FINAL REPORT

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**ACCELERATED TEST METHODS FOR LIFE PREDICTION
OF HERMETIC MOTOR INSULATION SYSTEMS
EXPOSED TO ALTERNATIVE REFRIGERANT/LUBRICANT MIXTURES**

PHASE 2: PROOF-OF-CONCEPT DEMONSTRATION

Prepared for:

The Air-Conditioning and Refrigeration Institute
under
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Prepared by:

Peter F. Ellis II
Alan F. Ferguson
Radian Corporation
P.O. Box 201088
Austin, TX 78720-1088

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1.0

INTRODUCTION

In 1992, the Air-Conditioning and Refrigeration Technology Institute, Inc. (ARTI) contracted Radian Corporation to ascertain whether an improved accelerated test method or procedure could be developed that would allow prediction of the life of motor insulation materials used in hermetic motors for air-conditioning and refrigeration equipment operated with alternative refrigerant/lubricant mixtures. Phase 1 of the project, Conceptual Design of an accelerated test method and apparatus, was successfully completed in June 1993. The culmination of that effort was the concept of the Simulated Stator Unit (SSU) test.

ARTI concurred with Radian's belief that the proposed new test method offers distinct advantages over existing procedures for estimating the relative life of hermetic motor insulation materials exposed to alternative refrigerant/lubricant mixtures. In addition to its potential for testing the endurance of existing insulation systems exposed to new alternative refrigerant/lubricant mixtures, the proposed test, if successful, could also have several additional applications including:

- Assessing compatibility interactions between replacement alternative refrigerant/lubricants and residual R-22/mineral oil in used equipment;
- Testing of alternative insulation systems in the event that the candidate refrigerant/lubricant is found to be either significantly more or significantly less aggressive than R-22/mineral oil; and
- Testing the effect of reduced purity standards for recycled or reclaimed refrigerants.

However, the SSU test was strictly conceptual at the conclusion of Phase 1. No device had been fabricated, a number of engineering design decisions related to test equipment had not been addressed, and there had been no demonstration that the proposed technology would provide meaningful accelerated estimates of the life.

Radian and ARTI concluded that the next reasonable step in development of the SSU test technology would be a proof-of-concept demonstration. The objective of the Phase 2 limited proof-of-concept demonstration was to:

- Answer specific engineering/design questions;
- Design and construct an analog control sequencer and supporting apparatus; and
- Conduct limited tests to determine the viability of the SSU test concept.

This report reviews the SSU test concept, and describes the results through the conclusion of the proof-of-concept prototype tests in March 1995. The technical design issues inherent in transforming any conceptual design to working equipment have been resolved, and two test systems and controllers have been constructed. Pilot tests and three prototype tests have been completed, concluding the current phase of work.

One prototype unit was tested without thermal stress loads. Twice daily insulation property measurements (IPMs) on this unit demonstrated that the insulation property measurements themselves did not degrade the SSU.

Two SSUs were each subjected to 20,600 simulated locked-rotor events per day. Both showed progressive deterioration of the resistive component of the turn-to-turn insulation over the course of the tests. One of the two SSUs suffered a coil-to-coil failure, one of the anticipated failure modes. Testing of the other SSU was terminated by schedule constraints prior to failure, but it also showed progressive deterioration.

A new phase of testing, designated as reproducibility testing, was authorized by ARTI effective 1 April 1995. In this phase, eight SSUs will be tested in virgin R-22/mineral oil, while a second set of eight SSUs will be tested in R-22/mineral oil with a high acid number. Statistical evaluations of the trends, data scatter, and numbers of replicated required for a given level of confidence will be determined.

2.0

REVIEW OF SSU CONCEPTUAL DESIGN

This section presents a brief overview of the evolution of the conceptual design for the SSU test. The research leading to the conceptual design, and the conceptual design itself have been reported previously [Ellis and Ferguson, 1993] and the reader is referred to that report for details not contained in this summary.

2.1

The Mechanism of Hermetic Motor Insulation Failure

Radian felt that development of an effective accelerated hermetic motor insulation life (AHMIL) test required a basic understanding of the factors and forces leading to motor winding failure.

An insurance industry survey [Stoupe 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 age of a failed hermetic 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. As a result of these findings, the conceptual design effort was focused on the factors affecting stator winding insulation life.

One clearly identified factor was transient, local thermal excursions above the breakdown temperature of both the insulation and refrigerant. For example, Carrier Corporation determined that in Class B hermetic motors, with insulation rated for 130° C (266° F), wire surface temperature transients to 200° C (392° F) or higher occurred at each start-up, while temperatures within the windings peaked at around 250° C (482° F) for brief periods. The average temperatures of integral-horsepower, random-wound motors can soar to 245° C (473° F) 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 from and more aggressive than the bulk fluid. Refrigerant dissolved in the varnish will boil 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. This lead to the thermochemical degradation model of insulation failure.

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 later in this section, 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.

As more experience accumulated with insulation failure of larger hermetic motors, those above 3 hp, it became increasingly apparent that the thermo-chemical degradation model did not completely explain the mechanisms of failure which were being observed. In particular, it was found that hermetic motor life was inversely related to power rating [Crawford, 1975].

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 showed very little general insulation aging [Crawford, 1975]. 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 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 in-rush surges and/or liquid refrigerant backflooding exceeds the restraining strength of the varnish;
- The wires begin to vibrate 120 times per 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 was 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 in hermetic motors occurred when two adjacent coils in the same pole become loose and vibrated 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 occurred when loosening of bonds between the magnet wires and ground insulation (slot liner) allowed motion between these components. While considerable slot liner wear at these locations was observed in some failed motors, it did not contribute to any of the failures 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 has less abrasion resistance 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.

2.2 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.

2.3 Precursor Tests

Radian identified three hermetic motor testing technologies currently used to assess long-term performance of hermetic motor insulation. Each test was found to have distinct advantages and disadvantages. The three tests were the:

- IEEE Standard 117 Motorette Test; the
- UL Standard 984 Motorette Test, and the
- Plug-reversal Test.

test. Table 2-1 compares these three tests from the perspective of an AHMIL

2.4 References

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Table 2-1

Comparison of Precursor Tests

Governed by Standard	IEEE Standard 117 Motorette	UL Standard 984	Plug-reversal Test
Test Description	<p>Yes, but test modified for hermetic motor applications</p> <p>IEEE motorettes are small models of electric motor stator windings, approximately 6.35 x 8.26 x 2.22 cm (2.5 by 3.25 by 0.875 inch), containing two random bifilar-wound coils, slot, phase, and wedge insulation.</p> <p>For hermetic motor testing, the motorettes are exposed in autoclaves containing refrigerant.</p> <p>Autoclaves are typically externally heated, and the motorettes are typically subjected to voltage, but not current stresses.</p>	<p>Yes</p> <p>IEEE Standard 117 motorettes are exposed to refrigerant and lubricant in autoclaves for 1440 hrs.</p> <p>Autoclaves are externally heated.</p> <p>Motorettes are <u>not</u> subjected to either voltage or current stress during test.</p>	<p>No governing standards. Each manufacturer has own variations.</p> <p>Full-scale, three-phase hermetic motor-compressor with gutted compressor is installed between evaporator and compressor of auxiliary supported loop. Phase to test motor reversed at approximately 2 sec intervals (i.e., plug reversal) causing rotor to reverse rotation, simulating locked or stalled rotor conditions.</p>
Thermal cycling	<p>Typically at elevated temperature below the insulation or refrigerant breakdown temperature for 18-20 hrs/day, with room-temperature "soak" for remaining hours.</p> <p>Provision is generally made to periodically dump liquid refrigerant onto the motorettes to simulate liquid refrigerant slugging.</p>	<p>288 hrs at 140° C (284° F) followed by 48 hrs at room temperature, repeated five times.</p> <p>No provision to slug with liquid refrigerant.</p>	<p>Thermal profile varies. In GE "Cyclic Reversal" test motor temperature was raised from 50 to 150° C (122-302° F) over 22.5 min by 2.5 sec plug reversals, separated by 0.5 sec nuls. Force-cooled back to 50° C (122° F) over 22.5 min with liquid refrigerant.</p>

Table 2-1 (cont)

	IEEE Standard 117 Motorette	UL Standard 984	Plug-reversal Test
Test Endpoint	Gross failure. Time-to-failure typically under 6000 hrs (250 days).	Pass-fail based on specified insulation properties at 1680 hrs (70 days).	Gross failure. Time-to-failure typically less than 10 ⁶ reversals, 2000 hrs (83 days).
Required Replicates	Ten under IEEE 117, many researchers use octets.	Six replicates required.	Octets are typical.
Intended Use	Studies of insulation aging.	Safety	Tests of modification of motor <u>design</u> .
Forces simulated	Electro-potential forces, thermal aging, periodic soaking with refrigerant.	Thermal aging, periodic soak with refrigerant/lubricant.	All forces of locked rotor operations: electro-potential, magnetodynamic, magnetostrictive, thermal aging, thermal shock, differential expansion.
Forces not simulated	Magnetodynamic and magnetostrictive forces, differential thermal expansion, locked-rotor current loads and thermal excursions.	Electro-potential, magnetodynamic and magnetostrictive forces, differential thermal expansion, locked-rotor current loads and thermal excursions.	
Major Advantages	Comparatively simple test device. Standard device construction facilitates comparative testing of diverse insulation products. Comparatively simple supporting utilities and controls.	Even simpler than IEEE Standard 117 test.	Most complete simulation of locked rotor operation.

Table 2-1 (cont)

	IEEE Standard 117 Motorette	UL Standard 984	Plug-reversal Test
Major Disadvantages for Comparative Insulation Life Testing	Does not simulate significant degradation forces.	Does not simulate significant degradation forces.	<p>Complex supporting utilities (complete refrigeration loop).</p> <p>Extremely difficult to decontaminate auxiliary loop following motor test or when changing refrigerant/lubricants.</p> <p>Would require fabrication of standardized motor design with varying insulation systems.</p>

3.0 CONCEPTUAL DESIGN OF THE SSU TEST

This section reviews the *conceptual* design of the Simulated Stator Unit (SSU) and proposed SSU Test. Section 4.0 describes the *as-built* prototype.

3.1 Overview

After consideration of the mechanisms of insulation failure in hermetic motors, and a review of the current methods used to test hermetic motor insulation systems, Radian concluded that an improved test device, designated as a Stator Simulator Unit (SSU), could be designed that 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 a typical 7.5 hp, 3-phase, 460 VAC hermetic air conditioning motor undergoing the General Electric Cyclic Reversal test (see Table 2-1).

The SSU is designed to emulate the following forces that have been determined 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.

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.

3.2 Summary Description of Concept

Figure 3-1 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 contains 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."

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

Figure 3-2 shows the details of the components included in the conceptual SSU. The SSU is 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 custom "E" laminations shown in Figure 3-2 were designed to simulate the slot geometry of a typical motor. As Figure 3-2 shows, the slots contain slot liner, two 40-turn coils of #18 wire separated by mid-stick insulation, and top-stick electrical insulation. When the unit is assembled, the "I" lamination rests on top of the custom "E" lamination forming an air gap over the center leg simulating the total stator-to-armature air gap in a typical 7.5 hp motor. 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 in-rush current pulses. The specified air gap was designed to prevent saturation of the steel SSU core with magnetic flux under simulated plug-reversal in-rush currents of 30 A.

Each SSU will be exposed to refrigerant/lubricant in an autoclave equipped with a headspace chiller and siphon cup similar to those typically used by A. O. Smith 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 3-1. Isometric Drawing of the SSU.

Figure 3-2. Conceptual design of the SSU components.

As noted above, in-rush current surges of approximately 30 A are impressed on one coil, simulating plug-reversal conditions, while the ends of the other coil are shorted together. Transformer action induces an approximate 30 A current in the shorted winding, so I^2R losses in both windings contribute heat to the unit.

Conceptually, the surges are delivered in microcycles consisting of about two seconds on and one second off, though the pulse duration and null duration are adjustable. Microcycles are impressed for the first half of a 40 minute mesocycle, raising the temperature from 40° C (104° F) to a conceptual design limit of 150° C (302° F), after which the SSU would be allowed to cool back to 40° C (104° F). Twenty-seven such mesocycles are impressed over an 18-hr period, followed by a 6-hr cooldown and soak period, completing one macrocycle. Quenches of liquid refrigerant from the siphon cup are superimposed on the SSU during the power cycles.

The copper wire is 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 produces motion in the opposite direction due to differential thermal contraction.

3.3 Conceptual Control and Data Acquisition System

In the Request for Proposals leading to the Phase 1 Conceptual Design, ARTI specified six combinations of insulation to be tested in each of four refrigerant/lubricants. Assuming eight replicates for each test, simultaneous testing of all six insulation combination in any specified refrigerant/lubricant would require 48 simultaneous tests.

Radian 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 two insulation permutations (or the same insulation system in two refrigerant/lubricants). In 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. In this scenario, two PC-PLC systems would allow simultaneous testing of a single insulation system in four alternative refrigerant/lubricant mixtures.

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 six-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 in-rush currents, while the other six SSU's are in a 20-minute cooling down period. The last major timing sequence is staggering of the in-rush pulse cycle for each of the six active SSUs. The above multiplexing scheme has only four of the 16 SSU's on the power line at any one time, resulting in savings in equipment costs for variable transformers and isolation transformers.

This system will control test conditions, perform the required tests at specified intervals, record the data, and allow trend analysis of the results.

Conceptually, several dielectric parameters were to 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.
- 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.
- Surge testing, imposition of a 2200 V DC 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.
- 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.

SSU failure may be defined by gross failure, i.e., test to destruction. However, it was hoped that trend analysis of the above parameters might lead to identification of a definable endpoint short of actual SSU failure.

4.0 AS-BUILT PROTOTYPE TEST UNIT

At the conclusion of Phase 1, Radian and ARTI agreed that the next logical step in development of the SSU test would be the construction of a prototype and proof-of-concept testing, to be conducted as the current Phase 2 effort. It was decided that one SSU test system with a single autoclave under analog, rather than digital, control would be constructed, followed by construction of a duplicate unit after debugging. By 5 December, the first prototype unit had been constructed and one SSU had been tested to failure.

Table 4-1 compares the conceptual design with the as-built prototype design. A few of the key points and developments are discussed in more detail below.

4.1 Control and Data Acquisition System

In the conceptual design, control and data acquisition were managed automatically by a PC-driven programmable logic controller. However, analog control and manual data acquisition systems were used for the prototype testing.

4.1.1 Electrical Controls

As discussed in Section 3, electrical excitation is impressed in three cycles. The basic excitation pulse, the microcycle, conceptually consisted of a 2 second power pulse, followed by a 1.0 second null period without power. In preliminary air tests, the microcycle pulse was adjusted to 2.5 seconds, with 0.5 second nulls. In refrigerant testing, the microcycle pulse has been set at 1 second with 1 second nulls.

Conceptually, microcycles were to be impressed for the first half of a 40-minute mesocycle, raising the temperature from 40° C (104° F) to 180° C (356° F)¹, after which the SSU would be allowed to cool back to 40° C. Twenty-seven mesocycles would be impressed over an 18-hour period, followed by a 6-hour cool down and soak period, completing one macrocycle.

Based on pilot test results, the mesocycle was adjusted to a 30 minute enabled period with a 10 minute disabled period. The 30 minute enabled period allows time for approximately five quenches of the hot SSU by liquid refrigerant from the syphon cup, and increases the number of microcycles impressed per day. Given that the experimental cooling time constant of the SSU is 1.6 minutes, the 10 minute disabled period is adequate to cool the SSU back to less than 40° C (104° F). The macrocycle was unchanged, 18 hours enabled and 6 hours disabled.

¹ In the conceptual design, the limit temperature was set at 150° C (302° F), but was raised for prototype testing to the 180° C (356° F) thermal limit of the Class H insulation used in the construction of the prototype SSU units.

Table 4-1

Comparison of Conceptual and As-built Prototype Designs

Feature/Requirement	Conceptual Design	As-built Prototype
Purpose	<p>Simulate thermal, magnetodynamic, and thermochemical environment of 7.5 hp, 3-phase, 460 VAC hermetic motor in repeated stalled rotor start condition (plug reversal condition).</p> <p>Eliminate requirement for auxiliary motor-compressor required for conventional plug reversal test.</p>	Unchanged
CONTROL SYSTEM		
Philosophy	Multi-plex computer automated control and data acquisition system.	Simplified analog control system. Manual and strip-chart data logging.
Number of control systems	3	2
Number of test units/control system	16	1
SIMULATED STATOR UNIT (SSU)		
Lamination Core		
Core dimensions, overall	10.16 by 6.668 by 4.128 cm (4.00 by 2.625 by 1.652 inch)	10.16 by 6.668 by 4.445 cm (4.00 by 2.625 by 1.75 inch)
Lamination material	M-19 electrical steel, 21.25/cm (54/inch)	M-19 electrical steel, 15.75/cm (40/inch)
DC permeability at 16,000 Gauss	5,500	Unchanged
Custom E-lamination	3.016 cm by 6.668 cm (1.1875 inch by 2.625 inch), minimum center leg width of 2.540 cm (1.00 inch).	2.858 by 6.668 cm (1.250 by 2.625 inch), minimum center leg width 2.286 cm (0.900 inch).
Standard I-laminations	1.111 cm by 6.668 cm (0.4375 inch by 2.625 inch).	Unchanged

Table 4-1 (cont)

Feature/Requirement	Conceptual Design	As-built Prototype
Air gap	1.194 mm (0.047 inch)	Unchanged
Magnetic Saturation at 30 A	None	Not saturated at 30 A, confirmed by experiment
Number of laminations	216	163
Stacking factor	Not addressed	98%
Retaining rods	Type 304L stainless steel	Unchanged
Lamination temperature sensor	Not addressed	Thermocouple attached to the Mark 1, Number 1 SSU lamination. Trials showed little variation between lamination temperature and oil temperature. Lamination thermocouple deleted from Mark 2 SSUs.
Windings and Insulation		
Insulation Class	B, F, or H (test variable)	H
Wire	#17, #18, or #19 with Phelps Dodge Armored Polythermaleze APTZ 2000, pre-lubrication compatible with refrigerant to be tested.	#19 with Phelps Dodge Armored Polythermaleze APTZ 2000, prelubricated with mineral oil.
Slot insulation	Test variable	Dupont Nomex aramid paper, 0.381 mm (15 mils)
Mid-stick	Test variable	Dupont Nomex aramid paper, 0.254 mm (10 mils)
Top stick (wedge)	Test variable	Dupont Nomex aramid paper, 0.508 mm (20 mils)
Phase (outside coils)	Test variable	Dupont Nomex aramid paper, 0.381 mm (15 mils)
Varnish	Schenectady isoproxy 800 or P.D. George U-475 EHR, diluted to manufacturer's specifications	Schenectady Isoproxy 800, diluted to manufacturer's specifications.
Ties	Glass cord, simulating new motor construction	Unchanged

Table 4-1 (cont)

Feature/Requirement	Conceptual Design	As-built Prototype
Primary (bottom) coil	20 bifilar (two-in-hand) turns.	19 bifilar turns. Number of bifilar turns reduced to 19 to accommodate winding internal temperature thermocouple.
Secondary (top) coil	20 bifilar (two-in-hand) turns.	19 bifilar turns.
Temperature sensor	Copper resistance technique proposed.	Thermocouple inserted into primary coil within the slot to measure winding internal temperature. Copper resistance technique demonstrated to be workable in principle, but erratic with prototype controls due to variability of contact resistance.
PRESSURE CONTAINMENT		
Pressure Vessel		
Working Pressure	≤66.6 Pa (0.5 mm Hg) absolute to 2.41 MPa(350 psi) gauge	≤6.66 Pa(0.5 mmHg) absolute to pressure excursion to 3.79 MPa (550 psi) gauge at 180° C (356° F). Working pressure for R-22 cycles between 689 kPa and 1.72 MPa(100 and 250 psig) gauge.
Temperature	Ambient to 150° C (302° F)	Ambient to 180° C (356° F).
Relief Pressure	Not addressed	4.27 MPa (620 psi) gauge
Pressure vessel rating	Not addressed	5.17 MPa (750 psi) gauge at 360° C (680° F)
Internal dimensions	10.16 cm (4.00 inch) diameter by 26.67 cm (10.5 inch) high	10.16 cm (4.00-inch) diameter by 30.48 cm (12.00-inch) internal height
Vessel Material	Type 316L stainless steel	Unchanged
Vessel Source	Parr Instrument Company, 2 L autoclave	Parr Instrument Company, custom autoclave
Service Penetrations		
High voltage, high current power connections	Eight leads required, pass-through not yet specified.	Eight Fusite ceramic pass-throughs, 1/8-inch NPT fittings in autoclave lid.

Table 4-1 (cont)

Feature/Requirement	Conceptual Design	As-built Prototype
SSU thermocouple pass-throughs	No provision	Dual-lead Pave hermetic motor thermocouple pass-through in autoclave lid.
Gas phase thermocouple	No provision	Swagelok fitting in side of autoclave
Oil phase thermocouple	No provision	Swagelok fitting in side of autoclave
Charging, pressure sensing, and pressure-relief penetrations	Not yet specified	Two swagelok fittings in side of autoclave.
Condenser coil penetrations	Two required	Two swagelok fittings in autoclave lid.
Condenser and Siphon Cup		
Siphon cup gross dimensions	Not designed	7.62 cm (3.00-inch) diameter by 4.128 cm (1.625 inch) high.
Condenser coil	Not designed	0.889 mm (0.035-inch) wall, 6.35 mm (0.25-inch) diameter soft copper, 61 cm (24-inch) internal length in four-turn helix with an inside diameter of 4.128 cm (1.675 inches). Bottom two turns of coil are positioned inside the siphon cup.
Peak condenser heat extraction rate	Unknown	988 Btu/hr (290 W) by experiment
Net dump volume	Unknown	119 ± 1 mL (7.26 ± 0.06 in ³)
Residual volume	Unknown	7 ± 1 mL (0.43 ± 0.06 in ³)
Syphon cup fill time	Unknown	Averages 230 ± 30 seconds
Syphon cup drain time	Unknown	20 seconds
UTILITIES		
Cooling water inlet temperature	Not addressed	13.3° C (56° F)

Table 4-1 (cont)

Feature/Requirement	Conceptual Design	As-built Prototype
Cooling water flow rate	Not addressed	12.6 mL/s (0.2 gpm)
ΔT at peak heat extraction rate	Unknown	5.6 Celsius degrees (10.1 Fahrenheit degrees) determined by experiment.
Head-space shell heater	Need not anticipated	Approximately 100 W continuous by heat tape required to preclude refrigerant condensation on headspace shell (head is chilled by conduction from the condenser pass-throughs).
REFRIGERANT AND LUBRICANT CHARGE		
Refrigerant	Test variable	Virgin commercial quality R-22
Lubricant	Test Variable	Virgin refrigeration-grade mineral oil
Refrigerant charge	Sufficient to activate syphon cup	334.5 g (11.8 oz)
Lubricant charge	Sufficient to immerse bottom turns of SSU	350 mL (21.3 in ³)
Net vapor space	Not calculated	1758 $\pm$ 20 mL (107.3 $\pm$ 0.6 in ³) by displacement
STRESS PROGRAM		
Electrical Excitation		
Macrocycle	18 hrs enabled (active), 6 hrs disabled (resting)	Unchanged
Mesocycle	20 min enabled (driven), 20 min disabled (coasting)	30 minutes enabled, 10 minutes disabled
Microcycle	2 sec pulse (on), followed by 1 second null (off)	1 sec pulse, 1 second null
Mesocycles/test day	27	26
Microcycles/day	10,800	20,600
Pulse current, primary winding	30 A	28.3 A at 21.1°C (70°F), decreasing to 21.2 A at 180°F (356°F)

Table 4-1 (cont)

Feature/Requirement	Conceptual Design	As-built Prototype
Pulse current, secondary winding	30 A	28.0 A at 21.1° C (70° F), decreasing to 21.0 A at 180° C (356° F)
Phase-to-phase voltage stress	460 V rms	575 V rms nominal, 540 V rms actual
Phase angle	72°	Unchanged
Power Factor	31%	30.9%
Thermal Cycling		
Peak temperature	Insulation rating temperature at end of 20 minute driven period.	Winding internal temperature reaches 180° C (356° F) set point within 3 minutes, thermal limiter circuit prevents excursion beyond set limit
Effect of syphon cup dump on winding temperature.	Unknown	Cup dump on hot winding drops from 180° C (356° F) to 75° C (167° F) in less than 2 minutes Temperature then rises to 180° C (356° F) in less than 2 minutes. Five full thermal shock 75→180→75° C (167→356→167° F) cycles occur during each 30 minute driven period, minimum of 130 thermal shock cycles per day.
MONITORED PARAMETERS		
Number of micro-cycles	Continuous	Continuous
Winding internal temperature	Not addressed	Continuous
Top winding surface temperature	Not addressed	Continuous on Mark 2, Number 1 SSU, will be discontinued on future SSUs.
Gas phase temperature	Not addressed	Continuous
Oil temperature	Not addressed	Continuous
Pressure	Not addressed	Dial gauge, pressure fluctuations not recorded.
Hi-pot resistance	Automatic, daily	Manual, daily

Table 4-1 (cont)

Feature/Requirement	Conceptual Design	As-built Prototype
AC Surge	Automatic, daily	Manual, daily
Capacitance	Automatic, daily	Manual, daily
Power dissipation factor	Automatic, daily	Manual, daily
Polarization index	Calculated from Hipot data, daily	Eliminated (experimentally impractical)

Figure 4-1 illustrates the analog logic required to control the electrical excitation activity. In this diagram, the macrocycle and mesocycle sequencers are permissive. The macrocycle sequencer must be enabled to permit the mesocycle sequencer to operate. Likewise, the mesocycle sequencer must be enabled to permit the microcycle generator to operate.

One additional permissive control, the thermal limiter, was added during prototype design. The thermal limiter inhibits generation of microcycle pulses when the core winding temperature of the SSU exceeds a pre-selected value [180°C (356°F) in the current testing], as a protection against thermal run-away.

One of the largest challenges in the design of the control system was to design a relay system that could withstand the test conditions and last longer than the equipment under test. The relays must provide excellent isolation when open, must reliably pass current or signal data when closed, and must withstand 2200 VDC high potential tests; 2200 VDC peak value surge waveform tests; must have relatively low capacitance when the winding capacitance and dissipation factor measurements are being made; and must withstand in excess of 10^6 cycles of 30 A surges. During the conceptual design, it was decided that electromechanical relays would be used to meet these requirements.

The primary failure mode of mechanical contacts is arcing. However, if an electromechanical relay is switched with no current flow then it should last almost indefinitely. A solid state relay inserted in the transformer primary power supply interrupts power to the electro-mechanical relays while the contacts are opening or closing, so that all contact action is in the unpowered state. Furnace contactors were selected as the electromechanical relays because they are economical, rugged, and have replaceable contacts.

The analog timer-driven sequencing logic of the prototype controls will be replaced with a PC-PLC for production testing, while the power relay controls will remain unchanged. Thus, the prototype control panel also serves as a test bed for the power relays.

4.1.2 Data Acquisition

Each current pulse is counted automatically by an incremental counter.

Four channels of temperature data are available for collection by strip-chart recorder during the prototype testing. One channel records the winding core temperature, another the refrigerant vapor temperature, and another the lubricant temperature. The fourth channel can be used to monitor either the lamination temperature or the upper end-turn surface temperature.

Figure 4-1. Simplified schematic of SSU electrical excitation control logic.

The tests and the test equipment used for daily Insulation Performance Measurements (IPMs) of the SSU insulation system are described below. Under the conceptual design, these tests were to be performed automatically. During the current prototype testing, they are performed manually.

The impressed voltages of the high voltage tests were initially reduced to about 50% or less of the standard recommended values to minimize the risk of stressing the SSU insulation system simply by the repeated application of the property monitoring tests. Subsequent testing demonstrated that NEMA MG-1 potentials recommended for field testing of used motors did not degrade the insulation systems of the SSUs.

Hipotential (Hipot) Testing

Hipot test are performed daily on the primary (slot) coil-to-ground, secondary (wedge) coil-to-ground and from coil-to-coil. The DC voltage used in this test averaged 1211 VDC and ranged from 1125 to 1287 VDC. This voltage supplied adequate current to define the charge time of the insulation capacitance, and the insulation resistance at the first few test days and the last two test days. For most of the test days the steady state insulation resistance was beyond the measuring range of the Baker ST112R.

The NEMA recommends a test voltage of two times the operating voltage plus 1000 volts for new motors. The insulation system of the SSU is designed to operate at 600 V rms so the recommended hipot test voltage would be:

$$(2 \times 600) + 1000 = 2200 \text{ V DC}$$

NEMA also specifies that the hipot test voltage not exceed 75% of the new test voltage specification for motors that have been in service.

$$2200 \times 0.75 = 1650 \text{ V DC}$$

To avoid excessive stressing of the SSU insulation with repeated daily testing, Radian has reduced the nominal test voltage by 45% to 1211 VDC.

Each Hipot test is performed for 5 minutes and data are automatically acquired and processed by a PC with the MTA 4.5 software installed. Data are taken at 0:15, 0:30, 0:45, 1:00, 1:30, 2:00, 2:30, 3:10, 4:00, and 5:00 minutes. The insulation capacitance was found to be completely charged at the 1 minute point and there is very little change for the remainder of the data points.

Surge Testing

The Baker ST112R was also used to surge test the SSU. Surge tests were performed on the slot coil with the wedge coil shorted and on the wedge coil with the

slot coil shorted. The peak voltage applied to each coil was 1,000 volts. Each of the coils traced out a classic "ringing" pattern for a single coil and the patterns were quite stable.

The surge test is normally performed with a peak voltage of 2200 VDC. However, Radian chose to use 45% of the recommended voltage to avoid excessive stressing of the SSU insulation. It is believed that this voltage is adequate to detect turn-to-turn shorts.

Capacitance and Dissipation Factor Testing

The Biddle tester is used to measure the capacitance and dissipation factor between the bifilar turns of both the slot coil and the wedge coil. The voltage used for this test is 500 V rms, 60 HZ, which is less than the design rated voltage of the SSU insulation system, so test voltage stress is not a concern as this test is performed. The combined reactive and resistive current through the wire varnish insulation was 0.3 mA. The bridge balance and the dissipation factor measurements were solid with no appreciable interference. Given the measured capacitance and dissipation factors, the resistive value of the wire varnish insulation can be deconvoluted mathematically.

Copper Resistance Temperature Tests

In the conceptual design, Radian described a method by which the SSU winding temperature could be determined directly, rather than through an implanted thermocouple through sensitive measurement of the resistance of the copper windings.

Experimentally, a Lambda DC power supply and a Fluke multimeter were used to measure the DC resistance of all of the SSU windings in series.

SSU Primary Coil Current and Secondary Coil Potential

The primary (slot) coil current was measured with a Tektronics 545 Oscilloscope connected across a 0.002 ohm current shunt in the primary power circuit. The Fluke multimeter was used to measure the voltage with respect to ground impressed on the secondary (wedge) coil of the SSU.

4.2 SSU

The SSU devices were fabricated by Jasper Electric, according to Radian's design specifications.

The pilot SSU, designated Mk1A-1, is shown in Figure 4-2 after the conclusion of the pilot testing. This SSU was constructed according to the dimensions shown in Figures 3-1 and 3-2, with the exception that #19 wire was used instead of #18, and the number of turns in each coil was reduced from 40 to 38. A very fine gauge

Figure 4-2. Mk1A-1 pilot SSU, after pilot tests.

Type K thermocouple was imbedded in the middle of the slot winding for measurement of the core winding temperature. A surface thermocouple was attached to the surface of the laminations to measure the lamination temperature.

The end turns of the Mk1A-1 SSU were entirely wrapped with lashing tape, limiting the exposure of the windings to thermal shock from liquid refrigerant quenches. This configuration was at variance with the typical construction of new hermetic motor stators and Radian's specifications.

Figure 4-3 shows a Mk1B prototype SSU prior to testing. The end-turn wrapping was made according to Radian's specification to better emulate factory motor construction. In addition, Radian changed the dimensions of the laminations as noted in Figure 4-4 to create a more uniform magnetic flux around the windings.

4.3 Autoclave (Pressure Boundary)

The autoclave serves as the pressure boundary for the system and contains the SSU, siphon cup and siphon condenser coil. The autoclave must provide safe, sure, leaktight containment of the pressurized refrigerant, while supporting the lead-through of numerous electrical connections and cooling water for the condenser.

After consideration of several alternatives, a modified Parr Instruments 2-L autoclave was selected as the pressure vessel. The as-built pressure vessel was modified to have a 30.48 cm (12-inch) internal depth, compared to the 26.67 cm (10.5 inches) of the standard autoclave, as well as a thickened reinforcing ring to allow three penetrations 120° apart around the girth of the vessel. The lid was modified to accommodate 11 penetrations, eight for the SSU power/sensor leads, two for the cooling water to the siphon condenser, and one for the two SSU thermocouple lead-throughs. The resulting pressure vessel was rated for 5.5 MPa (800 psi) gauge pressure, with a pressure relief valve at 4.3 MPa (620 psi) gauge pressure.

The eight SSU power/sensor lead-throughs were made with commercially available single-post ceramic hermetic motor lead-throughs. The thermocouple lead-through was also a commercially available device sold for hermetic motor service. The selected thermocouple lead-through incorporated leads for two thermocouples, though the pass-throughs can be ordered for up to eight thermocouples. Refrigerant vapor and lubricant temperature thermocouples were inserted through ports in the side of the autoclave.

Figure 4-3. Mk1B prototype SSU as received from manufacturer.

Figure 4-4. Mk1B SSU dimensions.

Figure 4-5 shows the autoclave and siphon-cup/SSU assembly during final assembly just prior to testing. As shown in this figure, the siphon cup and SSU are rigidly attached to the autoclave lid, creating a module for insertion into the autoclave. The siphon cup discharge is directly over the upper end-turns of the SSU. When testing, the autoclave contains enough lubricant to immerse the bottom end-turns and first few laminations of the SSU.

Figure 4-5 shows the pilot SSU and siphon cup condenser. After pilot testing, the cooling coil was modified to a horizontal helical configuration. Otherwise, the pressure vessel design remained unchanged for prototype testing, and can be considered as the final prototype design. For production units, all thermocouple leads can be brought out through the thermocouple lead-through, eliminating the need for thermocouple ports in the side-wall of the autoclave. It would also be advantageous to make the gas port, pressure relief, and gauging penetrations through the lid, possibly by combining these ports with the thermocouple lead-through, but such redesign work will not be undertaken during the current phase of work.

4.4 Cooling Loop

During pilot testing, cooling was supplied by tap water in a once-through loop. All subsequent testing was performed with 13°C (56°F) chilled water from a laboratory chiller. It has been determined that 12.6 ML/s/autoclave (0.2 gal/min/autoclave) of chilled water provides adequate cooling.

4.5 Refrigerant Charging and Recovery Procedures

Charging and recovery procedures are designed to comply with applicable regulations related to discharge of CFC refrigerants, and to assure that only *de minimis* quantities are released.

4.5.1 Charging Procedure

Commercial virgin DuPont refrigerant and compatible virgin lubricant are used for all tests.

Prior to insertion of the SSU module, 350 mL (21.4 in³) of virgin lubricant is decanted into the autoclave. The SSU module is inserted and the autoclave lid is sealed, evacuated to less than 13.3 Pa (0.1 mmHg) absolute, and baked at 150°C (302°F) for one hour to thoroughly dry the autoclave and contents.

Refrigerant charging is performed by the triple purge-and-trap method which is standard practice for air-conditioning and refrigeration repair. Following bakeout, refrigerant is introduced to create a positive pressure, then recovered by standard refrigerant recovery pump to a pressure of not more than 13.3 Pa (0.1 mmHg)

Figure 4-5. Prototype SSU test assembly.

absolute. The autoclave is again pressurized with refrigerant, and again evacuated to less than 13.3 Pa (0.1 mmHg) absolute. Following this evacuation, a metered charge of refrigerant is instilled using a standard refrigeration Dial-A-Charge apparatus.

4.5.2 Recovery of Spent Refrigerant

Spent refrigerant is either recovered directly using standard reclamation equipment, or through the intermediate step of cryogenic capture. Spent refrigerant is reclaimed directly using standard reclamation equipment. During the triple purge and trap charging procedure, the refrigerant purges are recovered directly. At the conclusion of a test, the spent refrigerant can be recovered directly from the autoclave if cryogenic capture is not performed.

Cryogenic capture after a test allows a precise gravimetric determination of the mass of refrigerant charged to the autoclave, and provides samples of refrigerant for subsequent laboratory analysis if desired.

For cryogenic capture, the gas fill port of the autoclave is attached to a tared, evacuated stainless steel pressure bomb immersed in a liquid nitrogen bath. When the gas port valve is opened, refrigerant migrates to the sample bomb where it freezes out. The vapor pressure of refrigerant at liquid nitrogen temperatures is measured in microtorrs, and a strong vacuum results. The lubricant bath is heated for one hour during the cryogenic capture to liberate dissolved refrigerant.

Following cryogenic recovery, the mass of recovered refrigerant can be determined gravimetrically. If refrigerant analysis is required, an aliquot of recovered refrigerant can be transferred to a smaller sample bomb. If cryogenic capture is performed, the refrigerant in the sample bomb is ultimately reclaimed using standard reclamation equipment.

4.6 Safety and Environmental Protection

The SSU controller is equipped with a thermal limiter designed to prevent thermal runaway, and has fuses that will interrupt power to the SSU in the event of a short-type failure during testing.

The SSU control panel is designed so that all points of contact with high currents or voltages are enclosed and shielded from inadvertent contact. Plug-type safety switches are provided for each control panel, allowing for positive lock-out of power to the individual panels. The laboratory is also equipped with a master "strike-to-kill" switch near the exit door for emergency shutdown.

The autoclaves themselves are located within a fume hood to protect against accidental contact with the electrodes on the top of the autoclaves, as well as to vent any fugitive fumes from the autoclaves.

To assure that refrigerant will not be vented in more than *de minimis* quantities during a pressure excursion, the autoclave pressure relief valves are connected to an evacuated capture canister which will allow expansive decompression of the refrigerant without venting to atmosphere.

As described above, spent refrigerant at the end of each test is ultimately recovered to a reclaim canister.

5.0 PROOF-OF-CONCEPT

This section of this report presents a summary of the experimental results as of 20 March 1995, the conclusion of the proof-of-concept phase of testing.

5.1 Pilot Test Results

The pilot tests were conducted using the Mk1A SSU (shown in Figure 4-2). The scope of these tests was to:

- Verify that SSU electrical and magnetic properties were as designed;
- Explore heat requirements and refine microcycle and mesocycle parameters,
- Debug the control system; and
- Debug the insulation performance testing procedures.

5.1.1 Basic Electrical and Magnetic Properties

Table 5-1 summarizes the results of basic SSU properties determined by testing in air. All of these data indicate that the assumptions in the design of the SSU were correct.

5.1.2 Properties In Refrigerant/Lubricant

The pilot SSU was installed in the autoclave and charged with refrigerant and lubricant using the triple-purge-and-trap procedure as described in Section 4.5.1, except that only 300 mL (18.3 in³) of lubricant was used. Cryogenic recovery was not used to quantify the refrigerant charge at the end of the pilot test, and the amount of refrigerant charge is not known precisely, but is estimated to be approximately 255 g (9 oz.).

Four temperatures were continuously recorded by strip chart during the pilot tests. These temperatures were the winding core temperature, the lamination temperature, the refrigerant vapor temperature, and the lubricant temperature. The vapor temperature thermocouple was positioned approximately mid-way between the apex of the upper end-turns and the base of the siphon cup, but offset laterally so that it was out of contact with liquid refrigerant draining from the cup. The lubricant thermocouple was positioned approximately 3 mm (0.125 inch) below the bottom of the lower end-turns.

Table 5-1**Basic Experimental SSU Properties**

Parameter	Result	Significance
Winding resistance	0.46 ohm @40° C	Nominal
Capacitance of bifilar winding	1.3 nF	Nominal
Hysteresis curve at 15 A	None	Nominal, the laminations are not saturated.
Inductance	0.004 Henry	Nominal
Voltage/Current Phase Shift	72°	Nominal
Power Factor	30.9%	Nominal
Thermal Time Constant in Air, heat up at 15 A.	1.03 minutes	SSU reaches greater than 98% of peak temperature in less than 4 minutes.
Thermal Time Constant in air, cool down	1.65 minutes	SSU cools to very near ambient temperature in less than 5 minutes.
Steady-state winding/lamination temperature difference	74 Celsius degrees	Slot lining is efficient thermal insulation. Differential thermal expansion under thermal shock should be large.

The thermal limiter circuit was installed, demonstrated, and calibrated to limit the core winding temperature to 180° C (356° F), the rated temperature of the Class H insulation used in the pilot and prototype SSUs.

The pilot testing showed that the thermal time constants in refrigerant without operation of the siphon cup were similar to the thermal constants in air. In the absence of liquid refrigerant quenches from the siphon cup, the SSU winding core temperature rose from 40° C (104° F) at the beginning of a mesocycle to 180° C (356° F) within three minutes, and remained at this level, with up to 2.5C° (5F°) fluctuations due to the thermal limiter circuit for the remaining 27 minutes of the enabled period. At the conclusion of the enabled period, the winding core temperature dropped back to 40° C

The pilot testing also showed that the lamination temperature varied only a few degrees from the oil temperature at the bottom of the autoclave, and the decision was made not to monitor lamination temperature in future tests.

5.1.3 Insulation Property Measurements (IPMs)

The pilot SSU was also used to verify and refine the insulation property measurements (IPMs) procedures to be used to monitor insulation performance during the test. Table 5-2 shows the insulation property measurements performed, the instrumentation used, and the specific insulation properties monitored.

5.1.4 Copper Resistance Thermometry

In the conceptual design, Radian described a method by which the SSU winding temperature could be determined directly, rather than through an implanted thermocouple through sensitive measurement of the resistance of the copper windings. Experimentally, a Lambda DC power supply and a Fluke multimeter were used to measure the DC resistance of all of the SSU windings in series.

The copper resistance thermometer was found to work well in principal. However, in the current controller, five silver-plated motor starter contacts are used to connect the power supply and complete the series connection of the SSU. The silver plated contacts oxidize over time and the combined contact resistance becomes a significant part of the SSU winding resistance, resulting in a wide scatter in the collected data and calculated temperature.

This problem might be overcome in future systems by the use of gold or platinum plated contacts. If this temperature measurement method can be perfected then the imbedded thermocouple may not be necessary. Further, the test confirms continuity through all of the SSU windings.

5.1.5 Microcycle Optimization

As a result of the pilot tests, it was decided that the microcycle profile would be 1 second on, 1 second off, while the mesocycle would have a 30 minute enabled period followed by a 10 minute disabled period.

Table 5-2

Monitored Insulation Property Measurements

Test	Instrument	Measured Property
Hipot	Baker ST112R/MTA4.5 Software	Steady-state DC resistance slot-coil-to-ground, wedge-coil-to-ground, and coil-to-coil.
Surge Test	Baker ST112R	Turn-to-turn arcing.
Capacitance	Biddle Tester	AC capacitance of the turn-to-turn insulation.
Dissipation Factor	Biddle Tester	Combined AC capacitive and resistive leakage of the turn-to-turn insulation, from which the AC resistance can be calculated.

5.1.6 Siphon Cup Optimization

The siphon cup appeared to operate only once during the pilot test, and the operation was not conclusive. Three possible causes of the difficulty were identified, and several modifications were made prior to the initial prototype test. The condenser coil design was modified from a vertical loop to a horizontal helix partially inserted into the cup to prevent possible reboiling of the refrigerant condensed into the cup. A heat tape was wrapped around the top of the autoclave as a headspace heater to keep the headspace temperature at about 45°C (113°F) to prevent possible condensation and refluxing of refrigerant on the headspace walls. The tap cooling water at approximately 20°C (68°F) was replaced with chilled water entering the condenser at 13°C (55°F).

5.2 Prototype Tests

Three "real" prototype tests were conducted using Mk1B SSUs. Prototype Test 1 was completed first, then Prototype Tests 2 and 3 were run concurrently.

The purpose of Prototype Tests 1 and 2 were to explore SSU behavior under "driven" conditions, that is, with the regular application of high density power surges. Prototype Test 3 was performed without high-density power surges to explore whether the regular daily Hipot, Surge, and AC capacitance and Dissipation Factor tests themselves degraded the SSU insulation properties.

5.2.1 Test Conditions

Prototype Test 1

This was the first "real" test, using a Mk1B SSU (Mk1B-1). Prior to the test, the autoclave was cleaned with hexane to remove any residues, and the Mk1B-1 SSU was installed. Prior to installation, the lamination thermocouple was removed. A stranded Type K thermocouple wire was spiral wound around the top end turns to sense end-turn surface temperature, and secured over the lashing cord so that it would not abrade the end-turn varnish. No electrical connectivity between this thermocouple and the SSU coils was detected at any point during the test. The leads for the winding core temperature and end-turn surface temperature were brought out through the thermocouple fitting in the lid of the autoclave, while the lubricant and vapor temperatures were monitored via the thermocouples inserted through the side ports.

The autoclave was charged using the triple purge-and-trap procedure described in Section 4.5.1. The lubricant charge was increased from 300 mL (18.3 in³) to 350 mL (21.4 in³) assuring better immersion of the bottom end-turns and first few laminations of the SSU. The refrigerant charge for Prototype Test 1 was increased to 335 g (11.8 oz.), as determined gravimetrically following cryogenic recovery at the end of the test.

The headspace of the autoclave was fitted with a heat tape to maintain a head temperature of approximately 38 to 43°C (100 to 110°F). During the test, the SSU was driven by approximately 20,600 microcycle current surges per day.

Under these conditions, the increased refrigerant/lubricant charge, compared to the pilot test charge, produced dramatic action by the siphon cup, with liquid refrigerant quenches (dumps) at about five minute intervals, clearly apparent from the SSU winding core temperature and surface end-turn temperature traces and fluctuations in the SSU pressure. Six quenches occurred during each 30-minute enabled period of the mesocycle, but no quenches occurred during the disabled period. At least the central four of the six quenches were "full quenches," defined by Radian as quenches that begins when the winding core temperature exceeds 160°C (320°F). The first and/or last quench was frequently truncated because the cup was frequently partially filled from the end of the last mesocycle and the first quench occurred before the core winding temperature peaked. The sixth peak was truncated when the 10-minute disabled phase of the mesocycle began before the peak temperature was recovered following the fifth quench. The power output of the driving transformer was adequate to produce rapid and complete recovery of the core winding temperature following each refrigerant dump.

Prototype Test 2

This test, using SSU MkB1-02, was performed following Prototype Test 1, and was essentially a replicate of Prototype Test 1. As in Prototype Test 1, the

lamination thermocouple was removed prior to insertion of the SSU, and vapor and liquid temperatures were measured by thermocouples inserted through the autoclave wall. However, the braided thermocouple around the upper end turns was eliminated.

Prior to the test, the autoclave was washed with hexane and baked with the lid open for 2 hours at 140° C (284° F). The autoclave was charged with 350 mL (21.4 in³) of virgin mineral oil lubricant, identical to Prototype Test 1, evacuated to less than 500 μ m of Hg vacuum, and baked for 3 hours at 140° C (284° F) to remove any moisture. The same triple-purge-and-trap method was used to instill 340 g (12.0 oz) of R-22.

The headspace of the autoclave was fitted with a heat tape to maintain a head temperature of approximately 38 to 43° C (100 to 110° F). During the test, the SSU was driven by approximately 20,600 microcycle current surges per day.

The siphon cup dumped approximately eight times per mesocycle in this test. The autoclave and siphon cup were those used in the Prototype 1 test. The operating parameters were not changed, with the exception that the refrigerant charge was increased slightly. This suggests that siphon cup performance is sensitive to initial conditions of refrigerant charge.

At a siphon cup rate of eight dumps per mesocycle, the power output of the controller was not adequate to bring the core winding temperature back up to the target 180° C (356° F), and the peak core winding temperature was 168° C (334° F).¹

Prototype Test 3

This test was performed in parallel with Prototype Test 2, using SSU Mk1B-3 and a new autoclave. The configuration and lubricant/refrigerant charges were identical. The autoclave headspace was also maintained in the 38 to 43° C (100 to 110° F) range.

This SSU was not subjected to microcycle current surges. Instead it was subjected to 3 amp currents on a 2.5 second on, 2.5 second off duty cycle.

The slight heat input from the headspace heater was sufficient to produce several siphon cup dumps per day. However, as the core winding temperature never reached 38° C (100° F), these siphon dumps did not produce any significant thermal shocks.

¹ The controller transformer will be replaced with one having larger capacity before future tests are performed.

5.2.2

Characterization of the Barothermal Environment

Pressures were recorded at 15 second intervals from 12.75 minutes through 31.0 minutes of a typical mesocycle in Prototype Test 1, and correlated with lubricant temperature, vapor temperature, end-turn surface temperature, and winding core temperature. The results are shown in Figure 5-1. The winding core temperature ($T_{(core)}$) and winding surface temperature ($T_{(surf)}$) are shown by solid lines. The refrigerant pressure (MPa), vapor temperature ($T_{(vap)}$), and liquid temperature ($T_{(liq)}$), are shown by broken lines, along with the calculated saturation temperature of the refrigerant ($T_{(sat)}$).

For purposes of analysis, the siphon cycles begin at pressure minima, which occur when the siphon cup is full and the moles of refrigerant vapor are at a minimum. The average cycle length is about 4.9 minutes. Immediately following a pressure minimum, the siphon cup discharges approximately 112 mL (6.8 in³) of liquid refrigerant at 13 to 18°C (56 to 64°F) directly onto the exposed upper end-turns of the SSU. The discharge requires approximately 20 seconds, after which the cup begins to refill.

Comparison of the end-turn surface temperature and the pressure curves show that end-turn surface temperature begins to plummet just following the pressure minima, while the pressure soars to peak values of 1.70 ± 0.01 MPa (247 ± 2 psi) gauge as the liquid refrigerant boils off.

Twenty to 30 seconds after the end-turn surface temperature plummets, the winding core temperature plummets from 180°C (356°F) to between 75 and 80°C (167 and 176°F). The winding core temperature reaches its minima at about the same time that the pressure reaches its maxima, indicating that much, if not all of the liquid refrigerant has evaporated. The winding core temperature then rebounds immediately due to the continued heat input.

The amplitude of the winding core temperature oscillation is 110 Celsius degrees (198 Fahrenheit degrees), while the amplitude of the surface end-turn temperature oscillation is about 60 Celsius degrees (108 Fahrenheit degrees). Figure 5-2 approximates the first derivative of the SSU surface end-turn surface and winding core temperature oscillations by depicting the incremental heating or cooling rates (i.e., the slopes of the temperature curves between each successive pair of point. This figure shows that the cooling rates exceed 100°C/minute (180°F/minute) for 15 to 30 seconds of each quench, and peak in the region of 133°C/minute (239.4°F/minute). The rebound once the siphon discharge ends is even more rapid, with peak heating rates in the region of 150°C/minute (270°F/minute).

Figure 5-1. Plot of SSU Temperature and Pressure Data from Minute 12.25 through Minute 31.00 of a typical mesocycle of operation.

Figure 5-2. Incremental cooling and heating rates of the winding end-turn surface and the winding core in 15-second increments during the time covered in Figure 5-1.

The measured temperature of the refrigerant vapor, ($T_{(vap)}$) in Figure 5-1, tends to track the end-turn surface temperature, which is not surprising given that the thermocouple is located in the gap between the bottom of the siphon cup and the apex of the end turn windings (the vapor temperature thermocouple is offset to one side so that it is not exposed to liquid refrigerant).

The thermal oscillations of the liquid within the test chamber are much more gentle than those of the vapor. Interestingly, the liquid temperature rises gradually during most of the refrigerant dump, only dropping as the core winding temperature minima are approached. This behavior is probably a function of thermal inertia of the SSU laminations.

The final curve in Figure 5-1 is the calculated saturation temperature ($T_{(sat)}$) of the refrigerant, based on the observed pressure. This curve shows that there is a very close approach between the winding surface temperature and the saturation temperature near the midpoint of the siphon cup cycle, but that the vapor temperature, liquid temperature, and winding core temperature remain above the saturation temperature at all times. Flashing will occur on all surfaces warmer than the saturation temperature.

The dynamics of the refrigerant result from competition between the condenser, which remains at an essentially constant temperature below the refrigerant dew point at all times, energized SSU, and the auxiliary headspace heater. Figure 5-3 traces the refrigerant vapor temperature-pressure trajectory in temperature-pressure coordinates. Zero in this figure corresponds to the pressure minimum which occurs just as the siphon cup begins to drain. The points in this plot indicate progressive 15-second time intervals. Radian believes that the siphon cup discharge begins at Point 0 and is complete by Point 2. Temperature falls from Point 0 to 6 while pressure rises due to flashing of the liquid refrigerant on the hot SSU, while pressure rises as the liquid evaporates. Point 6 occurs at the closest approach between the refrigerant saturation pressure and the end-turn surface temperature. The trajectory from Point 6 through point 11 represents an almost isothermal boil-off of the dumped liquid refrigerant. During this 1.25-minute interval, the vapor temperature rises only 1.5°C (2.25°F). The peak lubricant temperature occurs at this point, after which the pressure rises very rapidly to Point 12. Pressure declines from Point 12 to Point 20 despite rising temperatures because the refrigerant is recondensing into the cup.

Heat input from the SSU ceased at time = 30 minutes in Figure 5-1. The extremely rapid decay of SSU core temperature to approximately 35°C (95°F) in the absence of current pulses is clearly evident.

Figure 5-3. Refrigerant vapor pressure-temperature cycle during a typical siphon cup cycle. Each point represents an increment of 15 seconds in the cycle.

The siphon cup does not cycle during the 10-minute disabled phase of the mesocycle because its cycling requires heat input to vaporize the refrigerant so that it can migrate to the cup. However, the heat input from the headspace heater is sufficient to gradually fill the siphon cup, and 8 to 10 cycles occur during the 6-hour resting phase of the macrocycle. Both the end-turn surface temperature and winding core temperature fluctuate between 18 and 30° C (64 and 86° F) during these resting period cycles. These cycles do not occur if the headspace heater is turned off. While they were not a feature of the conceptual design, they have the effect of periodically bathing the top of the SSU with liquid refrigerant during the 6-hour resting period.

During each 24-hour period, the SSU is subjected to approximately 20,600 pulses, delivered in 26 mesocycles. For purposed of data analysis, an equivalent test day, or test day, was defined as 20,600 microcycles to allow for normalization of data from calendar days with interrupted operation due of external equipment malfunctions.

5.2.3 SSU Behavior

Table 5-3 summarizes the results of insulation property measurements (IPMs) performed daily on the Prototype Test 1 and Prototype Test 2 SSUs, and twice daily on the Prototype Test 3 SSU.

Prototype Test 3

Prototype Test 3 is discussed first because this test confirmed that the daily IPM procedures used did not themselves degrade the SSU performance.

SSU Mk1B-3 in Prototype Test 3 was subjected to 52 IPMs, each consisting of Hipot, DC Surge, AC Capacitance and Power Dissipation Factor. The first 38 of these IPMs were performed at reduced voltages, while the last 14 were performed at the NEMA MG-1 recommended voltage for field testing of used motors. No evidence was found that the daily insulation property measurements themselves degraded the behavior of the SSU. Consequently, the test voltages for future IPMs will be increased to the NEMA MG-1 recommended values for the testing of used motors.

Prototype Test 1

SSU Mk1B-1 failed during Test Day 17 of its test, after 356,278 microcycles, 456 mesocycles, 2219 full siphon quenches, and 16 complete macrocycles. Failure was manifested by excessive coil-to-coil current leakage which blew a fuse and stopped the test.

Electrical tests demonstrated conclusively that the coil-to-coil short was not associated with the end-turn surface temperature thermocouple, while DC surge tests indicated the absence of turn-to-turn faults within the slot or wedge coils.

Table 5-3
Prototype Test Results

Test	Prototype 1	Prototype 2	Prototype 3
SSU	MkB1-1	MkB1-2	MkB1-3
Test Objective	Test degradation under simulated locked rotor event conditions	Test degradation under simulated locked rotor event conditions	Test for degradation of insulation by daily property tests in the absence of simulated locked rotor events.
SSU condition at test termination	Failed	Degraded but not failed	Not degraded
Number of microcycles	356,278	793,030	Energized with 3 A for 2.5 minutes on, 2.5 minutes off to simulate normal motor operation. Headspace was heated, and condenser operated as in Tests 1 and 2.
Number of mesocycles	456	860	
Number of full quenches	2219	6894	The headspace heat was sufficient to produce periodic syphon dumps, but temperature variations were minor.
Avg number of full syphon quenches per mesocycle	5	8 ^a	
Number of Test Days	17 ^b	38 ^b	52 ^c
Peak core winding temperature.	180° C (356° F)	168° C (334° F) ^d	<38° C (100° F)

Table 5-3 (cont)

Test		Prototype 1	Prototype 2	Prototype 3
Daily Insulation Property Measurements (IPMs)				
Hipot Test	Purpose	Measure the DC ohmic resistance between slot coil and ground, wedge coil and ground, and coil to coil.		
	Test Voltage	1000 V rather than the NEMA MG-1 1760 V to minimize the potential damage to the insulation from repeated testing.	1225 V rather than the NEMA MG-1 1760 V to minimize the potential damage to the insulation from repeated testing.	1225 V through IPM 38, then 1750 V to end of trial.
	Results	The resistance of each coil to ground, and the resistance between coils was approximately 20 gigohms (10^9 ohms) on Day 0, peaked in excess of 100 gigohms on about Test Day 10, and decayed to around 26 gigohms on Test Day 16, the day prior to failure. Because the resistance was so high, the signal produced at 1000 V was extremely weak and therefore very noisy, and the data scatter correspondingly large. These data appear to indicate that the DC resistance of insulation improved somewhat through Test Day 10, then began to regress.	The initial coil-to-ground resistances were 330 gigohms, while the initial coil-to-coil resistance was 230 gigohms. All three resistances decayed approximately semi-logarithmically to 2 to 4 gigohms on Test Day 38.	Extremely "noisy" results ranging from 25 to off-scale at 330 gigohms. No significant change with time.

Table 5-3 (cont)

Test		Prototype 1	Prototype 2	Prototype 3
Surge Test	Purpose	Test for turn-to-turn arcing within each coil.		
	Test Voltage	1000 V peak	1000 V peak	1000 V through IPM 38, then 1700 V to end of trial.
	Results	No significant change in surge signature of either coil either before or after SSU failure.	No significant change.	No significant change.
AC Capacitance	Purpose	Measure the capacitance component of the AC impedance of the turn-to-turn wire insulation. An increase in capacitance would indicate either that the wires are migrating closer together, as would happen if the varnish softened over time.		
	Test Voltage	500 V RMS turn-to-turn	500 V RMS turn-to-turn 1000 V RMS coil-to-coil 1000 V RMS coil-to-ground	500 V RMS turn-to-turn 1000 V RMS coil-to-coil 1000 V RMS coil-to-ground
	Results	Less than 4% increase in capacitance through Test Day 16.	Approximately 40% increase in measured capacitance over the 38 Test Days.	Less than 3% increase in measured capacitance.
Dissipation Factor, and Ohmic resistance	Purpose	The power dissipation factor, a measure of the "lossiness" of the turn-to-turn insulation, captures the interactive effect of capacitance and ohmic resistance changes in the insulation. Given the co-measurement of the capacitance, the change in ohmic resistance can be calculated.		
	Test Voltage	500 V RMS turn-to-turn	500 V RMS turn-to-turn 1000 V RMS coil-to-coil 1000 V RMS coil-to-ground	500 V RMS turn-to-turn 1000 V RMS coil-to-coil 1000 V RMS coil-to-ground

Table 5-3 (cont)

Test	Prototype 1	Prototype 2	Prototype 3
Dissipation Factor, and Ohmic resistance (cont)	<p>Figure 5-5 shows the decay in turn-to-turn ohmic resistance of the two coils. The linear regression equations for the two sets of data, represented by dashed lines in Figure 5-5, are</p> $R = 16.7 - 0.46t, \text{ and}$ $R = 16.9 - 0.43t,$ <p>where R is the resistance in megohms and t is the elapsed time in test days.</p> <p>The starting turn-to-turn resistances of the two coils were quite close at about 16.8 megohms, and had decayed to about 9.5 megohms one day before failure, a 43% decrease. The average of the two slopes is -0.445 megohm/day. These regressions indicate that had the coil-to-coil failure not intervened, the turn-to-turn resistance would have decayed to less than 5 megohms by Test Day 26, and that turn-to-turn resistive failure would probably have occurred between Test Day 25 and Test Day 35.</p>	<p>Figure 5-6 shows the decay in turn-to-turn ohmic resistance of the two coils. The ohmic resistance increased through Test Day 4, then suddenly reverted to values close to the initial value. Subsequent values decayed in an apparently linear fashion. The dashed lines in Figure 5-6 represent the linear regression equations for the data points after Day 5. The equations are</p> $R = 5.74 - 0.06t, \text{ and}$ $R = 6.08 - 0.06t,$ <p>where R is the resistance in megohms and t is the elapsed time in test days.</p> <p>The initial resistances of the coils were much lower than those of MkB1-1, but rose rapidly to similar values under test. This may reflect thermal desorption of moisture from the varnish.</p> <p>It is known that varnish endurance is sensitive to peak temperatures near the thermal limit of the insulation. The fact that design peak temperatures could not be obtained may account for the difference in degradation slopes compared to MkB1-1.</p>	<p>No significant change.</p>

Table 5-3 (cont)

- a. It is assumed that the increased syphon quench rate resulted from an increase in the R-22 charge, as no other variables were altered. It appears that the syphon quench rate is sensitive to initial conditions.
- b. A Test Day is defined as 20,600 microcycles.
- c. This SSU was subjected to two Insulation Property Measurements (IPMs) per calendar day. Each IPM terminated an "equivalent test day," based on the premise that the SSU insulation was unstressed except for the IPM activities.
- d. The transformers used during the prototype study could not supply enough power to obtain the 180° C (356° F) target with 1-second pulses at a syphon quench rate of eight/mesocycle. Very near the end of the test, the target temperature was obtained by increasing the pulse width to 1.25 seconds. Higher power transformers will be used for future tests.

The point of leakage was traced to two of the eight power leads of the SSU. These two leads, Numbers 1 and 5, one from each coil, appear not to have been separated by the phase insulation.² Failure appears to have occurred within the area reinforced by the lashing cord, at approximately the location indicated by the arrow in Figure 5-4. Radian considers this to be a legitimate coil-to-coil failure.

There was no change in the DC surge signatures of either the slot or wedge coils prior to failure on Test Day 17. The signatures were not significantly altered after failure.

The Hipot resistance of each coil ranged from about 20 gigohms (10^9 ohms) on Day 0, peaked in excess of 100 gigohms on about Test Day 10, and decayed to around 26 gigohms on Test Day 16, the day prior to failure. Because the resistance was so high, the signal produced at 1000 V was extremely weak and therefore very noisy, and the data scatter correspondingly large. These data appear to indicate that the DC resistance of insulation improved somewhat through Test Day 10, then began to regress.

The turn-to-turn AC capacitance at 60 Hz increased by a few percent over Test Day 16.

The power dissipation factor, a measure of the "lossiness" of the turn-to-turn insulation, captures the interactive effect of capacitance and ohmic resistance changes in the insulation. Given the co-measurement of the capacitance, the change in ohmic resistance can be calculated. The turn-to-turn power dissipation factor for each of the coils increased steadily throughout the test.

Figure 5-5 shows the decay in turn-to-turn ohmic resistance of the two coils, calculated from the capacitance and power dissipation factor data. The linear regression equations for the two sets of data, represented by dashed lines in Figure 5-6, are

$$R = 16.7 - 0.46t, \text{ and}$$

$$R = 16.9 - 0.43t$$

where R is the resistance in megohms
t is the elapsed time in test days.

The starting turn-to-turn resistances of the two coils were quite close at about 16.8 megohms, and had decayed to about 9.5 megohms one day before failure, a 43% decrease.

² Radian believes that the leads of the slot coil should be separated from the leads of the wedge coil by phase insulation. The specification for future SSU's will be amended to assure phase separation of the coil leads.

Figure 5-4. The upper end-turns of SSU Mk1B-1 following failure. Failure occurred at approximately the location of the arrow between primary (slot) coil lead 1 and secondary (wedge) coil lead 5, which do not appear to be separated by phase insulation.

Figure 5-5. The turn-to-turn ohmic resistance component of the power dissipation factor for the primary and secondary coils of Mk1B-1 (Prototype Test 1).

The average of the two slopes is -0.445 megohm/day. These regressions indicate that had the coil-to-coil failure not intervened, the turn-to-turn resistance would have decayed to less than 5 megohms by Test Day 26, and that turn-to-turn resistive failure would probably have occurred between Test Day 25 and Test Day 35.

Prototype Test 2

This test was terminated by schedule constraints prior to gross failure of the SSU.

The Hipot initial coil-to-ground resistances were off scale (>330 gigohms), while the initial coil-to-coil resistance was 230 gigohms. All three resistances decayed approximately semi-logarithmically to 2 to 4 gigohms on Test Day 38. There was no change in the DC surge test results.

There was approximately a 40% increase in measured capacitance at 60 Hz over the 38 Test Days. The power dissipation factor also increased in an essentially linear manner.

Figure 5-6 shows the decay in turn-to-turn ohmic resistance of the two coils, calculated from the capacitance and power dissipation factor data. The ohmic resistance increased through Test Day 4, then suddenly reverted to values close to the initial value. Subsequent values decayed in an apparently linear fashion. The dashed lines in Figure 5-6 represent the linear regression equations for the data points after Day 5. The equations are

$$R = 5.74 - 0.06t, \text{ and}$$

$$R = 6.08 - 0.06t$$

where R is the resistance in megohms
t is the elapsed time in test days.

The initial resistances of the coils were much lower than those of MkB1-1, but rose rapidly to similar values under test. This may reflect thermal desorption of moisture from the varnish.

Varnish endurance is sensitive to peak temperatures near the thermal limit of the insulation. The fact that design peak temperatures could not be obtained during this test may account for the difference in degradation slopes compared to MkB1-1.

Figure 5-6. The turn-to-turn ohmic resistance component of the power dissipation factor for the primary and secondary coils of Mk1B-2 (Prototype Test 2).

5.3

Repeatability Tests

The proof-of-concept testing phase concluded with Prototype Test 3. A new phase of testing, designated as reproducibility testing, was authorized by ARTI effective 1 April 1995. In this phase, eight SSUs will be tested in virgin R-22/mineral oil, while a second set of eight SSUs will be tested in R-22/mineral oil with a high acid number. Statistical evaluations of the trends, data scatter, and numbers of replicated required for a given level of confidence will be determined.

The SSU specification has been further refined to assure the proper placement of phase insulation in the end turns to avoid the difficulty encountered with Prototype 1.

Based on information in the literature, the peak core winding temperature will be increased to 200° C (392° F), 20C° (36F°), above the rated temperature for the wire varnish as a more realistic simulation of core winding temperature during locked-rotor events. The power transformers in the control units will be upgraded to provide this increased temperature.