DCN 93-226-309-02
DOE/CE/23810-21

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ACCELERATED TEST METHODS FOR PREDICTING THE LIFE OF MOTOR MATERIALS EXPOSED TO REFRIGERANT/LUBRICANT MIXTURES

FINAL REPORT FOR PHASE 1: CONCEPTUAL DESIGN

Prepared for:

The Air-Conditioning and Refrigeration Technology Institute
Under
ARTI MCLR PROJECT 655-51300

Prepared by:

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Notice

This research project is supported, in whole or in part, by U.S. Department of Energy grant number DE-FG02-91CE23810: Materials Compatibilities and Lubricants Research (MCLR) on CFC-Refrigerant Substitutes. Federal funding supporting the MCLR program constitutes 93.67% of allowable costs. Funding from non-government sources supporting this project consists of direct cost sharing of 6.33% of allowable costs; and significant in-kind contributions from the air-conditioning and refrigeration industry.

18 August 1993

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1.0 INTRODUCTION

1.1 Background

Refrigeration equipment, including chillers, space air conditioners, and other refrigeration equipment, are all collectively referred to in this report as refrigeration equipment.

Most stationary electrically powered refrigeration equipment relies on hermetic or semi-hermetic motor-compressor units. In hermetic motor-compressor units, the electric motor and compressor are permanently sealed in a steel case, eliminating the potential for leaks of refrigerant from rotating shaft seals. Motor-compressor units are sometimes semi-hermetic, meaning that the case is designed so that disassembly for motor or compressor maintenance is possible. In either case, very long, reliable motor life is of great economic importance because of the difficulty in accessing the motor for repair.

The development and selection of insulation materials--nonconductive polymeric films, sheets, wire coatings and varnishes, and other non-metallic components--for hermetic refrigeration motors, including air conditioning motors, operating with conventional chlorofluorocarbon (CFC) refrigerant/lubricant mixtures occurred primarily in the 1960's and 1970's. There appears to have been little subsequent development of improved insulation materials, though there were continuing proprietary investigations into the effects of modified motor design on reliability. The materials in common use are demonstrably reliable, as evidenced by the longevity of equipment such as domestic refrigerators and freezers. These materials are economical. The major innovations have occurred in the economics of selection and application of hermetic motor and wire insulation material.

The federally mandated phase-out of chlorofluorocarbon (CFC) refrigerants requires that alternative refrigerants be identified, and the U.S. Department of Energy and the Air-Conditioning and Refrigeration Technology Institute (ARTI) are supporting an extensive program to identify suitable alternatives which are more reactive HCFC's, which tend to break down in the lower atmosphere, reducing the amount of reactive chlorine reaching the stratospheric ozone layer, or ideally with HFC's which contain no chlorine at all. Selection of alternative refrigerants frequently also requires selection of alternative lubricants which are compatible with the alternative refrigerants. Selected alternatives must be compatible with existing refrigeration equipment without sacrificing reliability.

Earlier phases of the ARTI program has included evaluation of the stability and thermodynamics of alternative refrigerants and refrigerant/lubricant mixtures, as well as screening candidate refrigerant and refrigerant/lubricant mixtures for significant degradation effects on the metals, plastics, elastomers, and individual motor

insulation materials used in hermetic motors. These screening tests for motor materials relied upon observations of gross properties changes (i.e., dissolution, swelling, shrinkage, cracking, alteration of tensile properties) in specimens aged by the ASHRAE sealed tube method, and on destructive "stress-to-failure" electrical properties tests, including dielectric breakdown potential, burnout current at 500 V, and resistance to blistering under rapid temperature transients.

Results of tests of this sort, while useful for screening motor materials, are most difficult to interpret in terms of life expectancy. There are several reasons for this difficulty. The test conditions, particularly the conditions under which the failure inducing stress is applied, are not representative of service conditions because the test specimen is typically removed from the sealed tube prior to stressing. This removes the refrigerant/lubricant component of the insulation system. The applied current or voltage stress required to produce failure is typically several times the maximum design value. Results tend to be highly scattered. While such tests may allow qualitative comparisons of responses to materials and different refrigerant/lubricant mixtures, they do not yield rate data which can be used to project properties as a function of time.

In the current phase of its program, ARTI is supporting tests of promising candidate refrigeration/lubricant systems in key refrigeration component systems such as bearings and hermetic motor insulation systems to screen for more subtle detrimental effects and allow estimates of motor-compressor life.

1.2   Development of an Improved Accelerated Hermetic Motor Life Test

ARTI contracted Radian Corporation to attempt the development of improved accelerated test methods or procedures allowing prediction of the life of motor insulation materials used in hermetic motors for air conditioning and refrigeration equipment operated with alternative refrigerant/lubricant mixtures.

1.2.1   Basic Criteria Defining an Acceptable Improved Test

Effective long-term reliability testing of hermetic motor insulation systems requires the simultaneous testing of a variant of components, varnishes, slot liners, phase separators, and wedges in combination since interactions between these materials can be significant.

ARTI identified the following criteria which would have to be satisfied for the improved method to be generally useful to the refrigeration equipment industry.

To be technically useful, the proposed new method or procedure would need to:

- Use equipment and instrumentation commonly available or readily obtainable by ARTI member companies which perform engineering evaluations;
- Not operate at temperatures above 150°C, which would likely cause abnormal thermal decomposition of the refrigerant/lubricant mixture, unless the method is intended expressly to test effects of thermal excursion;
- Provide safe operation at the moderate pressures and moderate temperatures resulting from simulation of the hermetic motor refrigerant/lubricant operating environment;
- Provide results in as short a time as possible, but within months rather than years.

To be practically feasible, the new method or procedure would also have to:

- Offer clear technical advantages over existing methods; and
- Be cost effective.

It was recognized by ARTI, ARTI's industry advisory board, and by Radian that the probability of successful development of a significantly improved accelerated motor life test was not great, but that the potential benefits of an improved test justified a modest exploratory effort.

1.2.2 Scope of the Current Work

As a consequence, the work was divided into two phases. Phase 1, the subject of this report was a conceptual design and technical feasibility study with the following scope:

- Summarizing the current information on mechanisms of degradation of non-metallic hermetic motor materials, and the test methods currently used to evaluate the compatibility and stability of those materials with refrigerant/lubricant mixtures; and
- Proposing a conceptual test method or methods and data analysis procedures, based on readily available or obtainable equipment and instrumentation, that will predict the life of motor insulation materials exposed to alternative refrigerant/lubricant mixtures after test periods of not more than several months; or

- Defining the technical limitations preventing the proposal of a test method or methods meeting the criteria discussed previously.

1.2.3 Technical Approach

Radian Corporation conducted an exhaustive automated literature search, for information pertaining specifically to:

- The mechanism(s) of degradation and failure of hermetic motor insulation materials; and
- Methods and approaches currently used for accelerated "life" testing of hermetic motor insulation systems.

The information obtained from the literature searches was supplemented by extensive personnel communications with representatives of the refrigeration industry, hermetic motor manufactures, and hermetic motor rewinding companies.

A summary discussion of the mechanisms of degradation and failure of hermetic motor insulation systems is presented in Section 2, while a summary discussion of current approaches to life testing or prediction of hermetic motors is presented in Section 3.

Citations for key literature documents and a listing of telephone contacts are included in Section 6.

1.3 What Has Been Accomplished

Radian found that the majority of hermetic motor insulation failures occur in the stator windings of the motors as a result of a combination of thermal, chemical, and mechanical interactions.

Radian found that the refrigeration industry has relied for the last 20 years on two accelerated test methods for evaluation of hermetic insulations systems. Both methods are described in some detail in Section 3.

The IEEE Motorette test relies on a simplified simulation of a stator winding as a test device. The windings of the motorette are stressed with potential, but not current, in a refrigerant/lubricant environment while being heated to system operating temperatures by external heaters. By nature of the design of the motorette, the magnetic forces operating on the windings are not simulated. Motorettes were developed for comparative testing of insulation materials, and the motorette test is specified by Underwriters Laboratories for testing of alternative hermetic motor insulation materials.

The refrigeration industry has long used variations of the "plug-reversal" test to evaluate effects of design modifications on three-phase motors. To Radian's knowledge, plug-reversal tests have not been used to assess insulation compatibility *per se*. The plug reversal test uses an entire hermetic motor-compressor unit as the test piece. The compressor is modified so that the motor can rotate in either direction with equal ease. The test unit is inserted into a complete refrigeration loop between the evaporator and a working compressor. The polarities of two of the three phases are repeatedly reversed with each reversal causing the motor to stall and rotate in the opposite direction. Plug reversal simulates locked rotor operation, and it has been postulated that the number of reversals to failure is proportional to actual motor life.

Plug reversal tests simulate the full range of forces and factors operating on hermetic motors. However, the overall test apparatus is complex. Plug reversal tests have additional complications if used for the evaluation of insulation compatibility with alternative refrigerant/lubricant mixtures. Two of the inherent drawbacks of plug-reversal testing for evaluation of insulation with alternative refrigerant/lubricant mixtures are that:

- There is a significant probability that failure of some other component of the supporting refrigeration loop may fail consistently prior to motor failure; and
- The entire test loop must be entirely purged of one refrigerant/lubricant mixture before another is introduced.

In a practical sense, the latter requirement could mean that complete new test loops would be required for each refrigerant/lubricant mixture tested.

In this project, Radian has produced the conceptual design for an improved hermetic motor insulation test device, a simulated stator unit or SSU. The SSU represents a significant improvement over the IEEE motorette device because the SSU much more fully simulates the complex interactions of thermal, chemical, magnetic, and mechanical forces acting on stator windings, the most vulnerable component of hermetic motors. At the same time, the SSU eliminates much of the complex supporting equipment of the plug-reversal test, combining the best features of the motorette test and the plug-reversal test.

Radian believes that the proposed device potentially represents a significant improvement in the state-of-the-art of hermetic motor insulation test devices. Radian believes that the proposed device and test methods will:

- Allow estimation of the life of unused hermetic motor insulation systems in alternative refrigerant/lubricant mixtures *relative* to the conventional refrigerant/lubricant mixture being replaced;

- Allow estimation of the life of used hermetic motor insulation systems (previously exposed to a conventional refrigerant/lubricant), in alternative refrigerant/lubricant mixtures *relative* to the conventional refrigerant/lubricant mixture being replaced.

Testing for any particular refrigerant/lubricant mixture will probably require not more than three months exposure. The time required to test any suite of insulations systems and refrigerant/lubricant mixtures will depend upon the number of parallel test devices in operation.

The results will be relative, i.e., how does the performance of the insulation system in the alternative refrigerant/lubricant compare to its life in the conventional refrigerant/lubricant being replaced.

Radian believes that an accelerated test which allows prediction of the absolute, rather than relative, life of hermetic motor insulation or of entire hermetic motors remains beyond the current state-of-the-art.

2.0 MECHANISMS OF FAILURE OF HERMETIC MOTOR INSULATION

2.1 Description of the Hermetic Motor Insulation System and Operating Environment

The stators (and rotors) of hermetic motors, like other electric motors consist of stacks of thin stamped sheets of electrical steel, each coated with electrical insulation to prevent eddy current heating in the magnetic cores. The slots in the magnetic cores are lined with a sheet of film insulation material designated as slot liner. The pre-insulated wire is wound into coils on special winding machines which prevent crossover or twisting of the parallel wires in the coil. Cross-overs represent probable sites of premature failure.

The first coil winding is inserted into the slots in the magnetic core and pressed firmly to the bottom of the slots. A strip of phase insulation is inserted on top of the first winding, followed by installation of the second coil winding. The two windings are held in place with a wedge of insulating material called the slot wedge. Insulating cord is then used to bind everything in place.

The final component of the insulation system is varnish. The entire assembly is submerged in a varnish bath, frequently under vacuum, until the windings are permeated with varnish. The assembly is withdrawn from the varnish bath at a constant slow rate, resulting in reproducible varnish film thicknesses, and baked to cure the varnish.

The slot and phase insulation films prevent rubbing of the wire against the magnetic core and provide the dielectric material rated to withstand electrical stresses between coils with adjacent applied phase voltages. The slot wedges hold the windings in place, and the varnish bonds the wires of each coil together, preventing wire-to-wire motion.

The hermetic motor is enclosed in the hermetic motor case where it is bathed in lubricant and cooled by refrigerant vapor which passes through the motor housing on its way to the suction inlet of the compressor. Vapor temperature entering the hermetic motor varies considerably depending on system design, load, and ambient conditions but is typically on the order of 20°C for air conditioning equipment. The refrigerant vapor passes around the rotor and in some cases through channels in the rotor as well.

Hermetic motors are protected by thermal sensors to prevent sustained operation above the lesser of the maximum rated temperature of the insulation or 150°C, as the refrigerant/lubricant is unstable at higher temperatures.

Under normal operating conditions, the motor is not subjected to liquid refrigerant, but slugs of liquid refrigerant can enter the motor under abnormal conditions. In addition to mechanical shock as the liquid slug collides with the spinning rotor, liquid slugging imparts a severe thermal shock as the liquid refrigerant boils upon contact with the hot motor components.

2.2   Causes of Hermetic Motor Failures

An insurance industry survey [Stouppe and Lau, 1989] of over 15,000 refrigeration and air conditioning system failures found 76.6% of the failures were electrical in nature. Of these electrical failures, 86.6% involved failure of the stator windings, 5.2% involved motor control equipment, and 8.2% involved auxiliary motors, fans, and controls. Of the 23.4% of the failures which were not electrical, 18.9% involved the compressors, and 4.5% involved other components of the refrigeration loop. The survey found that the typical age of a failed hermetic refrigeration motor was nine years, while the typical aged of a failed air conditioning motor was 10 years.

The survey found that 84.0% of all hermetic motor failures involved the stator windings, 9.6% involved the rotor bars, 1.4% involved the bearings, and 5.0% involved motor control equipment.

2.2.1   Extrinsic Failures

Hermetic motors can fail for a variety of reasons extrinsic to the insulation system or interactions between the insulation system and the refrigerant/lubricant mixture. Some of these factors include:

- Short-cycling;
- Stuck contacts;
- Broken thermal protection devices;
- Operation with incorrect refrigerant/lubricant charges;
- Frequent or repeated compressor slugging;
- Inadequate condenser cooling;
- Moisture contamination; and
- External shorts, electrical current abnormalities, and lighting strikes.

While all of these causes of failure may result in a "burnt" motor, their origins lie outside the motor insulation system and the normal operation of the hermetic motor. Evaluation of these modes of failure is beyond the scope of this discussion.

2.2.2 Intrinsic Modes of Failure

The intrinsic modes of failure, those which are inherent in the insulation system itself, are the modes of failure of concern in any estimation of the effect of alternative refrigerant/lubricant mixtures on insulation life. The understanding of these failure mechanisms has evolved over time from a simple thermal degradation model, through a thermochemical aging model, to a model involving both thermochemical aging and thermomagnetodynamic fatigue.

The Thermal Degradation Model

The simplest model for the degradation of hermetic motor insulation is the thermal degradation or threshold temperature model. Quite simply, hermetic motors can not be operated above certain critical temperatures without rapid failure of the insulations system.

Operation of systems charged with R22 above approximately 150°C results in thermal breakdown of the refrigerant and the formation of HCl, HF, and reactive halogenated organic acids, all of which can attack the insulation materials directly.

In addition, the insulation materials become saturated over time with refrigerant. Some of the decomposition products of the refrigerant significantly reduce the dielectric strength of the insulation, particularly of the wire and varnish.

Even at temperatures below the stability limit of the refrigerant, insulation exhibits a distinct maximum temperature ($t_{\max}$) above which rapid, irreversible degradation of properties occurs. Figure 2-1 illustrates the occurrence of $t_{\max}$ for a hermetic motor wire insulation in R22/mineral oil. This figure shows that degradation rates as measured by increases in the capacitance dissipation factor ($\tan \delta$), are slow until $t_{\max}$ is reached, but increase very rapidly beyond that point. This figure also shows that $t_{\max}$ is sensitive to materials variations.

The Thermochemical Aging Model

It is well known that operation at elevated temperatures (even below $t_{\max}$) shortens motor insulation life. Analysis of historical operating data for different classes of non-refrigeration motors have shown that within each insulation class motor life decreases rapidly with increasing operating temperature, with results conforming to the Arrhenius equation ($k = Ae^{-E^*/RT}$, where A is the pre-exponential, or frequency, factor, T is the absolute temperature, E^* is the activation energy, and R is the appropriate

Figure 2-1. The manifestation of $t_{\max}$ in hermetic motor wire enamels and varnishes as indicated by increases in the capacitance dissipation factor ($\tan \delta$), after Spaushus and Sellers, 1969.

gas constant) [Brancado, 1992]. Figure 2-2, plotted by Brancado from Arrhenius regressions of Class B and Class H motor life data, shows the effect of increased operating temperature on motor life in non-Arrhenian, but intuitively more understandable, coordinates. This figure shows that Class B motor life is halved for each 11°C rise in operating temperature. For Class H motors, the life is halved for each 8°C rise in operating temperature.

In the early 1960's work by General Electric investigated the capacitance degradation of hermetic motor wire immersed in R22/mineral oil. An example of the results are shown in Figure 2-3, which illustrates results for two different wire coatings (C_1 , C_2) tested at two pressures ($P_1 = 50$ psia, $P_2 = 200$ psia) over a range of temperatures.

Both the pre-exponential (or frequency) factor (A) and activation energy (E^*) of the Arrhenius Equation can be determined from the slopes and intercepts of the plots in Figure 2-3. Once these parameters are quantified, the degradation rate can be calculated at any other operating temperature.

The inflection in each of these plots corresponds to $t_{\max}$, and demonstrates that different degradation mechanisms are active once rapid degradation begins. The segments to the right of the inflection represent the kinetics of aging at temperatures below $t_{\max}$ (i.e., normal operating temperatures). Because different mechanisms with different rate constants operate above and below $t_{\max}$, data obtained above $t_{\max}$ cannot be used to determine degradation rates below $t_{\max}$. For Class F and Class H insulations, $T_{\max}$ may exceed the breakdown temperature of the refrigerant/lubricant.

It is worth noting however that while many hermetic motors are equipped with thermal protection devices to prevent sustained operation at temperatures above a set protection limit (i.e, above the lesser of $t_{\max}$ or the refrigerant/lubricant breakdown temperature) transients above both $t_{\max}$ and the refrigerant breakdown temperature probably occur in most motors under normal operating conditions. Carrier Corporation determined that in hermetic motors rated at 130°C full-load continuous-service, wire surface temperatures on start-up were on the order of 60°C higher than the nominal operating temperature, so that wire surface temperature transients to 200°C or higher occurred at each start-up, while temperatures within the windings peaked at around 250°C for brief periods. The average temperatures of integral-horsepower, random-wound motors rated at 130°C full-load continuous-service can soar to 245°C in just 15 seconds when cycling under locked-rotor conditions, and peak internal temperatures would be even higher [Hall, 1969]. Under these conditions, refrigerant/lubricant in tight crevices in the windings may break down, creating a local environment much different and more aggressive than the bulk fluid. Refrigerant dissolved in the varnish boils under these conditions, and it is not unreasonable to suspect that microscopic blistering may occur. Thus, the coating is subjected to both thermal shock and an increasingly aggressive local environment as a result of start-up surges.

Figure 2-2. Responses of non-refrigeration motor life to operating temperature for two motor insulation classes, redrawn from Brancado, 1992.

Plotted by Brancado from Arrhenius regressions of motor life data.

Figure 2-3. Arrhenius plots of conductance degradation rates of two hermetic motor wire insulation materials at two pressures in R22/mineral oil, after Spaushus and Sellers, 1969.

The inflections in each curve correspond to t_{max} , and demonstrate that different degradation mechanisms with different rate constants operate above and below t_{max} . This means that degradation data obtained above t_{max} cannot be used to estimate degradation rates below t_{max} .

The industry recognition that hard-start conditions may be the life-limiting operational step lead directly to development of the plug-reversal test, described in more detail in Section 3, and the apparently generally accepted premise that hermetic motor life is directly proportional to the rate of hard-start or locked rotor events [Hourahan, 1984]. Stated in other terms, the assumption is that a particular hermetic motor design has a certain number of hard starts in its lifetime.

Magnetomechanical Thermochemical Degradation Model

As General Electric continued to investigate the causes of failure of larger hermetic motors, those above 3 hp, it became increasingly apparent that the thermochemical degradation model did not completely explain the mechanisms of failure which were being observed. In particular, GE found that hermetic motor life was inversely related to power rating [Crawford, 1975].

Consequently, GE conducted detailed post mortems on a large number of hermetic motors in the 5 hp and larger size range after failure in an aggressive plug-reversal test. Failure patterns showed very little general insulation aging [Crawford, 1975]. Once failure causes like stuck contactors, shorted capacitors, and failure of thermal protection devices were eliminated, the predominant root cause of failure was found to be mechanical abrasion or fretting of the wire-to-wire insulation, resulting from wire motion [Crawford, 1975]. Both reciprocating axial wire motion within the slots and bending/reverse bending motion of the end turns of hermetic motor stator windings were quite visible in 1/125th-speed motion pictures prepared by Crawford [Crawford, 1975; Leoni, 1993].

The mechanical wearing occurred when operational stresses caused a breakdown of the bond between the varnish and other insulation materials. Four key sources of stress were identified:

- Varnish weakening at higher temperatures,
- Magnetic forces due to winding currents,
- Differential thermal stresses; and
- Different coefficients of thermal expansion.

The following sequence to failure was identified:

- Operation at elevated temperature weakens the varnish/wire bond (thermochemical aging);

- The combination of magnetic and differential thermal expansion forces created by inrush surges and/or liquid refrigerant backflooding exceeds the restraining strength of the varnish;
- The wires begin to vibrate 120 times a second under the AC magnetic field, further degrading the varnish bond and progressively increasing the magnitude of relative wire motion;
- Abrasive wear leads to baring of conductors and contact probably at 120 times/second as a result of magnetodynamic forces in the windings, producing low-power intermittent arcing which accelerates insulation damage at that point;
- The low-power, intermittent arcing draws enough power to weld the conductors;
- High induced currents in the shorted loops leads to rapid failure.

The role of mechanical fatigue of the varnish bond is well demonstrated through an inverse correlation between motor power (magnetic flux intensity) and cycles to failure.

The most common location of looseness and failure in stators was wire-to-wire within the largest two coils, most often at a point between about one inch inside the slot (the laminated iron) and a point about one inch beyond the surface of the iron in the end turns. The two largest coils have the most turns and greatest mean turn length, as well as the least amount of mechanical support as they leave the slot and join the end turn bundle.

Coil-to-coil wear occurs when two adjacent coils in the same pole become loose and vibrate against one another. Because the voltages between coils are higher, arcing is more severe once the wire enamel is abraded.

Wire-to-ground insulation wear occurs when loosening of bonds between the magnet wires and ground insulation (slot liner) allows motion between these components. While considerable slot liner wear at these locations was observed in some failed motors, this did not contribute to any of the failures studied by GE for at least two reasons. First, the deepest wear observed in the ground insulation was less than 16% of the film thickness. Second, the wire insulation was less abrasion resistant than the film. Thus, either no failure occurred at these locations, or the failure was actually wire-to-wire. There were apparently no "cut-throughs."

This magnetomechanical thermochemical aging model appears to offer the most complete description of the factors affecting the intrinsic life of hermetic motor insulation materials.

2.3   Implications for an Improved Accelerated Life Test

The magnetomechanical thermochemical degradation model has significant implications for development of an accelerated test for the life of hermetic motor insulation systems exposed to alternative refrigerant/lubricant mixtures. The most important of these implications are that attention can be focused on the stator windings, as these were the point of failure in the overwhelming majority of failures, and that the accelerated test must mimic the differential thermal expansion, thermal, and magneto-mechanical forces operating on stator windings.

3.0 CURRENT METHODS FOR ESTIMATION OF THE LIFE OF HERMETIC MOTORS

Two types of tests have been widely used by the air conditioning and refrigeration industry as "accelerated motor life" tests, the IEEE Motorette Test, and the "Plug Reversal Test." A third methodology was explored by General Electric in the early 1960's but subsequently abandoned. These three methods, which serve as the basis for the improved method proposed by Radian, are discussed below.

3.1 Motorette Tests

The IEEE motorette was codified in 1956 under IEEE Standard 117, and revised in 1974, for the express purpose of providing a convenient means of testing new electric motor insulation materials [IEEE 117-1974].

3.1.1 Description of Motorette

Motorettes are designed to be small-scale models of electric motor stator windings [IEEE 117-1974, Cypher and Harrington, 1952]. Each motorette consists of a pair of simulated slots, fabricated from two pieces of mild carbon steel (such as AISI 1010). The pieces have cross-sections resembling square-bottomed U's with different widths. The broader piece forms the bottom and outer walls of the slots, while the smaller piece forms the inner walls. The two pieces are bolted to a stainless steel base with stainless steel fittings. The two slots are 2.375 inches long and the total width is 2.5 inches. Slot depth is approximately 0.75 inches.

The two slots are lined with slot insulation, a prefabricated random-wound bifilar coil representing the first phase is inserted, followed by phase insulation and a second prefabricated random-wound bifilar coil, and slot wedges. Each coil consists of 20 turns of AWG Number 18 magnet wire wound bifilar (two-in-hand) for a total of 40 wires per coil.

Following assembly, motorettes are dipped in varnish, withdrawn from the bath at a constant slow rate and oven dried in as close a simulation of motor fabrication practice as is practical.

Normally, only one lead from each of the bifilar coils is connected to a voltage source during testing. The other (dead) ends of the coils are simply capped. This means that motorette coils are subjected to voltage stresses but not to impressed current heating, differential thermal expansion, or magnetic effects.

3.1.2 Application to Non-Refrigeration Motors

Motorettes were originally designed for testing of electric motors not associated with air-conditioning or refrigeration.

Motorettes for non-refrigeration motor testing are exposed in constant-temperature convection ovens to simulate motor operating temperatures. Table 3-1, from IEEE 117, shows the recommended test temperatures and approximate exposure time to failure. Most of the recommended test temperatures are above the decomposition temperatures of refrigerant/lubricant mixtures. The motorettes are periodically removed from the ovens and vibrated at right angles to the plane of the end coils in an attempt to simulate vibration forces on the coils, though this vibration is applied when the coils are not at peak temperature.

Analysis of motorette time-to-failure data obtained at three or more elevated temperatures allows determination of the Arrhenius constants of a particular motor insulation system. In an approach developed for estimation of motor life in nuclear power plants, motorette test results can be used both to assign a particular insulation system to an IEEE insulation class, and to estimate the life expectancy of motors operating under a range of scenarios. As an example, Figure 2-2 shows idealized results for Class B and Class H electric motors. Two values are extracted from the resulting Arrhenius plots, the "halving interval constant (HIC)" and the activation energy (E'), where the HIC is the temperature rise in kelvins resulting in a 50% decrease in life expectancy.

Given values for HIC and E' , Brancato presents a series of calculations allowing the estimation of motor life under a wide range of operating scenarios, including variable load and variable ambient temperatures. The method also allows calculation of the benefits of using a higher rated insulation system [Brancato, 1992].

3.1.3 Adaptation to Hermetic Motor Testing

Motorettes have been adapted for testing under simulated hermetic motor conditions [Emmons, 1964; Emmons, 1967; Petry, 1971; Tokunaga, et al, 1971]. Two primary adaptations were required. The first was that the motorette (or motorettes) was inserted in an autoclave (pressure vessel). Typically PARR 2-L autoclaves, having an internal diameter of 4.0 inches and free working height of 10.5 inches, were used.

Consideration of Table 3-1 shows that most of the motorette test temperatures recommended under IEEE Standard 117 are considerably higher than both $t_{\max}$, the temperature above which hermetic motor insulation degrades rapidly, and the refrigerant/lubricant breakdown temperature (see Section 2). Testing above the lessor of $t_{\max}$ or the refrigerant/lubricant breakdown temperature would produce misleading

Table 3-1

**Temperature and Exposure Time (Days) Guide
 for IEE Standard 117 Motorette Testing
 (Not Suitable for Refrigeration Motors)**

Exposure Temperature (°C)	Class A (105°C)*	Class B (130°C)	Class F (155°C)	Class H (180°C)	Class H220 (220+°C)
300					1
290					2
280					4
270					8
260					16
250				1	32
240				2	
230				4	
220			1	8	
210			2	16	
200		1	4	32	
190		2	8		
180	1	4	16		
170	2	8	32		
160	4	16			
150	8	32			
140	16				
130	32				

*Maximum full load operating temperature

results. Thus, most of the accelerated test temperatures proposed under IEEE standard 117 cannot be applied to motorettes used to simulate hermetic motors.

Another means was required to accelerate the tests, and the method selected was frequent severe thermal shocking of the motorette. Thus, the second major variant in hermetic motorette testing was the introduction of some means of applying liquid refrigerant to the coil on a periodic basis to simulate thermal shocking and liquid slugging. This variation was adopted both to better simulate worst-case hermetic motor operation, and more importantly to shorten test duration. The most common method of accomplishing this feature is through the use of a cooling coil and siphon cup in the head space of the autoclave. The cooling coil causes the refrigerant to condense into the siphon cup until the cup fills, triggering the siphon action. Then the liquid refrigerant drains onto the top of the coil, imparting a thermal shock. Typical autoclave operation results in a liquid refrigerant dump, lasting approximately 30 seconds, occurring at approximately 5 minute intervals [Emmons, 1964; Emmons, 1967; Petry, 1971; Tokunaga, et al, 1971].

Typically, the heat for hermetic motor motorettes is externally applied to the autoclave, though some tests have been performed in which all eight bifilar coil leads were brought out of the autoclave and the coils were at least partially heated by electrical resistance.

While test profiles vary, typical profiles expose the motorettes at the specified test temperature for 18 to 20 hours per day, followed by a cool down and room temperature "soak." It appears that this dormant period is quite important in the aging of the insulation system because it allows the insulation components to absorb refrigerant/lubricant. If the units remain continuously at elevated temperature, the refrigerant/lubricant is driven from the insulation. In some cases the autoclaves are vibrated at right angles to the plane of the end turns of the coils during the dormant period.

Like other motorettes, hermetic motorettes are typically run to failure, with failure being defined as shorting during the test, or failure of coil-to-coil, phase-to-phase or phase-to-ground high potential tests applied at specified intervals during the exposure. Times to failure are typically under 6000 hours [Emmons, 1967].

Different numbers of motorette have been used by different researchers to assure statistical validity. IEEE Standard 117 calls for a minimum of 10 units. UL Standard 984-1989 specifies six motorettes. Eight appears to be the most common number used. The comparative parameter most commonly used is the median time to fail (MTTF), typically calculated using Weibel statistics. An attractive alternative for incomplete data sets relies on the common observation that time to failure data typically show a geometric distribution (the logarithms of the times to failure are normally

distributed). Based on this assumption, it is possible to estimate the median time to failure well before all the units have failed [Crawford, 1970].

3.1.4 Motorette Testing Under UL Standard 984

Underwriters Laboratories has standardized motorette testing for the purpose of screening new insulation materials or combinations [UL 984-1989]. The procedure differs somewhat from that described above.

The UL 984 procedure specifies the testing of six IEEE 117 motorettes containing typically 15 to 20 turns of bifilar wound coils. They are oriented in the autoclave(s) so that each motorette is partially immersed in refrigerant lubricant during the cool portion of the thermal cycle to such a depth that the turn-to-turn, phase-to-phase, and phase-to-ground insulation materials are all exposed to liquid refrigerant/lubricant.

The test vessels are sealed and evacuated to less than 0.1 mm Hg at 149°C for one hour. After cooling to room temperature, the specified lubricant is added to the vessel to produce the partial immersion described above, and the vessel is evacuated to less than 0.1 mm Hg for one hour at 70°C. Finally the vessel is charged with refrigerant vapor in such a manner that no air is introduced into the system. The refrigerant charge is sufficient to produce a pressure between 150 and 350 psig at 140°C.

The six motorettes are held at 140°C for 288 hours followed by 48 hours at room ambient temperature. During the cool-down portion of the cycle, the autoclaves are oriented so that the motorettes are partially immersed in lubricant as described above. This cycle is repeated for a total of five repetitions, producing a total heated exposure of 1440 hours.

Following the final thermal cycle, each motorette is subjected to the following "Dielectric Voltage-Withstand" tests:

- 1 minute application of 60 Hz, 600 V AC phase-to-phase;
- 1 minute application of 60 Hz, 600 V AC phase-to-ground; and
- 1 minute application of 60 Hz, 120 V AC turn-to-turn in each coil,

using a precalibrated thermomagnetic electromechanical type device designed to trip at 0.5 to 0.75 A within 3 seconds.

The insulation system is considered acceptable if five of the six motorettes withstand the applied voltages without tripping.

3.1.5 Advantages and Disadvantages of Motorettes

The principle advantages of motorettes for testing of the response of hermetic motor insulation systems to alternative refrigerant/lubricant mixtures are that:

- Fabrication of the devices is governed by a standard increasing the probability that results by different facilities can be compared;
- The device lends itself to the testing of different combinations of insulation materials;
- The motorette devices and supporting instrumentation, while not trivial, are comparatively simpler and less costly than those required for the more elaborate plug-reversal tests described below.

While non-hermetic motorettes can be used to derive Arrhenius data from which motor life can be calculated, this is not practical with hermetic motorettes for several reasons. Referral to Table 3-1 shows that the standard motorette test temperatures for most classes of motor insulation are far higher than the refrigerant/lubricant breakdown temperature. In fact, the nominal rated temperature of some of the systems exceeds the refrigerant/lubricant breakdown temperature. This means that elevated temperature cannot be used as a test accelerant for most systems.

The frequent thermal shocking of hermetic motorettes with liquid refrigerant does accelerate the test, but no algorithm was found in the literature which suggests a means by which the resulting data can be used to project the absolute life of hermetic motor insulation systems.

However, if hermetic motor insulation tests are conducted using the same exposure methodologies, then the effect of an alternative refrigerant/lubricant on a given insulation system relative to the conventional refrigerant/lubricant being replaced can be calculated.

$$\text{Relative life} = \text{MTTF}_{\text{alt}} / \text{MTTF}_{\text{conv}}$$

where MTTF_{alt} is the median time to failure in the alternative refrigerant/lubricant and $\text{MTTF}_{\text{conv}}$ is the median time to failure in the conventional refrigerant/lubricant (most likely R22/mineral oil). Unfortunately, there appears to have been little standardization of the exposure protocol.

In contrast to tests in which the motorettes are run to failure, the UL-984 motorette test simply provides a pass-fail criterion. However, application of this criterion to alternative refrigerant/lubricant mixtures may be appropriate.

However, the two most important shortcomings of the hermetic motorette test are that it does not well simulate the differential thermal expansion forces acting on the coils, and it fails to simulate the magnetomechanical forces. As was discussed in Section 2, these forces tend to dominate the most common stator winding failure mechanism--wire-to-wire fretting and abrasion of insulation.

3.2   Sealed-Tube Aging Tests

General Electric also developed a simplified procedure for determining the Arrhenius constants of magnet wire varnish systems [Spauschus and Sellers, 1969; Spauschus and Field, 1979]. In this method, bifilar coils of magnet wire were sealed into heavy glass tubes with the desired refrigerant/lubricant. One lead of each of the bifilar coils was sealed through the top of the glass tube, allowing monitoring of the dielectric properties of the insulation.

Typically, different sealed tubes were aged for several hundred hours at each desired temperature. The degradation in dielectric properties was linear at each temperature, allowing calculation of a degradation rate. Plotting the logarithms of the degradation rates as a function of reciprocal absolute temperature (Arrhenius coordinates) provided important information concerning the kinetics of insulation degradation. Figures 2-1 and 2-3 were generated using this methodology.

While this approach can yield useful information about varnish aging, it is not of itself suitable for the testing of complete insulation systems for the following reasons:

- The test device contains only wire and does not address the degradation of other insulation components or the interactions between components; and
- The device simulates only the thermochemical aging aspects of the hermetic motor environment.

However, the method clearly demonstrates that trended dielectric property data can be used to assess degradation rates and provide comparisons between different insulation systems (or between the same system in different refrigerant/lubricants).

3.3   Plug-Reversal Tests

3.3.1   Evolution of Plug-Reversal Tests

In the 1960's there was a concerted move on the part of a number of laboratories, including General Electric and A.O. Smith (which had significantly advanced the art of hermetic motorette testing), to the use of full-scale "plug reversal"

tests (also called "rapid reversal" tests) using actual hermetic motors. While the concept of plug-reversal tests is relatively simple, the methodology has not been standardized and there are wide variations in the details [Petry, 1969; Petry, 1973; Hourahan, 1984; Hurtgen, 1971; Hurtgen, 1975; Kohne, 1975; Crawford, 1975, Okubo, et al, 1975].

Plug-reversal tests are applicable to three-phase hermetic motors. The test unit is a complete hermetic motor-compressor, modified so that the compressor can turn with equal ease in either the forward or reverse direction. This is most commonly achieved by removing the valves from the compressor. The test unit is installed between the evaporator and an auxiliary compressor in a complete refrigeration loop, so that the hermetic motor of the test unit experiences the same operating environment as a normal hermetic motor.

The test motor is energized and run in the "forward" direction for a brief period of time, the power is momentarily interrupted, and the polarity of two of the phase windings is reversed ("plug reversal") causing the motor to reverse direction.

Typically, the motor is energized for 1 to 3 seconds in each direction, with the power-interrupt between surges being 0.25 to 0.5 second. Each reversal produces an inrush current on the order of ten times the normal amperage, with corresponding surges in the magnetic fields. During the inrush, thermal dissipation is approximately 100 times normal. Motor temperature is controlled by adjusting the lengths of the power pulses and power interruptions.

The plug reversal test is designed to simulate the most severe aspect of hermetic motor operation, hard-starting or locked rotor starts. It has been postulated that hermetic motors have a certain number of hard starts, and that this capacity and the frequency of hard starts in actual operation determine the life of the motor [Hourahan, 1984].

Plug reversal tests are typically run to failure, defined as outright shorting, a 15% loss in phase-to-phase insulation, or high potential shorting failure. Because standard motors lack the bifilar windings of motorettes, turn-to-turn resistance cannot be monitored.

Plug reversal tests have been used extensively in programs to improve hermetic motor insulation and design. The results are interpreted in relative terms, i.e., percent improvement in plug reversal life of a design modification compared to a base case.

Three basic types of plug reversal test protocols are run. In the simplest, the motors are operated at a fixed temperature until failure occurs. In stepped temperature tests, the test begins at the rated maximum operating temperature of the motor, and is periodically raised to increase the thermal stresses. Shite and Jiahua

[1985] presents a mathematical treatment by which plug-reversal data under stepped temperature regimes can be interpreted to yield Arrhenius constants. However, this treatment is probably not applicable to hermetic motors because it does not account for breakdown of the refrigerant as test temperature is increased.

Most constant-temperature or stepped-temperature test procedures include a dormant period of several hours per day in which the pump is allowed to cool to room temperature.

General Electric recognized that the conventional plug-reversal tests did not simulate refrigerant slugging and did not impose severe thermal shocks and the stresses due to rapid differential thermal expansion. They developed the "Cyclic Reversal" test variant to include these factors [Hurtgen 1971; Hurtgen 1975; Crawford 1975]. In this test, motor temperature was raised from 50°C to 150°C in 22.5 minutes by plug reversals every 2.5 seconds with 0.5-second interrupts between reversals. When the temperature reached 150°C, the motor was de-energized and the stator was force-cooled with liquid R22 applied at a rate which brought the temperature back to 50°C in an additional 22.5 minutes. This cycle was repeated until failure occurred. Under the cyclic reversal test, the stators of 90% of motors in the 5 to 7.5 hp range failed in less than 10^6 reversals (approximately 2000 hrs) with 5×10^5 reversals being representative, while 100% of stators in the 7.5 to 12 hp range failed in less than 10^6 reversals. Similar motors under the conventional plug reversal test ran 6 to 12 months [Crawford, 1975].

3.3.2 Advantages and Disadvantages of Plug-Reversal Tests

Plug-reversal tests have been shown to be sensitive indicators of the impact of motor insulation design on the relative life of hermetic motors. These tests, particularly the cyclic reversal test developed by GE, represent the most complete simulation of hermetic motor operating conditions. With the development of the cyclic reversal test, test durations have become short enough that significant amounts of data can be produced in acceptable periods for product development.

Plug-reversal testing has several drawbacks, particularly as applied to the testing of alternative refrigerant/lubricants. The first drawback is the complexity of the supporting refrigeration apparatus. This is not particularly significant when testing different insulation systems with the same refrigerant/lubricant. However, exhaustive cleaning of the supporting loop would be required before it could be charged with an alternative refrigerant/lubricant to prevent contamination of the new refrigerant/lubricant mixture. This could easily include replacement of the auxiliary compressor unit.

The second drawback is that other components of the motor, most notably the bearings, could be a major point of failure in the alternative refrigerant/lubricant. This could cause a significant number of units to fail for reasons not related to insulation performance, and might cause failure of the auxiliary compressors as well.

Another drawback is that results are motor dependent. Combined with the variations in test protocol used by different laboratories, this means that comparing plug reversal test results from different laboratories is problematic at best.

4.0 CONCEPTUAL DESIGN OF AN IMPROVED STATOR SIMULATOR DEVICE FOR TESTING OF ALTERNATIVE REFRIGERANT/ LUBRICANT MIXTURES

4.1 Overview Description

After consideration of the mechanisms of insulation failure in hermetic motors (Section 2), and a review of the current methods used to test hermetic motor insulation systems (Section 3); Radian concluded that an improved test device, designated as a Stator Simulator Unit (SSU), could be designed which would replace the conventional IEEE 117 motorette. The SSU, as used in the proposed test protocol, is designed to emulate the electric, magnetic, and thermal environment of the stator winding insulation system in 5 HP and 7.5 HP, 3-phase, 460 VAC hermetic air conditioning motors undergoing the General Electric Cyclic Reversal test.

The SSU will emulate the following forces which have been determined by General Electric to act on hermetic motor stator windings and cause insulation failure:

- Thermal aging, including transient excursions;
- Chemical aging;
- Differential thermal expansion;
- Mechanical forces induced by strong magnetic fields (magnetodynamic forces); and
- Transient voltage stresses resulting from simulated starting cycles.

Each SSU will be exposed to refrigerant/lubricant in an autoclave equipped with a headspace chiller and siphon cup similar to those typically used for IEEE 117 motorette tests. As with plug-reversal and motorette tests, eight identical SSU's will be exposed to each refrigerant/lubricant mixture to provide a valid statistical basis for evaluation of the results. Figure 4-1 shows a plastic mock-up of an SSU, siphon cup, and headspace chiller in a clear "autoclave." The refrigerant/lubricant valving and electrical lead connectors have been omitted from this mockup.

Plug-reversal in-rush currents will be simulated by intermittent 30 Amp (A) AC pulses. This current represents approximately ten times the normal current drawn by the motor.

Figure 4-1. Mock-up of the SSU in an "autoclave" with headspace chiller and siphon cup. Refrigerant valving and electrical connections are not shown.

A = SSU lamination core, B = top end turns of coils,
 C = bottom end turns of coils, D = siphon cup, E = headspace
 chiller, F = centralizers, G = threaded rod, H = autoclave,
 I = maximum liquid level in autoclave.

The SSU is an improvement over IEEE 117 motorette testing for evaluation of alternative refrigerant/lubricants because the SSU provides a better simulation of hard-start thermal pulses than even current-driven motorettes, more realistic differential thermal expansion forces, and simulation of the strong magnetodynamic forces operating on the end turns of the stator windings. While General Electric found that these magnetodynamic forces are a critical factor in failure of hermetic motors larger than 3 hp, conventional IEEE 117 motorette tests do not simulate these forces at all.

The SSU offers several advantages over cyclic reversal tests using actual motors. The devices are estimated to be relatively inexpensive at less than \$100/SSU if purchased in quantity. The relative simplicity of construction means that geometrically identical units having different combinations of insulation can be fabricated with relative ease. Provided that different laboratories adhere to the same design specifications and test protocols, then results from different facilities should be directly comparable. This is not the case with current plug-reversal or cyclic-reversal test data.

Because testing of SSU's will occur in autoclaves, the supporting apparatus of a complete refrigeration loop with auxiliary compressor will not be required. Testing should require less refrigerant/lubricant than comparable plug-reversal testing, which may be an important factor for some alternative combinations. Use of smaller quantities of refrigerant/lubricant should also reduce waste disposal costs. Decontamination of the supporting apparatus between test runs with different refrigerant/lubricant mixtures will be simplified.

Conditions during the SSU tests will be managed by an automatic control and data acquisition system, discussed in detail later in this section. This system will control test conditions, perform the required tests at specified intervals, record the data, and allow trend analysis of the results.

Several dielectric parameters will be used to evaluate SSU performance.

- Winding capacitance will provide a measure of changes in wire-to-wire separation, particularly within the slots. An increase in capacitance indicates softening of the varnish and motion of the wires closer together under the magnetostrictive forces within the slot.
- Capacitance (power) dissipation factor will provide a measure of the changing dielectric resistance of the insulation.

- Surge testing, imposition of a 2200 V AC voltage waveform on the slot and wedge coils, will detect coil failure due to turn-to-turn shorts, the most common cause of hermetic motor insulation failure identified by General Electric.
- DC high potential testing measures the DC coil-to-coil and coil-to-ground insulation resistance and detects dielectric degradation and failure of the insulation.
- Polarization Index, the ratio of the DC high potential result after 10 minutes to the result after one minute, may provide yet another measure of motor insulation condition.

Industry-accepted guidelines exist for evaluation of each of these test results, allowing identification of logical test endpoints, short of actual SSU burnout. It is also possible that trend analysis results for each of these parameters may allow projection of the time to a set endpoint well before that endpoint is reached. If this proves to be the case, then test times could be further shortened. Whether this will prove to be the case can only be determined by experiment in subsequent phases of this project.

SSU performance testing will produce results that reflect insulation life *relative* to a reference refrigerant/lubricant. For example, if R-22/mineral oil is used as the conventional refrigerant/lubricant, then the ratio of results of tests of a particular alternative refrigerant/lubricant mixture to results from R22/mineral oil will indicate the relative life of the SSU in the alternative refrigerant/lubricant mixture.

Radian found that development of an absolute life prediction test is beyond the state of the art.

4.2 SSU Design Considerations

Figure 4-2 is an isometric drawing of the SSU. The SSU consists of a laminated electrical steel core, simulating the stator stack of a hermetic motor. The core will contain slot insulation, two coils separated by phase-to-phase or "mid-stick" insulation, and slot wedge or "top-stick" insulation. The coil placed first in the slot is designated as the "slot coil" or "slot phase," while the coil placed second in the slot is designated as the "wedge coil" or "wedge phase."

Radian has elected to simulate the stator of a 3-phase, 460 VAC, 5 hp to 7.5 hp hermetically sealed motor. The average length of the lamination stack for a 5 hp motor is 4.15 inches with a range from 2.75 to 5.89 inches. The average length of a 7.5 hp motor is 4.25 inches with a range of 3.38 to 5.0 inches. The proposed length of the

Figure 4-2. Isometric drawing of the SSU.

SSU core is 4.0 inches. The laminations will be fabricated from M-19 electrical steel (0.0185 inch) with a DC permeability of 5500 at 16,000 Gauss. This stack height provides a typical constrained straight run for the field wiring in the slots. The use of insulated electrical steel laminations, rather than solid, machined steel core elements, will suppress eddy current heating. The overall dimensions of the SSU core will be 4.00 x 2.625 x 1.625 inches. With the coils inserted, the overall length will be 6.5 inches.

American Wire Gauge (AWG) Numbers 17, 18, and 19 wire are commonly used in 5 hp and 7.5 hp, three phase, 460 volt motors, but for the last several decades, testing of hermetic motor insulation systems has been performed using Number 18 wire, and Radian proposes that this wire be used for SSU construction.

Figure 4-3 shows details of the components included in the SSU. The SSU will be constructed from 216 standard "I" laminations, 216 custom "E" laminations, and four end brackets, held together with austenitic stainless steel threaded rods and nuts. The torque applied to the nuts should be sufficient to hold the assembly rigid prior to the varnish dip and bake, but should not place excessive stress on the lamination stack, as excessive stress on the steel laminations may increase the electrical losses. The torque required will be determined by experiment and specified for all production units. Assembly torque will be controlled to assure that the electrical properties of the test units are as similar as practical.

The custom "E" lamination shown in Figure 4-3 was designed, after consultations with several hermetic motor manufacturers and rewinders, to simulate the slot geometry of a typical motor. As Figure 4-3 shows, the slots will contain slot liner, two 40-turn coils of Number 18 wire separated by mid-stick insulation, and top-stick electrical insulation. When the unit is assembled, the "I" lamination rests on top on the custom "E" lamination forming a 3/64-inch (0.04688-inch) air gap over the center leg. The typical air gap between the stator and rotor of a 5 or 7.5 hp motor is 0.025" on each side of the rotor; resulting in a total air gap for the magnetic field of approximately 0.05". Accurate simulation of the magnetic forces acting within an actual motor requires that the steel core not become saturated with magnetic flux during the simulated inrush current pulses. Calculations showed that the 0.05" air gap will prevent saturation of the steel SSU core with magnetic flux under simulated plug-reversal inrush currents of 30 A.

Each 40-turn coil will be wound with 20 bifilar (two-in-hand) turns of Number 18 wire. Bifilar winding increases turn-to-turn voltage stress during testing and allows determination of wire-to-wire dielectric properties.

As noted above, inrush current surges of approximately 30 A will be impressed on one coil, simulating plug-reversal conditions, while the ends of the other coil will be shorted together. Transformer action will induce an approximate 30 A current in the shorted winding, so I^2R losses in both windings will contribute heat to the unit. The surges will be programmed for about 2 seconds on and one second off.

Figure 4-3. Details of the SSU components.

The copper wire will be heated very quickly due to the simulated plug reversal current flow. The electrical insulation in the slot is also a good thermal insulator. Thus, the copper is expected to reach a high temperature quickly while the temperature of the steel laminations lags behind, resulting in differential thermal expansion. With the wire constrained within the slot, the only place for differential thermal expansion motion is at the end of the slot in the end turns. This action creates one of the critical forces found by General Electric to be contributory to failure.

When liquid refrigerant from the siphon cup falls onto the top end turns of the SSU, rapid quenching of the copper coils will produce motion in the opposite direction due to differential thermal contraction.

The exact timing of the current pulses will be adjusted so that the average winding temperature reaches the maximum target operating temperature in 20 minutes. Then a 20 minute cool down cycle is planned. Figure 4-4 shows the thermal profile of an actual hermetic motor under cyclic reversal test conditions following a similar timing scheme [data from Crawford, 1975]. The total number of surges applied to each device under test will be automatically logged. Plug reversal tests with actual motors typically run 500,000 reversals before failure.

Each SSU will be subjected to the alternating heat-up, cool-down cycles for 18 hours out of each 24. Each simulated plug reversal will require a total of three seconds, resulting in a total of 10,800 surges (simulated reversals) per 24-hour day. At this rate 500,000 simulated reversals would be accomplished in 46-days. Conservatively, 90 days may be required for each test.

4.3   SSU Assembly

4.3.1   Insulation Permutations and Number of SSU's

ARTI has requested the testing of three types of insulation film, two types of varnish, and one type of wire. The six permutations of these materials are shown in Table 4-1. Table 4-2 shows the specifications of the film components in each of the categories in Table 4-1. The materials in Table 4-1 fall into three insulation classes with maximum average full load operating temperatures, as indicated. Radian anticipates that the different permutations will be tested at 140°C average winding temperature per UL Standard 984 unless the decomposition temperature of the alternative refrigerant/lubricant is lower.

Even though only one wire type was specified by ARTI, the pre-lubrication used for construction of the SSU's must be compatible with the refrigerant to be tested. Phelps Dodge Armored Polythermaleze APTZ 2000 wire is pre-lubricated with one of three lubricants; white mineral oil, paraffin base, or glycol ester. The wire for the lot of

Figure 4-4. Simulated thermal cycle profile for an SSU, after Crawford, 1975.

Table 4-1**Permutations of Insulating Materials**

Class B (130°C)^a	Class F (155°C)	Class H (180°C)
DuPont Mylar PET Film ^b ; Schenectady Isoproxy 800 ^c	Westinghouse DMD-100; Schenectady Isoproxy 800	DuPont Nomex Aramid Paper; Schenectady Isoproxy 800
DuPont Mylar PET Film; P.D. George U-475 EHR	Westinghouse DMD-100; P.D. George U-475 EHR	DuPont Nomex Aramid Paper; P.D. George U-475 EHR

^aMaximum continuous full-load operating temperature

^bSlot, phase, and wedge insulation

^cVarnish

Table 4-2**Dimension and Product Specifications
for Film and Sheet Insulation**

	PET Class B	DMD-100 Class F	Nomex Aramid Class H
Slot Liner ^c	10 ^a (1000M021) ^b	14(P10G373 003)	15(410)
MID-Stick ^d	7.5(750M021)	8(P10G323 003)	10(410)
Top-Stick ^e	14(1400M021)	20(P10G3143 003)	20(410)
Phase (outside slot) ^f	7.5(750M021)	8(P10G323 003)	10(411)

^aInsulation thickness is in mils (1 mil = 0.001 inch).

^bManufacturer's product number.

^cThe film or sheet lining of the slot, preventing wire-to-core contact.

^dThe phase separation insulation between the coils within the slots.

^eThe wedge-shaped piece of insulation which secures the coils within the slot.

^fThe phase insulation between the end turns of the coils outside the slots, an extension of the mid-stick insulation.

SSU's to be tested with R-22/mineral oil will be pre-lubricated with white mineral oil. If R-134a is to be tested, for example, then APTZ 2000 wire that has been pre-lubricated with glycol esters will be used.

As mentioned previously, tests of eight replicate SSU's are required for reasonable statistical analysis of the results. Given six combinations of insulation, this means that 48 SSU's will be required for the evaluation of each refrigerant/lubricant mixture, a total of 192 SSU's if R22/mineral oil and three alternative refrigerant/lubricants are tested, as originally anticipated by ARTI. Several extra SSU's of each insulation design will also be required as initial inspection may disqualify some units.

4.3.2 SSU Fabrication

The SSU's will be assembled in a qualified refrigeration motor rewinding shop under a detailed specification. The pre-cut custom "E" laminations will be assembled with controlled torque on the retaining nuts as described previously.

Pre-cut slot insulation will be inserted into the slots.

The coils will be wound on coil winding machinery that is designed to prevent wire crossovers and then the fabricated coils will be placed carefully in the lamination slots to avoid wire crossovers. Crossed-over wires are a known source of premature motor failures.

The mid-stick/phase insulation will be inserted between the two coils, and the top-stick or wedge insulation piece will be inserted. The coils and phase insulation outside the slots will be tied securely with lacing cord to emulate actual motor field winding construction.

Varnish for dipping the completed assemblies will be diluted according to the manufacturer's specifications, and dipping will take place under a specified vacuum to assure consistent impregnation. For example, if the assembly temperature is 21.1°C then the vacuum will be 18.8 mm Hg. If the assembly temperature is 26.7°C then the vacuum will be 26.1 mm Hg prior to dipping. After dipping, the varnish will be heat-cured according to the varnish manufacturer's recommendations. For example, the Isoproxy 800 will be cured at 190°C for 4-hours to achieve optimum resistance.

4.3.3 Drying to a Standard Moisture State

After connection to the autoclave terminals and insertion into the autoclave, each SSU will be dried under partial vacuum (approximately 300 mm Hg) at moderately elevated temperature. The dry-out cycle will be carefully controlled so that all refrigerant/oil combinations tested will be subjected to approximately the same residual moisture conditions. The temperature of the SSU's will be increased in steps of

5°C each hour to an end point of 80°C. The high potential waveform will be digitalized and stored for trend analysis. In addition, the one-minute and 10-minute DC high potential insulation resistance tests will be made and logged on each SSU each hour just prior to the increase in temperature. The insulation resistance and polarization index will be calculated and stored. Normally, as motor assemblies are dried, the polarization index passes through a minimum, then increases again. However, the newer varnishes do not exhibit the same polar characteristics exhibited by the insulations of the 1960's and 1970's, and the SSU is a relatively small device compared to a 50 to 100 hp motor.

Trend analysis of the high potential current waveform may provide a clue to the moisture content in each SSU and allow all units to be dried to the same moisture content. As each SSU cools down from 80°C, its 1-minute insulation resistance will be tested at 10°C intervals down to the 40°C point. A plot of insulation resistance vs. log temperature will establish the insulation temperature coefficient (K_i), which will be used subsequently to adjust insulation resistance readings to a standard reference temperature. The high potential current waveform and the 10-minute insulation resistance will also be tested at 40°C, and the polarization index calculated and recorded for reference.

4.3.4 Charging the Autoclaves

The autoclaves will be charged according to the procedures outlined in UL Standard 984-1989. At the conclusion of the drying cycle, a volume of the specified lubricant sufficient to immerse the bottom turns of the coils and approximately one inch of the SSU core will be instilled into the autoclave, and the vessel will be evacuated to less than 0.1 mm Hg for one hour at 70°C. Finally the vessel will be charged with refrigerant vapor in such a manner that no air is introduced into the system. The refrigerant charge will be sufficient to produce a pressure between 150 and 350 psig at 140°C.

4.4 Design of the Control and Data Acquisition System

Radian has designed a PC-based control and data acquisition system in which two octets of SSU's will be under the control of a single 486 personal computer (PC) and programmable logic controller (PLC). Programmable logic controllers were selected for sequencing because these devices can easily manage the necessary input/output and multiplexing routines.

The two octets of SSU's under the control of a given PC-PLC system could represent the two permutations of a given insulation class from Table 4-1. Under this scenario, three PC-PLC systems would allow simultaneous testing of all of the insulation permutations in a single refrigerant/lubricant mixture. Alternatively, the two octets of SSU's could represent a single permutation of the insulation systems in two of the four refrigerant/lubricant mixtures. Under this scenario, two PC-PLC systems would allow simultaneous testing of a single insulation system in four alternative refrigerant/lubricant

mixtures. Under this scenario, testing of the Class B insulations could occur first, as these insulation systems are expected to fail more rapidly than the Class F or Class H materials.

A sophisticated timing and multiplexing strategy was adopted to minimize the control and data acquisition equipment requirements for each PC-PLC system. The 16 SSU's under the control of each PC-PLC are divided into groups of four for timing purposes. Each group of four SSU's has a 6-hour rest period during each 24-hour period. The rest periods are staggered so that only 12 units are active at any one time. The 12 active units are further divided into two groups of six. At any time one group of six SSU's are in a 20-minute heating period by simulated plug-reversal inrush currents, while the other six SSU's are in a 20-minute cooling down period. The last major timing sequence is staggering in the inrush pulse cycle of each of the six active SSU's. The above multiplexing scheme results in only four of the 16 SSU's being on the power line at any one time resulting in savings in equipment costs for variable transformers and isolation transformers.

Five loop diagrams are provided to show the relationship of the various pieces of test equipment, the autoclave units located in the test rack, the PLC multiplexing, and the PC-based data acquisition, logging and displaying system. These loop diagrams do not show electrical safety features such as circuit breakers. Loop Diagram 1 provides information on power measurement and control. As noted in the previous paragraph, only four of the 16 SSU's will be active at any one time. Therefore 4-each of T1, T2, T3, SC1, SC2, and SC3 will be required. The autoclave, with the SSU and thermocouples installed, is shown in the center of Loop Diagram 1. PLC multiplexing functions are shown to the right of center and PC-based data acquisition, logging, and display functions are shown on the far right side of the loop diagram. The variable transformer (T1) will be used to adjust the supply voltage so that the required peak refrigerant temperature is achieved at the end of each 20-minute heat up period.

The simulated plug reversal heating period is 2 seconds and the rest period between simulated reversals is 1 second for a total period of 3 seconds. One of the conceptual design objectives was to have an automatic testing system that can withstand the test conditions and last longer than the equipment under test. Electromechanical relays will be used due to the excellent isolation provided by the open contacts. These contacts must reliably pass current or signal data when closed and must withstand 2200 VDC high potential tests; 2200 VAC peak value surge test waveform tests; and must have relatively low capacitance when the winding capacitance and dissipation factor measurements are being made.

The primary failure mode of mechanical contacts is arcing. If an electro-mechanical relay can be switched with no current flow then it should last almost indefinitely. CRQ-1 will be a solid state relay. The PLC commands will set power

PC/ACCO/LOGIC/PLAY

LEGEND

- Digital Communication
- Electrical Wiring
- Analog to Digital Signal Converter
- Type "J" Thermocouple
- Current Transformer
- Transformer
- Control Relay
- PLC Programmable Logic Controller
- SC Signal Converter
- SSU Simulated Stator Unit
- TE Temperature Element

POWER MEASUREMENT AND CONTROL LOOP DIAGRAM 1

Job No.	Drawing No.	Rev.
	810524	

handling electromechanical relays prior to energizing CRQ-1 and will de-energize CRQ-1 prior to de-energizing the electromechanical relays. CRQ-1 will be selected to turn on at a zero voltage crossover and to shut off at a zero current crossover. Sequencing in this fashion should minimize relay failures.

Relay CRM-1 will be energized for 100 milliseconds prior to the end of the 2 second heating cycle. Then signal converters SC1, SC2, and SC3 will digitize and log the SSU AC power supply data. The computer will calculate the phase angle and power will be calculated using the formula:

$$\text{Power} = I \times E \times \cos \Theta$$

where I = Current

E = RMS Volts, and

Θ = Phase Angle Between I and E.

Relay contacts CRQ-1, CRP-1, CR10-1, CR11-1, and CR12-1 are closed when power is applied to the SSU. The slot coil will receive approximately 30 A of AC current. As contacts CR11-1 and CR12-1 short circuit the wedge coil, and allow transformer action to induce currents of approximately 30 A in this coil as well. The wedge coil current will be monitored with a current transformer, digitized by signal converter SC1, and logged.

A power factor correction for each SSU was considered as a means of reducing operating volt-amp requirements, and then deleted after discussions with Mr. Joseph Leoni of Baker Instruments. In actual motor service without power factor correction, a voltage spike occurs when power is applied. This voltage spike is due to residual magnetism in the laminations and has a rise time of approximately 0.2 μ s. If power factor correction were applied, then the resonant frequency of the SSU windings and the power factor correction capacitor would drop to 60 Hz and no voltage spike would occur, eliminating a potentially important source of electrical stress on the SSU.

Loop Diagram 2 shows the proposed copper resistance thermometer and the thermocouple details. The average temperature of the windings will be monitored by measuring and logging the change in resistance of the windings. The copper resistance will be measured approximately 130 milliseconds after the completion of the 2 second heating period, which allows time for subsidence of transient currents and electro-mechanical contact bounce.

One DC power supply is required for each group of 16 SSU's under test. This one supply will be multiplexed so that average winding temperature data will be recovered and logged every 6 seconds for each of the 16 SSU's. This results in approximately 200 data points for each 20-minute heat up cycle.

PLC/LOGIC DISPLAY

LEGEND

	Digital Communication		Type "J" Thermocouple		PLC Programmable Logic Controller
	Electrical Wiring		Current Transformer		SC Signal Converter
	Analog to Digital Signal Converter		Transformer		SSU Simulated Stator Unit
	Control Relay		TE Temperature Element		

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COPPER RESISTANCE THERMOMETER AND THERMOCOUPLES LOOP DIAGRAM 2

Job No.	Drawing No.	Rev.
	810523	

The DC power supply will be connected to provide a constant current source. The current will be adjusted so that 1 millivolt of voltage change across the coil terminals represents approximately 1°C change in average winding temperature. To accomplish this, a precision meter shunt will be placed in series with the coil under test and the remote sense terminals of the power supply will be connected across this shunt. When the constant current is not being used to measure a SSU coil, the stator wiring will be connected together by the contacts of relay CRS so that power supply current is not interrupted. The PLC will be programmed to close CR1-1, CR2-1, CR10-1, and CR12-1, connecting the two coils in series, prior to opening CRS; the computer will take its coil voltage and current sample; then, the contacts of CRS will close prior to opening the other relay contacts. This programmed sequence will allow the stored energy in the SSU coils magnetic field to dissipate prior to opening the contacts and will prevent arcing and destruction of the relay contact surfaces.

The remote sense windings of the DC power supply voltage regulator will maintain constant voltage across the shunt, therefore the current through the shunt resistor will remain constant, independent of resistance changes in the SSU coil. Signal converters SC5 and SC6 monitor the selected SSU coil current and voltage and provide 0 to 10 VDC signals to the computer. The computer will calculate the SSU coil resistance (R_2) by dividing the voltage signal by the current signal and voltage, current, and resistance values will be logged.

The SSU coil resistance at 75°C will be measured during the initial dry out period and logged for reference for the remainder of the life test. Average SSU coil temperature for each copper resistance measurement will be computer calculated using the following equation:

$$T_2 = 75 + (309.6 (R_2 - R_1))/R_1$$

where R_1 = SSU coil resistance at 75°C, and
 R_2 = The latest resistance test data.

Three type J (iron-constantan) thermocouples will be included in each SSU. Temperature element TE1 will measure the temperature of the lubricating oil in the bottom of the autoclave. TE2 will be embedded in the coil and centered in the slot to measure the peak coil temperature. TE3 will be located in the refrigerant vapor space at least 0.5 inch away from the autoclave wall and the SSU, and will provide an indication of the ambient exposure temperature of the refrigerant. Each thermocouple will be sampled and logged every 6 seconds for all 16 units.

Wire-to-wire capacitance, insulation power factor, AC surge test, DC high potential test, and polarization index determinations will be automatically performed and logged once a day at the end of the 6-hour cool down period and as close to 40°C as possible. Loop Diagram 3 shows the control and data acquisition for measuring the

PCACOLLOID DISPLAY

START/STOP
DATA

CBS & CRA
STATUS

LEGEND

	Digital Communication		Type 'J' Thermocouple		PLC Programmable Logic Controller
	Electrical Wiring		Current Transformer		SC Signal Converter
	Analog to Digital Signal Converter		Transformer		SSU Simulated Status Unit
			CR Control Relay		TE Temperature Element

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CAPACITANCE AND DISSIPATION FACTOR TEST LOOP DIAGRAM 3

Job No. _____ Drawing No. _____ Rev. _____
R10572

capacitance and power factor of the SSU insulation. Changes in the wire-to-wire capacitance of the SSU can provide an indication of generalized changes in the copper wire insulation system. For example if the insulation softens with aging in the refrigerant/oil test environment, then the wires may move closer together resulting in an increase in the wire-to-wire capacitance. The insulation power factor provides a measure of the dielectric quality of the wire insulation and varnish. Insulation power factor measurements should be sensitive to gradual general deterioration of the varnish and wire insulation system.

The coil of control relay CR3-1 will be energized by the PLC during the capacitance and dissipation factor testing for the slot coil and then be de-energized. Likewise, the coil for relay CR4-1 will be energized for the capacitance and dissipation factor testing of the wedge coil and then be de-energized.

Loop Diagram 4 shows the control and data acquisition for the AC surge measurements. Changes in the AC surge test waveform of the SSU can provide information on localized copper wire insulation damage. The peak voltage (2200 volts) of the transient waveform has enough potential to jump small gaps and can detect insulation pin holes causing turn-to-turn shorts. General Electric found that the precursor to actual motor burnout was pinpoint transient turn-to-turn arcing in the end turns of the coils.

Each of the SSU coils will be AC surge tested. The coils of control relays CR5-1, CR10-1, CR11-1, and CR12-1 will be energized by the PLC during the slot coil testing and on completion of the slot coil surge test will then be de-energized. Likewise, the coils for relays CR6-1, CR10-1, CR12-1, and CR13-1 will be energized for the wedge coil testing and then be de-energized. Note that the windings of the coil not under test are shorted by the appropriate relay contacts to prevent high voltage transients in the coil not under test.

Under normal test conditions the waveform will be automatically logged and later compared by the test engineer to previous stored waveforms for indications of insulation deterioration. If either coil overloads the test equipment and causes a current trip, the current trip will be logged and the test cycle of the failed unit will be terminated.

Loop Diagram 5 shows the control and data acquisition for the DC high potential measurements. Three types of insulation failure can be detected with the high potential test as follows:

- Excess leakage current (ma),
- Arcing failure, or
- Continuity failure (major winding short).

PC/ACOL COMBIPLAY

START/STOP
DATA

CPS & CPG
STATUS

LEGEND

	Digital Communication		Type 'J' Thermocouple		PLC Programmable Logic Controller
	Electrical Wiring		Current Transformer		SC Signal Converter
	Analog to Digital Signal Converter		Transformer		SSU Simulated Sator Unit
			CR Control Relay		TE Temperature Element

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SURGE TEST LOOP DIAGRAM 4

Job No. Drawing No. 810521 Rev.

PC/ACCO/LOO/IMP/LAY

START/STOP
DATA

CR7, CR8, & CR9
STATUS

LEGEND

	Digital Communication		Type 'J' Thermocouple		PLC Programmable Logic Controller
	Electrical Wiring		Current Transformer		SC Signal Converter
	Analog to Digital Signal Converter		Transformer		SSU Simulated Stator Unit
			Control Relay		TE Temperature Element

No.	Date	Revisions	By	App.
RADIAN CORPORATION A member of Radian Group, Inc. (formerly Radian Corporation) 10000 Radian Drive, Dallas, Texas 75243				
HIGH-POTENTIAL TEST LOOP DIAGRAM 5				
Job No.	Drawing No.	Rev.		
	B10520			

Each of the SSU coils will be high potential tested to ground and then between the two coils. The coils of control relays CR7-1, CR10-1, and CR13-1 will be energized by the PLC during the slot coil testing and on completion of the slot coil high potential test will then de-energized. Likewise, the coils for relays CR8-1, CR11-1, and CR12-1 will be energized for the wedge coil testing and then be de-energized. Control relays CR9-1, CR10-1, CR11-1, CR12-1, CR13-1 will be energized during the coil-to-coil high potential test and then be de-energized. The ends of the coil under test are shorted together by the appropriate relays; this protects the instruments and SSU from induced current/voltage surges in the event of coil failure during the test.

During life testing, the high potential tester will be set for 2200 VDC (2 X 600 V + 1000). Analog data from the high potential tester for kilovolts applied to the coil under test and the leakage current to ground in microamps will be digitalized and provided to the computer. Under normal test conditions, the computer will calculate the 1-minute and 10-minute resistance to ground values, and calculate the polarization index (10-min. resistance/1-min. resistance). However, a current trip of 690 μ A in the high potential test will automatically terminate the test.

The value of the insulation resistance at 40°C (R_c) is another good measure of the state of standard motor insulation systems. Per ANSI/IEEE Standard 43, if the R_c is equal to or less than R_m (1.6 megohm for a 600 VAC machine) then overpotential tests should not be performed and reconditioning of the motor is recommended. Normally a new machine has R_c values from 10 to 100 times R_m . As the insulation system ages under refrigerant/lubricant testing, analysis of trends in insulation resistance may suggest a logical SSU test termination point based on this parameter.

As discussed above, the SSU's will be dried as nearly as practical to the same standard moisture contents. The polarization index is expected to increase, as the SSU's are operated in the test environment. The small amounts of moisture driven off during the test will become part of the test atmosphere. As the insulation system ages the polarization index will peak and gradually decrease. Evaluation of trend analysis of the high potential test waveform may suggest a logical SSU test end point. The actual test protocol will be determined in Phase 2 of this project after a pilot study.

4.5   General Description of Test Facility and Major Equipment

As should be apparent from the preceding discussion, a relatively sophisticated laboratory will be required to support testing of alternative refrigerant/lubricants using the SSU device and control system described above. The simultaneous testing of a single insulation combination in four refrigerant/lubricant mixtures will require two complete PC-PLC controllers, each managing 16 SSU's. The alternative, simultaneous testing of all six insulation combinations sequentially in the different refrigerant/lubricant mixtures would require three complete controllers, each managing 16 SSU's.

To the extent possible, the specified equipment will be commercially available. Each PC-PLC control system will consist of an IBM-compatible 486 computer, PLC, AD/DA interface, mass data storage and backup devices.

The three major instruments used to sense SSU performance are the surge tester, the high potential tester, and the capacitance tester. Each of these devices is widely used in the electric motor industry for product quality control. Instruments of each kind, designed for automated control and multiplexed operation, are available from multiple sources.

The SSU is designed to fit within a PARR 2-L autoclave, though alternative autoclaves may be used.

The laboratory space used for SSU testing will have to be reserved for this purpose for safety reasons, and the personnel working in the area will have to be experienced electrical engineers and technicians. This dedicated laboratory space should have a minimum area of 400 square feet per PC-PLC control system. The laboratory will require the following utilities and auxiliary systems:

- Approximately two-thirds of a ton of air conditioning per PC-PLC;
- An estimated 2 KVA dedicated stable power source per PC-PLC;
- An uninterruptable power supply for the PC-PLC's, adequate to allow an orderly shutdown in the event of a power failure;
- Sixteen autoclaves per PC-PLC;
- Sixteen autoclave safety enclosures per PC-PLC;
- Chiller water utility for the autoclaves;
- Refrigerant/lubricant handling equipment; and
- Ventilation safety equipment in event of an inadvertent refrigerant/lubricant release.

5.0 FUTURE WORK

The work described in the previous sections concludes the activity under Phase 1 of this project, Conceptual Design.

This section describes very briefly the activities which would logically occur under subsequent phases, presuming that ARTI elects to proceed with development of the SSU and test procedure.

5.1 Phase 2 and Phase 3 Activities

Recognizing that the SSU and test procedures described in this report are not a demonstrated technology, the logical and necessary second phase of this project would include detailed design, SSU prototype testing, and a pilot test of the complete test apparatus. The third phase would be the sequential testing of different insulation systems in four refrigerant/lubricant mixtures, one of which would be R22/mineral oil. Figure 5-1 illustrates the major steps in each of these subsequent phases.

5.1.1 Phase 2

The first primary activity under Phase 2 would be completion of a detailed system design, including final specification of all instrumentation and hardware items. As part of the final design activity, four pairs of SSU's will be fabricated with one of the Class B insulation systems. Each of the pairs will be assembled with different torques on the nuts which clamp the SSU together. A fifth pair with crossed coils (the slot pass in one slot is the wedge pass in the other slot) will also be tested to see if the inductance of the two coils is more closely balanced in this configuration.

Each of the SSU's will be subjected to electrical tests to verify the properties calculated during the conceptual design. In addition, careful visual observations will be made to assure that there is no gross flexing of the SSU core under the 30 A simulated locked-rotor condition. Design modifications will be made to the SSU support rack if necessary.

This phase will conclude with a pilot scale test. A pilot scale laboratory, including one PC-PLC control system, one set of test instruments, and 16 autoclaves, will be assembled and debugged. Two octets of SSU's will be fabricated from one of the Class B insulation combinations, and subjected to the test program described in Section 4. One octet will be exposed to R22/mineral oil, while the other will be exposed to an alternative refrigerant/lubricant. A Class B insulation combination will be used because these combinations are expected to degrade faster than the other combinations.

Figure 5-1
Anticipated Phase 2 and Phase 3 Schedule

*Note each run constitutes the testing of one insulation combination in four refrigerant/lubricant mixtures.

Figure 5-1. Anticipated Phase 2 and 3 Milestones and Schedule.

The purpose of this phase of development will be to demonstrate that the proposed SSU test procedure works as anticipated and does produce meaningful data which can be used to estimate relative life of insulation systems. During this phase, operational problems will be identified and corrected, and the test procedure will be finalized.

Ideally, the data acquired from the two quartets of Class B insulation will be usable for baseline purposes in the subsequent phase. However, it is also possible that problems encountered in this phase may make the data useless for future comparisons. This could be the case for example, if the test procedure were altered for some reason in mid exposure.

5.1.2 Phase 3

As was shown in Table 4-1, ARTI has identified six combinations of insulation to be tested. This phase of testing will include sequential testing of each of these combinations in four refrigerant/lubricant mixtures.

At the beginning of this phase, the test facility will be expanded with the acquisition of a second PC-PLC control system, and duplicates of the three test instruments used to monitor SSU performance. The second test stand will be a duplicate of the pilot test unit. These two units will allow simultaneous testing of a single insulation combination in four different refrigerant/lubricant mixtures. Testing will begin with the Class B materials, followed by the Class F materials, and concluding with the Class H materials. Nominally, this program will require six sequential trials, designated as Runs 1 through 6 in Figure 5-1. The estimated length of each trial is 14 weeks. However, it is quite possible that some combinations of refrigerant/lubricant may not be tested with all insulation systems. While there are six permutations of insulation, there are only two permutations of wire and varnish. General Electric has identified wire/varnish-related failure modes as the most common in hermetic motors. If a particular refrigerant/lubricant was found to severely degrade performance of one of the wire/varnish combinations in the Class B insulation systems, there would be no point in testing the same wire/varnish combinations in the Class F and Class H systems, and that portion of the test series could be truncated.

5.2 Estimated Schedule

Figure 5-1 illustrates the anticipated schedule for Phase 2 and 3. Phase 2 is projected to require 30 weeks, while Phase 3 will require 112 weeks, for a total of 142 weeks. However, the results for the first Class B insulation combination in the four refrigerant/lubricants should be available after approximately 56 weeks, as shown in Figure 5-1.

5.3   Required Resources

From a review of Section 4.5, it should be quite apparent that the resources required to perform the refrigerant/lubricant mixture testing desired by ARTI will be significant. Assuming the pre-existence of suitable general laboratory space suitable for conversion for SSU testing, it is estimated that the non-expendable equipment required for Phase 2 will be on the order of \$150K, with a similar requirement (approximately \$140K) for Phase 3. Expendable materials will be on the order of \$10K in Phase 2, and \$30K in Phase 3. Engineering and technical manpower is estimated at 14 man-months in Phase 2 and 32 man-months in Phase 3. Each of these estimates has an uncertainty of at least $\pm 20\%$.

The magnitude of the effort required clearly justifies the establishment of a single central laboratory to perform the required testing with all participating air conditioning and refrigeration manufacturers benefiting from the shared results.

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H. O. Spauschus and R. A. Field, 1979, "Laboratory Evaluation of Hermetic Motor Insulation," ASHRAE Transactions, 85(2), pp. 741-746.

D. E. Stoupe and T. Y. S. Yau, 1989, "Air Conditioning and Refrigeration Equipment Failures," National Engineer, 93(9), pp. 14-17.

S. G. Sundaresan and F. E. Kalivoda, 1982, "Reliability Life Testing and Evaluation of Three-Phase Motors," Proceedings of the Purdue Compressor Technology Conference, Purdue University, West Lafayette, TN, pp. 84-88.

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UL 984-1989, Standard for Hermetic Refrigerant Motor-Compressors, American National Standard ANSI/UL 984-1989, ANSI and Underwriters Laboratories, 1990, pp. 27-28.

These were the most useful sources recovered from an exhaustive automated search of the literature for information related to:

- Causes and mechanisms of hermetic motor insulation failure;
- Life testing methods applied to hermetic motor insulation systems; and
- Statistical treatment of hermetic motor life test data.

More than 70 references, including journal articles and society standards were recovered and reviewed.

6.2   Personal Communications

Members of the ARTI advisory panel provided valuable perspectives and insights, particularly as related to the current state-of-the-art of hermetic motor insulation testing.

Radian also contacted numerous individuals associated with the refrigeration and hermetic motor industries. Table 6-1 provides a list of persons and organizations contacted.

Table 6-1**Key Industry Telephone Contacts**

Company	Name	Location	Phone/Fax
ARTI	Steve Szymurski	Arlington, VA	(703) 524-8800 (703) 528-3816 (Fax)
Active Fabricators, Inc.	Ted Heston	Willowbrook, IL	(708) 986-5100
Walker Magnetics	Bruce Langley		(508) 852-3674 x.515 (508) 856-9931
General Magnetics		Dallas, TX	(214) 296-4711
Dexter Magnetics		Dallas, TX	(214)-699-1121
Magnetics Division Spang & Company			(412) 282-8282
Magnetics Division Spang & Company	Frank Hall	Dallas, TX	(214) 475-8066
Alegheny Ludlum Steel	Elvira Tafi	Leechburg, PA	(800) 289-7454
Arnold Engineering			(815) 568-2000
Thomas & Skinner	Doyle Mink	Indianapolis, IN	(317) 923-2501 (317) 923-5919
Armco Steel	Bill Turbison		(410) 563-5500
Magnetics Inc.	Lowel Bosley	Butler, PA	(800) 245-3984
Author of "Trans- former & Ind. Design Handbook"	Col. Wm. T. McLyman		
Magnetics Materials Producers Assoc.		Chicago, IL	(312) 922-6222
Masingales Armature	Lewis Masingale John Masingale	San Antonio, TX	(210) 732-5168
San Antonio Arma- ture	David Reynolds	San Antonio, TX	(210) 227-0291

Table 6-1
(Continued)

Company	Name	Location	Phone/Fax
Hamilton Electric		Austin, TX	(512) 472-2428
Austin Armature Works		Austin, TX	(512) 442-7869
Hisco	Marshall Tanner	Austin, TX	(512) 834-9773
General Electric	Michael Minnic	Fort Wayne, IN	(219) 428-2908 (219) 428-2907
Underwriters Lab.	Larry Kettwich	Chicago, IL	(704) 272-8800 x.2484
Trane, Co.	Robert Doerr	La Crosse, WI	(608) 787-3696
AVO International	Bret Hammons	Dallas, TX	(214) 330-3568 (214) 333-3533
Reliance Electric	Walt Stiffler	Cleveland, OH	(216) 266-7750 (216) 266-7714
Lennox Industries Inc.	Len Van Essen	Fort Worth, TX	(214) 416-7515
The Trane Co.	Dick Ernst	La Crosse, WI	(608) 787-2292
A. O. Smith Co.	Jerry Spears	Tipp City, OH	(513) 667-2431 x.2333 (513) 667-2431 x.2379
Dupont	John Barkley	Circleville, OH	(614) 474-0483
Westinghouse	Bruce Muler	Bedford, PA	(814) 623-9014 x.108
Phelps Dodge	Don Barda Vic Heniser	Fort Wayne, ID	(912) 458-5484
P. D. George	Mark Winkler	St. Louis, MO	(314) 621-5700

Table 6-1
(Continued)

Company	Name	Location	Phone/Fax
Schenectady International, Inc.	Terry McKaine Robert (Bob) Allen Oliver Beardmore	Schenectady, NY	(518) 370-4200 (518) 382-8129
EIL Instruments	Dick Maxner	Houston, TX	(713) 271-3100
AGM Electronics		Tuscon, AZ	(602) 722-1000
Fluke Inc.		IL	(708) 705-0500
Rod-L Electronics	Dan Norman	Menlo Park, CA	(800) 548-6305
BCE Inc.	Jim Forsythe		(208) 343-1473
Simpson Electric Co.	Sid Borman		(708) 697-2260
LDJ Electronics	Leonard Frieman		(313) 528-2202
Empro Manufacturing Company, Inc.	Michael Harriman	Indianapolis, IN	(317) 823-4478
Ram Meter Inc.		Ferndale, MI	(313) 398-6767
Weschler Instruments	Gary Hauze	Cleveland, OH	(216) 238-2550
Lambda Electronics Inc.	Mike Waggner Mike Petnaga	Melville, NY	(800) 526-2324 x.349 or x.313
Magnetic/Triad		Hunington, IN	(219) 356-7100
Superior Electric	Jim Haydon	Bristol, CT	(203) 582-9561

END

**DATE
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