exhibited cracking at $5x10^9$ rad when subjected to an unspecified number of turns. Several low-voltage random-wound motors were successfully tested in [9]. The motor containing polyimide insulated wire was subjected to $3x10^9$ rad and successfully operated but experienced a subsequent 4 kV dielectric breakdown attributed to the Neoprene lead wires. Two other motors with polyester-imide magnet wire films were subject to doses of 10^8 rad and $3x10^9$ rad and passed subsequent operability and electrical tests.

Based on this information, a conservative threshold gamma radiation dose value of 10^9 rad is generically established for polyimide (e.g., MW16 and MW71) and high temperature polyesters with polyamide imide top coat (e.g., MW35 and MW36).

7.2.2.5 Nomex Papers and Fibers. Nomex is the DuPont trademark for its aromatic polyamide (aramid) materials that can be supplied in either paper or fiber form. In [48] DuPont presents radiation resistance data that is summarized in Table 7.12. The radiation source was 2 MeV electrons (beta rays). However, since the penetration distance of 2 MeV electrons in organic materials will significantly exceed 10 mil (0.25 mm), the data adequately represents the degradation expected from gamma rays. Since the physical properties of Nomex paper differ for the paper's *machine direction* (MD) and *cross direction* (XD), the table contains the data for both directions. The physical property data is presented as a percent change from initial values. Typical initial values for 10 mil Nomex 410 are roughly 20% elongation, 180 lb/in MD tensile strength, and 90 lb/in XD tensile strength. The table data indicate that dielectric strength is virtually unaffected by radiation doses up to $3.2x10^9$ rad. Tensile strength data suggest a threshold level of $4x10^8$ rad with little significant damage at the maximum tested dose. The most radiation sensitive parameter, elongation, indicates insignificant (almost threshold) effects at a dose of $1x10^8$ rad. Similar, but slightly better, data are provided in [49] for Nomex M papers which contain mica. It should be noted that virtually all insulating system applications (e.g., slot liner, phase/coil separators) of Nomex paper do not require the maintenance of significant mechanical properties after motor fabrication. In these applications dielectric strength is the most important characteristic.

Supporting radiation resistance data for Nomex is available from other sources. CERN in [9] reports on the testing of two Nomex paper materials.[20] For one material no mechanical damage was detected after a dose of $5x10^8$ rad. The second test noted a slight change in color after 10^9 rad and almost no damage after repeated (100) 360º backward and forward bends (Swiss Std. VSM 23780). The CERN report concludes that threshold to mild damage occurred at the maximum radiation exposure, 10^9 rad.

Table 7.12
Radiation Resistance of 10 Mil Nomex 410 Paper

Total Dose Mrad	Tensile Strength		Elongation		Dielectric Strength V/mil (¼ in. dia. electrode)
	MD %	XD %	MD %	XD %	
0	100	100	100	100	870
100	96	100	89	92	855
200	100	99	92	91	845
400	100	99	96	88	845
800	94	97	76	82	850
1600	87	86	60	47	860
3200	81	81	36	27	885
6400	65	69	18	16	790

Based on this information, no observable effects occur in Nomex paper for a dose of 10^8 rad. At doses in the range of $2x10^8$ - $4x10^8$ rad minor degradation (i.e., 10% or less change in properties) occurs. Using our definition of radiation threshold, $2x10^8$ - $4x10^8$ is considered as the threshold dose. Since these doses significantly bound those expected for radiation-only applications, Nomex papers should be considered to be insensitive to radiation at or below these dose levels. Based on a 50% reduction in elongation, a conservative service limit for Nomex papers is $1.6x10^9$ rad.

Woven and felt-like Nomex *fiber* products are often used for securing and bracing the end turn winding areas. In these applications the Nomex serves as a medium to absorb and retain resin. After resin curing, the physical strength of the Nomex/resin

[20] CERN 82-10 also measured an aramid paper adhesive tape with a synthetic rubber, thermosetting adhesive. As expected, adhesive degradation was the limiting factor with peel strength decreasing to 50% of the initial value at 10^8 rad.

composite is principally provided by the resin.[21] However, poor radiation resistance of the fibers could reduce overall strength by weakening the bond strength of the composite. DuPont in [50] reports on both beta and gamma radiation effects on Nomex fiber break strength as a percent of initial values. The DuPont data are summarized in Table 7.13. In [2] EPRI indicates Nomex yarns are unaffected by 3.3×10^8 rad at room temperature and retain 45% elongation and 62% tensile strength at 500ºF and 1.4×10^8 rad. The similarity between the Nomex paper and fiber data should not be unexpected, since both contain the same aramid material. Based on this similarity, available data on Nomex fibers, and the use of Nomex fiber materials in motor rewinds, the dose limits defined above for Nomex paper are considered equally applicable to Nomex fiber products.

Table 7.13
Effect of Radiation on Nomex Fiber Break Strength

Dose	Break Strength Retained	
Mrad	Gamma	Beta
200	70%	81%
600	-	76%
1000	55%	-
2000	45%	-

7.2.2.6 Mica Paper Tapes. Mica is used in form-wound motors as a constituent in mica paper tapes. The mica paper tapes also contain other materials, including a resin binder, backing materials of fiberglass or woven / mat polyester, and possibly films (e.g., Mylar, Kapton). Since mica is an inorganic material, it is generally considered highly resistant to gamma radiation. In [51] tests on flexible mica paper, mica flake, and rigid-mica mat at doses of 10^{10} rad produced no significant effect other than color darkening. Simon, in [8], reports on testing of mica-epoxy resin composites. Figure 7.9 illustrates typical results where the flexure strength of fiberglass or fiberglass / mica composites were less affected by radiation than the base resin. Based on this testing, mica is considered as inherently resistant to the gamma dose levels encountered in radiation-only harsh applications. The overall radiation resistance of mica tape may be influenced by the other tape materials. As noted below, Fiberglass, like mica, is highly resistant to radiation degradation. The epoxy, polyester, and silicone resins serve as tape binders. Except for compatibility with the VPI treatment resins, they do not

21 The resin strength dominates in the composite due to differences in stress-strain characteristics of the Nomex fiber and most resins, with the possible exception of silicones. The fibers would only begin to accept load after stretching 1% - 2% while most resins will fail in tension after elongation of only a few percent.

contribute significantly to overall performance of a fully fabricated winding. The information in Section 7.2.2.2, indicates these resins are highly tolerant of radiation. Based on their minor contribution to performance in the fabricated winding and recognizing their inherent tolerance to radiation, mica papers containing these resins are given a threshold dose of $2x10^8$rad. As described below in Sections 7.2.2.8 and 7.2.2.9, Mylar (polyester film) and Dacron (polyester fibers) are more sensitive to radiation induced degradation. Both the film and backing constituents in mica tapes are principally used to facilitate the fabrication process. Consequently, mica paper tapes containing polyester materials should still be highly tolerant of radiation. Based on the Dacron and Mylar data described below and recognizing the minor function role of these polyester materials in mica paper tapes, a threshold dose of 10^8 rad is suggested for mica paper tapes containing polyester materials.

7.2.2.7 Fiberglass Fibers. Since fiberglass is an inorganic material, it is generally considered to be highly tolerant to radiation. The most commonly used fiberglass material is E glass consisting of 50%-55% SiO_2 and 8%-13% B_2O_3. Under gamma radiation exposure, E type fiberglass is virtually unaffected by the radiation. Under neutron exposures; however, the boron captures a neutron, transmutes to Li and emits a high energy alpha particle which causes intense local damage. Since this only impacts the use of E type fiberglass products under neutron exposures, the effect does not occur for the gamma and beta exposures in most nuclear power plant locations. Simon, in [8], summarized the radiation resistance of fiberglass reinforced epoxy impregnated test specimens. Generally, the fiberglass reinforcing either improved or did not affect the radiation resistance of the epoxy resin. Simon reports flexural strength results where the glass finish is varied (e.g., caramelized, heat cleaned, and various coupling agents such as amino silane). Radiation resistance slightly improved with the use of coupling agents. The results for caramelized and heat cleaned specimens were mixed and in some cases slightly lower than those of the specimens with coupling agents. The slightly improved performance for the fiberglass specimens with coupling agents is likely related to superior bonding between the glass and resin. Figure 7.10 illustrates typical data when the glass finished is varied. Based on this data, the threshold gamma radiation resistance of fiberglass is considered to be greater than 10^9 rad which exceeds typically required radiation-only dose levels.

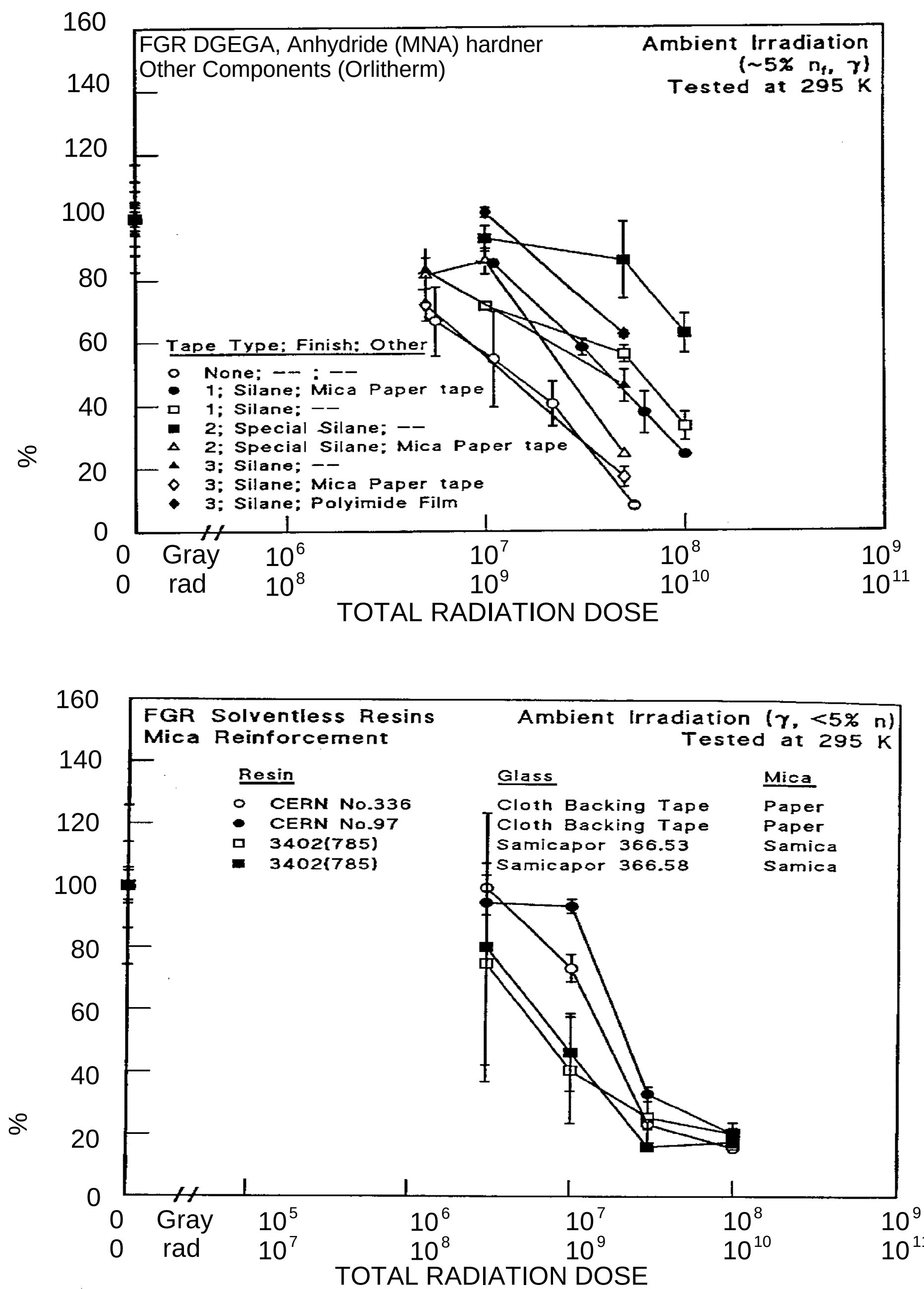

Figure 7.9a & 7.9b
Radiation Resistance of Various Fiberglass/Mica Epoxy Resins Composites

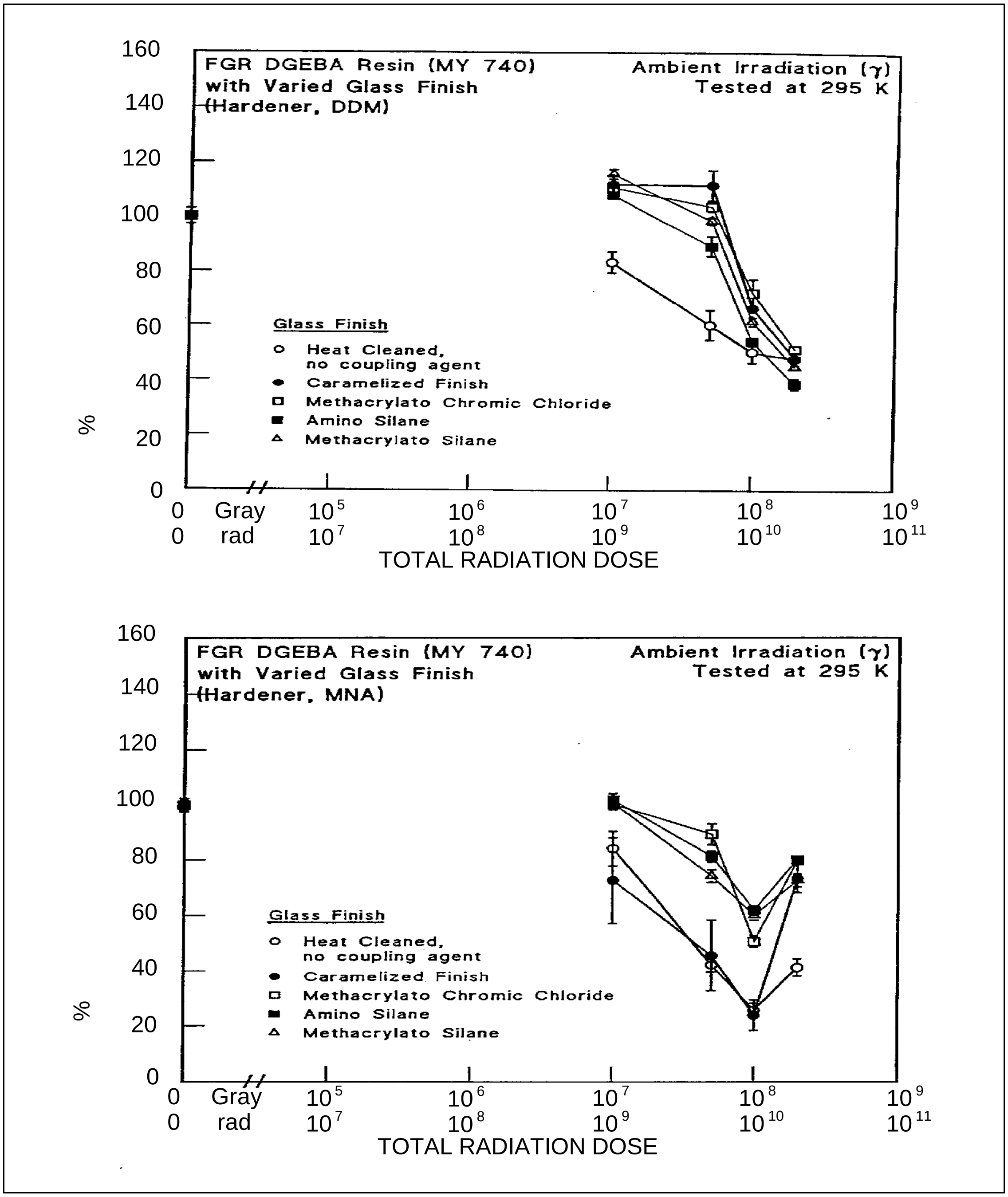

Figure 7.10a & 7.10b
Effect of Surface Finish on Radiation
Resistance of Fiberglass/Epoxy Composites

7.2.2.8 Dacron Fibers. Dacron, the DuPont trade name often used to generically identify polyester (i.e., polyethylene terephthalate) textile materials, is less radiation resistant than aramid materials like Nomex and Kevlar. An incipient-to-mild dose limit of $2x10^7$ rad is identified for Dacron fabric in [9] with moderate-to-severe degradation beginning at a dose of approximately $6x10^7$ rad. According to [2] Dacron fibers are not significantly degraded below $2.5x10^7$ rad.

Since polyethylene terephthalate in an oriented film form is called Mylar or polyester film, radiation information for Mylar (films) may be cautiously applied to Dacron (fabrics). For example, the conclusions in [2] regarding minimal outgassing and lack of accelerated radiation damage at temperatures up to 200ºC should also describe Dacron characteristics. Based on these data, a threshold-to-mild dose of $2x10^7$ rad and a service limit dose of $5x10^7$ rad are selected for Dacron fabrics and fibers.

7.2.2.9 Mylar Film. Mylar is the DuPont trade name often used to generically identify polyester (i.e., polyethylene terephthalate) films. [2] cites threshold changes in tensile strength and elongation properties at $4x10^7$ rad with the properties degrading to 50% of the initial values with doses of 3 - 6 $x10^8$ rad. [52] summarizes testing on Mylar and indicates that 80% elongation remains after $5x10^7$ rad and slight tensile strength loss was noted at 10^8 rad. Mylar capacitors have been found serviceable after 10^8 rad. There is no acceleration of radiation damage at higher temperatures up to 200ºC and outgassing is minimal (mostly H_2). An incipient-to-mild dose limit of $3x10^7$ rad is identified for Mylar film in [9] with moderate-to-severe degradation beginning at a dose of approximately 10^8 rad. Based on these data, a threshold-to-mild dose of $3x10^7$ rad and a service limit dose of 10^8 rad are selected for Mylar film.

7.2.2.10 Kapton Film. Kapton is the DuPont trade name for polyimide film. Like polyimide wire enamel, Kapton films are one of the most radiation resistant insulating polymers. DuPont in [53] provide radiation information on Kapton films. Exposure of a 1 mil film to a Cobalt 60 gamma source produced insignificant changes at 10^8 rad but elongation fell to roughly 52% of the unirradiated value at 10^9 rad. Data on the effects of Beta radiation on a 2 mil film indicated an 89% retention of initial tensile and elongation at 10^9 rad and 75% retention at $3x10^9$ rad. CERN in [9] identifies polyimide as useful to doses in excess of $2x10^9$ rad. EPRI in [2] selects a threshold dose of 10^7 rad based on tensile strength data from one source. EPRI notes that DuPont films show a threshold loss of elongation at $4x10^8$ rad and other sources indicate stable physical and electrical properties to 10^9 rad. In [51], NASA reports a threshold dose of 10^9 rad for Kapton films and no deterioration in the physical or electrical properties of a polyimide resin (ML) at the maximum tested dose of $1.5x10^8$ rad. These dose capabilities are significantly in excess of the doses potentially experienced in radiation-only harsh environments. Based on these references, a threshold dose for Kapton film exceeds $2x10^8$ rad with the film useful to doses in excess of 10^9 rad.

7.2.2.11 Pressure Sensitive Adhesive (PSA) Tapes. Pressure Sensitive Adhesive (PSA) tapes are often used as assembly aids during coil fabrication and in some cases may be used to insulate coil and lead wire connections. The most often used tapes for safety-related rewinds are made with Kapton or fiberglass backing and a silicone, acrylic, or rubber adhesive. A variety of different backing and adhesive materials is available. The radiation resistance of the PSA tapes is based on the weak-link material (backing or adhesive). For fiberglass and Kapton tapes, this should be the adhesive. However, other backings may be less tolerant than the adhesive. CERN in [9] reports of tests on a variety of PSA tapes with backings of polyamide / mica paper, polyamide paper, polyester film, polyimide (Kapton) film, and polyhydantoin film, combines with resin or rubber adhesives. For virtually all of the tested tapes, the adhesive's peel strength decreased substantially before the tape's other physical properties were significantly affected. For all the tested tapes, CERN identifies incipient-to-mild doses of 10^8 rad and above and moderate-to-severe doses of 10^9 rad, based on relatively high dose rate (i.e., 10^7 rad / hr) exposures. This test information suggests a conservative service limit for PSA adhesives of approximately 10^8 rad. The radiation limits for the tape backing should be based on material specific (e.g., fiberglass, Kapton, Mylar) data, with threshold and service limits for the composite tape based on the weak-link material.

7.2.2.12 Sleeving. Sleeving for safety-related motor rewinds is generally a fiberglass woven material with or without an elastomeric coating. As discussed above, the fiberglass fabric is highly resistant to radiation. Uncoated fiberglass sleeves are used in applications where the resin treatment (e.g., VPI) is intended to coat the fabric and provide dielectric strength. Under these conditions the radiation resistance of the treated sleeve can be estimated using the resin data. Coated sleeves are generally supplied with a vinyl, acrylic, or silicone rubber coating. Since vinyl coatings have lower temperature ratings (Class B), they are generally not preferred for safety-related applications. The radiation resistance of silicone coated sleeves can be reasonably estimated using the data for silicones provided in Section 7.2.2.3. Based on information in [9], the radiation resistance of acrylic rubber is similar to silicone rubber. According to that reference, threshold-to-mild degradation occurs at doses up to approximately $5x10^6$ rad with mild-to-moderate degradation occurring up to a dose of approximately $5x10^7$ rad.

7.2.3 Fabricating Systems

The material presented in this section demonstrates that the conservative application of material radiation test data combined with analysis can form an adequate qualification basis for motor insulating systems exposed to radiation-only harsh environments. In other words, motor insulating systems designed and fabricated using materials with demonstrated radiation resistance, including margin, are adequately qualified for radiation-only environments. No specialized fabrication techniques other than those used to produce a high quality, safety-related, mild environment motor rewind are needed. Consequently, additional fabrication guidance and requirements, beyond those used for mild environment motor applications, are not necessary. Guidance on the procedures, controls, and documentation needed to demonstrate the acceptability of such motor repairs are contained in EPRI NP-6407 [55].

7.2.4 Material Procurement and Acceptance

As discussed in Section 7.2.2, no special techniques, other than those used to produce a high-quality, safety-related mild environment motor rewind, are needed for motors qualified for radiation-only harsh conditions using the analysis and partial test data contained in this section. Since the radiation tolerance levels were developed for generic material classes, the procurement and acceptance processes need only insure that the specified material was supplied. Consequently, the general guidance contained in EPRI TR-103585 [54] applies to such radiation-only harsh qualified materials. Additional material controls or verifications, beyond those used to accept materials for mild environment safety-related motor repairs, should not be necessary. When a specific material is qualified to radiation levels significantly beyond those stated for the applicable generic material classification, then additional controls may be necessary to insure that an identical material is provided.

7.3 Evaluation of Available Systems

The following discussion describes a random-wound VPI system that has been type test qualified for dose levels in excess of $2x10^8$ rad. It also describes three motor systems tested by CERN. Except for the neoprene lead wires in one system, these CERN systems demonstrated tolerance to doses greater than 10^8 - 10^9 rad. These three systems provide further partial test evidence that motor insulating materials are highly tolerant to typical radiation-only harsh environment total doses.

7.3.1 Random-Wound Systems

TVA's efforts to qualify a single 20 hp, 460 Vac, 1775 rpm, 3 phase, TEFC random wound motor are documented in [38]. A summary of the relevant test conditions is provided by Table 7.14. The motor operated successfully during the functional tests conducted after all the test phases prior to the LOCA simulation. However, the motor was not successfully qualified to the LOCA steam simulation conditions (not tabulated here). Although this program did not qualify the motor system to LOCA conditions, the previous qualification test phases can be used to support qualification of the insulating system design for both thermal aging, radiation, and vibration/seismic conditions. The thermal aging time was based on an activation energy of 1.2 eV for the insulating resin using product data provided by the manufacturer. The TVA qualification test report, applicable material specifications, and TVA fabrication procedures and controls are available by contacting EPRI PSE and requesting Report No. TR-104872, supplement 2..

Table 7.14
Summary Test Conditions for a Random-Wound Motor - Wyle Report No. 18070-1

Test	Type	Summary Conditions
1.	Normal Radiation	0.63×10^8 rad @ approximately 4.6×10^5 rad/hr
2.	Thermal Aging	2295 hours @ 200ºC = 40 years @ 130ºC
3.	Vibration Aging	1 hour, 1.5g @ 60 Hz
4.	Seismic	sine sweep - sine-beat (3.3g H, 2.2g V) - Triax random (5 OBE, 1 SSE) - 10g peak, 5% damping for SSE
5.	Accident Radiation	1.54×10^8 rad @ approximately 8.5×10^5 rad/hr

The random-wound motor was fabricated at the TVA Power Service Shop using the materials identified in Table 7.15. The insulation system uses a blend of IMI 707/711 solventless polyester resins. The coil extensions are fully taped with 1/2 lap layers of fiberglass tape to aid in resin retention during VPI processing and curing.

A TVA qualification report [9] describes successful testing of three random-wound low-voltage (480V) motors to gamma radiation levels between 10^8 rad and 3×10^9 rad. Table 7.16 identifies the components of motor sample 181-1975 that was subjected to 10^8 rad while operating unloaded, tested for insulation resistance (essentially infinite), and a voltage breakdown test (failed at 3.9 kV AC). Individual components were subsequently examined and were found to be in excellent condition, except for the neoprene motor leads which were stiff but still serviceable. Table 7.17 identifies the components of motor sample 262-1975 that was subjected to 10^9 rad and 3×10^9 rad with subsequent tests for motor operation, insulation resistance, and dielectric strength (4kV). The motor passed all the tests and was still operating according to specifications after 3×10^9 rad. Finally, Table 7.18 identifies the components of motor sample 263-1975 that was subjected to exposures up to 3×10^9 rad with motor operation, insulation resistance, and dielectric strength (4kV) tests performed after every 10^9 rad. The motor passed all the tests except for the final 4kV test after exposure to 3×10^9 rad. These tests confirm that, with careful selection of high quality radiation resistance materials (e.g. polyimide, Nomex, epoxy), the resulting insulating systems should easily tolerate extremely high radiation levels (e.g., 10^8 rad to 10^9 rad) without failure.

Table 7.15
Random-Wound System Components - Wyle Report No. 18070-1

Component	Material
Magnet Wire	Heavy Polyimide (MW 16C), Phelps Dodge
Slot Liner	Nomex 414 Paper
Wedge	Nomex 410 square formed wedge
Tie tape	Nomex, Western Filament NFB-1X
Connection & Lead Tape	Heat cleaned glass, Mutual C-150, 1 half-lap layer
End-turn Tape	Heat cleaned glass, Mutual C-150, 1 half-lap layer
Coil Resin	180°C solventless polyester, slightly thixotropic, 50% IMI 707, 50% IMI711
Motor Lead	Belden silicone insulated - glass braided lead wire
Lead Sealant	Dow Corning 732 silicone rubber sealant
Lead Sleeving	Bently Harris, 1151 Superwall
Lead Blocking	Nomex felt
Filler Strips	Nomex 410 Paper
Slot Separator	Nomex 410 Paper
Phase Separator	None

Table 7.16
Insulating System Components for CERN 380 V Random-Wound Motor 181-1975

Component	Material
Magnet Wire Insulation	Polyester-imide
Slot Insulation	Nomex
Phase Insulation	Nomex/Mylar
Coil Resin	Tetrahydrophthalic polyester (Norsodyne 292T)
Motor Lead	Neoprene
Insulating Sleeves	silicone impregnated fiberglass braid

Table 7.17
Insulating System Components for CERN 380 V Random-Wound Motor 262-1975

Component	Material
Magnet Wire Insulation	Polyester-imide
Slot/Phase Insulation	Nomex
Coil Resin	Tetrahydrophthalic polyester (Norsodyne 292T)

Motor Lead	Kapton + silicone impregnated fiberglass braid
Insulating Sleeves	Kapton tape

Table 7.18
Insulating System Components for CERN 380 V Random-Wound Motor 263-1975

Component	Material
Magnet Wire Insulation	Polyimide
Slot / Phase Insulation	Kapton
Coil Resin	Bisphenol A epoxy - acid anhydride hardener
Motor Lead	Kapton + silicone impregnated fiberglass braid
Insulating Sleeves	Epoxy impregnated fiberglass braid

7.3.2 Form-Wound Systems

No type test qualified radiation-only harsh, form-wound systems were provided to EPRI for inclusion in this guideline. The form-wound systems described in Section 6.3.2 were exposed to 1.5×10^7 rad, but this exposure should be significantly below their radiation capability. This testing could be used as a type test qualification basis for radiation-only environments at or below this dose level. The test as a qualification basis can apply to the insulating systems or selectively to the individual materials (e.g., lead wire insulation). Note that this test program included both thermal aging, mechanical aging, and seismic simulations.

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8.0

DEVELOPING NEW HARSH ENVIRONMENT QUALIFIED SYSTEMS

8.1 Introduction

This section briefly describes the advantages of developing new harsh environment qualified motor insulation systems. It also identifies several factors that should be considered whenever new rewind systems are developed, qualified and assembled for use by a number of motor repair facilities.

Several factors suggest that development of new harsh environment qualified motor insulating systems for motor rewinds will benefit utilities. Most of the harsh environment qualification testing currently referenced by utilities was performed several decades ago by motor manufacturers and NSSS vendors . Much of the earlier motor qualification testing did not include all the test sequences (e.g., thermal aging, radiation, or accident steam) currently required to meet the criteria specified in documents such as 10 CFR 50.49, NUREG-0588 Cat I, or IEEE 334-1994. Many of the originally qualified insulating system materials are no longer available or are cost-prohibitive to use. With changes in materials, facilities, and manufacturing methods, suppliers of qualified motors either justify the changes through analysis and partial testing, limited their qualification certification to older EQ standards (DOR Guidelines or NUREG-0588 Cat. II), or refused to supply replacement harsh qualified motors. Given the relatively small replacement market for harsh environment motors, there appears to be little economic incentive for motor manufacturers or others to individually implement new insulating system qualification programs using modern materials and fabrication techniques.

8.2 Rewind/Repair Advantages

There are two potentially significant advantages to repairing/rewinding harsh qualified motors in lieu of replacement. The first advantage involves cost and schedule; the second relates to reductions in warehouse inventory.

Replacement, harsh environment qualified, form-wound motors can cost upwards of $250,000 with long lead times (e.g., 26 - 52 weeks). Rewinding / repairing costs are significantly lower and can save $150,000 - $200,000 per motor with substantially reduced lead times. The cost saving for the larger size (e.g., 50 - 100 hp) random-wound motors can be in the range of $75,000 - $150,000 per motor with repair lead times of a few days or weeks. The cost savings are not as significant for small random wound motors, including those used in MOVs. However, if replacement motors are not available in utility or vendor stock, four to five month lead times are not uncommon for these smaller motors. Rewound / repaired motors could be provided at comparable costs within a few weeks.

Another benefit of the rewind / repair option, as an alternative to replacement, is the potential for reducing the safety-related motor inventory. Except for MOV motors, most harsh qualified motors in a single unit plant are application unique and can only be interchanged with their safety system's redundant counterpart. Since these safety-related motors are critical items, a failed motor must either be replaced / repaired or the plant shutdown within a few days until the motor is replaced / repaired. Because these motors are critical to safety and power production, most utilities procure and warehouse spare motors, either individually or through participation in a shared spares program, particularly for motors with long replacement lead times. Without an available spare, a utility faces the risk of a long forced outage.

Utilities may opt for a third option, *timely repair of the existing motors*. If a degraded / failed motor can be repaired with a few days or weeks, a utility need not warehouse costly, replacement motors that may never be needed.[1] Except for the harsh environment qualified insulating system, all the other motor components can be readily replaced with items equivalent to those originally qualified. However, the insulating system materials and fabrication methods are generally proprietary. Even if the insulation system design data is available, the original materials may be unavailable or the process incompatible with the repair facility's capabilities. The availability of qualified harsh environment insulating systems for rewinds would significantly strengthen the repair option. In summary, cost, schedule, and inventory reduction incentives suggest that utilities should develop harsh environment qualified motor rewind systems.

8.3 Qualification Program Recommendations

Virtually all existing motor qualification type tests have focused on demonstrating the qualification of insulating systems fabricated by a single motor manufacturer or

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1 This is particularly true for safety-related motors that are normally in stand-by duty and see little operational aging during a plant's lifetime.

repair facility. Consequently, the insulating system design, materials, fabrication methods, procedures, and personnel training reflect the skills, techniques, equipment, and capabilities of a single facility or manufacturer. Although others should be able to fabricate similar qualified windings with adequate information and training, the availability and cost-effectiveness of qualified harsh rewinds would be significantly enhanced if future efforts to qualify rewind systems were designed to have broader applicability.

Sections 4.0 through 7.0 of this guideline discuss motor qualification and a number of issues which should be evaluated when developing objective evidence supporting qualification of harsh environment motor rewinds. These topics included: evaluating existing motor qualification tests and analysis for specific harsh applications; specifying, procuring, and accepting insulating materials; fabricating the rewind; and evaluating substitute materials. The detailed material and recommendations provided in these sections should aid in the development of new qualification programs.

The ideal motor rewind system would be:

- easy to fabricate
- relatively low in cost (by using common materials and labor saving techniques)
- tolerant of minor variations in materials or the fabrication process
- highly resistant to aging and accident conditions

Unfortunately, systems possessing all these attributes do not exist for LOCA type harsh conditions. Of these four characteristics, the two most important are resistance to aging / accident conditions and tolerance to material / fabrication variations. Fabrication ease may be important when it directly relates to variation tolerance. Given the inherently high cost of safety-related motor repair, material and labor direct labor costs are of secondary concern. The following material identifies several topics and provides additional suggestions that should be considered if new motor rewind insulating system qualification programs are initiated.

8.3.1 Electrical Characteristics

The qualification program should focus on the appropriate range of voltages (system and turn-to-turn) and rated temperature rise encountered in most harsh motor applications. Although the average temperature rise for Class B motors is 80 °C, most manufacturers have limited the rated temperature rise for harsh environment Class B applications to lower values (e.g., 65°C). Similarly, form-wound constructions are found on 460, 575, 4 kV, and 6.6 kV rated motors in harsh applications. However, in U.S. reactor types only 460 and 575 Vac applications require qualification for inside containment LOCA conditions. Finally, commercial form-wound motors may be designed with turn-to-turn voltages of 100 vpm but motor manufacturers generally limit turn voltages in harsh qualified form-wound motors to values of 50 vpm or less.

8.3.2 Aging and Accident Conditions

Aging and accident conditions should *represent* those encountered in most applications. Experience suggests that simply combining the worst case conditions from a range of applications produces composite conditions that are overly severe. Where feasible, analysis and partial testing should be used to limit the severity of the aging and accident conditions. Examples include the use of thermal lag analysis to limit inside containment MSLB superheat temperatures and shielding or diffusion calculations to limit the significance of accident beta radiation levels.

8.3.3 Material Selection

Safety-related motor repairs can cost from five to ten times more than equivalent commercial repairs due to procedures, process / material controls, and documentation requirements. Since material costs become relatively insignificant, only high quality materials with superior capabilities should be used . Emphasis must also be placed on materials that will have long-term availability. For example, solvent-based resins have a questionable future due to EPA regulations in the United States. Consequently, new qualification programs should focus on solventless and water-based resins. Other environmentally-based regulations may limit the future availability of other material formulations or chemical intermediates. Preference should also be given to materials produced by several suppliers. When equivalent materials (e.g., polyimide magnet wire, silicone insulated lead wire, mica tapes) are available from several suppliers, products from several manufacturers should be included in the qualification program. This broadens the testing applicability and minimizes the need to perform substitution evaluations.

8.3.4 Material Control

Material manufacturers that adequately control product changes should be selected. This control minimizes the additional shop / utility efforts necessary to accept the materials as commercial grade items. When accepting commercial materials for use in qualified rewinds, utilities are responsible for demonstrating that there are no significant material changes. This effort is greatly simplified if manufacturers have established adequate controls over the materials and production methods used to manufacture their products. Preference should be given to manufacturers with documented product controls. Examples include: compliance with military or federal specifications, listing on the federal Qualified Products List (QPL), listing by Underwriters Laboratories (UL), or implementing a quality assurance program in accordance with recognized quality standards, such as the ISO9000 series. Ideally, arrangements should be made with manufacturers so that appropriate notifications are made whenever product changes occur. Joint utility commercial grade manufacturer surveys should be considered, since they facilitate the use of manufacturer certification as a basis for material acceptance.

8.3.5 Material Substitution

Ideally, material substitutions should not be necessary. However, manufacturers often make changes to the composition or processing of insulating materials or eliminate or redesign a product line. Other manufacturers often provide equivalent or superior products. Material substitutions should be permitted in all cases when the fabricated insulating system containing the substitute material is equivalent or superior to the originally qualified system. The dielectric, mechanical, and thermal capabilities, and environmental tolerance should be equivalent or superior during both normal and accident conditions. Although a new qualification testing program may be warranted when major insulating system material or fabrication changes are made, full requalification is not necessary when relatively minor substitutions are properly evaluated. Substitution evaluations can be greatly facilitated if information on the characteristics of the original materials and systems are readily available. There are several methods of providing this information, including retaining material and insulating system samples for future comparisons and performing limited baseline tests on material or system samples (e.g., motorettes). Data from these baseline tests can be compared to the results of similar tests performed with substitute materials/systems and the comparative results used to determine the adequacy of the substitution. For example, aged or unaged sealed system formettes could be immersion or steam tested for several days to establish moisture tolerance, level of environmental sealing, and fabrication quality. Periodic dielectric, insulation resistance, or power factor tests could be used to determine the level of degradation produced by the test. Similar tests on systems with substitute materials could be made and the results compared with the original system data. If equivalent or superior performance was achieved with the substitute system, the testing could demonstrate the adequacy of the substitute material with respect to overall system moisture tolerance and environmental sealing.

8.3.6 Reproducibility

Materials and fabrication methods should be selected that minimize quality and performance variations among rewound motors. Fabrication methods should be easily replicated by competent repair facilities. Since the systems will be fabricated in various facilities, highly complex or specialized fabrication methods, using difficult to handle materials, should be avoided. Furthermore, the systems should be amenable to fabrication in a wide range of motor sizes. For example, a qualified random-wound system design may need to be installed in both fractional horsepower and very large integral horsepower motors. The goal should be an environmentally resistant design that can be consistently replicated with relative ease for a specific range of motor sizes.

8.3.7 Qualifying the Facility

Some objective evidence must be available demonstrating that the overall fabrication process, at each rewind facility, produces windings that are equivalent in capability to those originally qualified. A range of options are available. One method would be for each shop to fabricate a sample winding or motor that would be used to assess the overall quality of the shop's fabrication process. The sample would be subjected to a series of tests and inspections that verify overall quality and capability. If the sample passed the tests and inspections then the facility would be acceptable. These tests might include power factor tip-up tests, voltage-endurance tests, dielectric breakdown tests, NEMA MG-1 sealed system tests, or destructive examination of coil and connection constructions. Alternatively, sample coils, fabricated with each repaired motor, could be tested or destructively examined to verify characteristics critical to qualification.

8.3.8 Process and Procedure Guidance

Since qualified rewinds will be fabricated by various facilities, sufficient guidance must be available to insure that all fabrication steps critical to qualification replicate those used to fabricate the qualification test specimens. The fabrication guidance should include appropriate drawings, procedures, and photographs and should be written to facilitate the development of shop-specific procedures and controls. The guidance should recognize that variations in motor design, size, and construction or shop equipment may require some modifications to certain fabrication steps. In those cases where critical skills are required, it may be appropriate to establish tests and criteria that can be used to certify shop personnel.

8.3.9 Specialized Equipment

The fabrication process should use equipment that is available in most modern rewind shops. The qualified rewind method should not employ processes or special equipment that cannot be replicated or procured by such rewind shops. For example, VPI processing procedures should reflect the capabilities of most VPI equipment. The resin curing process should not require specialized ovens (e.g., equipment to rotate windings during cure). Similarly, specialized machine taping, coil forming, hot pressing, or brazing equipment should not be necessary.

8.3.10 Production Tests and Inspections

The fabrication process should include appropriate production and post-production inspections and tests to verify the overall quality of the winding construction. These inspection / test activities should consider both characteristics critical to qualification and those important to overall quality. The selected production and post-production tests and inspection techniques should be within the capabilities of quality rewind shops.

8.4 Qualification Using Analysis and Partial Test Data

In addition to establishing type test qualification of rewind insulating systems, consideration should be given to developing additional data supporting the qualification by analysis and partial test data presentations contained in Sections 6 and 7. Specialized insulating system designs are needed to tolerate the environmental conditions of LOCAs and many severe HELBs. However, standard commercial insulating systems may be more than adequate when radiation is the only harsh environmental condition or when TEFC type enclosures limit the severity of internal motor conditions during low pressure HELB steam events. The technical conclusions contained in Sections 6 and 7 of this report would be strengthened if future qualification testing efforts provided data supporting the generic conclusions contained in these sections. Specifically, HELB testing of TEFC type enclosures could provide additional data further demonstrating the inherent protection provided by these enclosures and radiation fragility tests could demonstrate the significant dose margin between required qualification doses and those necessary to produce failures in representative insulating systems.

Appendix A

MOTOR RETREATMENT

During development of this guideline, questions were raised regarding acceptability of the common practice of cleaning and retreating motor windings for harsh environment motors. After some discussion, the task group agreed that this issue was beyond the scope of the current document. However, several observations regarding this practice can be made. First, the acceptability of this practice for harsh environment motors involves a number of considerations including the need for the treatment, motor condition prior to cleaning / treating, type of environmental conditions occurring during the harsh environment (e.g., steam / humidity), and motor type, design, and required performance.

The retreatment may be necessary because the motor winding exhibited poor performance during operation or condition monitoring tests (e.g., insulation resistance). This suggests 1) the winding has been exposed to significant aging stresses not fully addressed in the qualification, 2) the winding was not properly fabricated, or 3) unexpected damage occurred during installation, operation, or maintenance . In any of these cases, retreatment may temporarily correct the symptom (e.g., low insulation resistance) under normal conditions but the winding may or may not be able to function during harsh conditions, particularly after additional in-service aging. Further, it would be difficult to conclude that the winding would function during accident environments without some additional objective evidence (testing and analysis) demonstrating performance under such harsh conditions. This is particularly true for any accidents (e.g., LOCA) that would subject the winding to steam or high humidity conditions. For a radiation-only environment, the retreatment could be more easily justified.

Alternatively, cleaning and retreating might be performed as a periodic preventive maintenance activity rather than as corrective maintenance. In this case, one might argue that the treatment only improves an already fully qualified motor. While this may be generally true, there must be evidence that cleaning and retreating will not expose the winding to degrading conditions or place the winding in a state more prone to failure during the accident conditions. Both the cleaning and treatment methods should be considered.

The most obvious issue regarding retreatment is compatibility of the winding materials (particularly the original resin) with the new resin. Ideally, the retreatment resin should be identical to the original resin. Generally, if the winding is exposed to high humidity / steam accident conditions, retreatment as corrective maintenance is not recommended. For radiation-only harsh conditions, evaluations may conclude that the practice is acceptable particularly when material compatibility is established.

Target:
Nuclear Power

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