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

PHASE 3: REPRODUCIBILITY AND DISCRIMINATION TESTING

FINAL REPORT

Prepared for:

The Air-Conditioning and Refrigeration Technology Institute
under
ARTI MCLR Project 655-51300

Prepared by:

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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 appeared to offer 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 if 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.

Phase 2 of the project, *Proof-of-Concept Demonstration*, was completed in March 1995. The objectives of the Phase 2 limited proof-of-concept demonstration were to:

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

The technical design issues inherent in transforming any conceptual design to working equipment were resolved, and two test systems and controllers were constructed. Pilot tests and three prototype tests were 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.

The current phase of development (Phase 3), *Reproducibility and Discrimination Testing*, was authorized by ARTI effective 1 April 1995. The objectives of this phase were to:

- Construct two additional autoclaves (for a total of four test apparatuses);
- Convert the two analog sequencers to digital operation (as originally planned in the conceptual design);
- Test eight SSUs in virgin R-22/mineral oil to establish a baseline for R-22/mineral oil;
- Test eight additional SSUs in aggressive refrigerant (R-22/mineral oil deliberately contaminated with air, water, and hydrochloric acid at five times the acceptable limits established by ARI Standard 700); and
- Evaluate test reproducibility and discrimination between baseline and aggressive refrigerant/lubricant mixtures.

A number of technical problems were encountered and overcome during Phase 3. A total of 14 trials were completed in Phase 3. Six of these trials were judged to be invalid due to a variety of equipment problems which were resolved during this phase of work. During the course of resolving these problems, it was determined that the O-rings of the pressure relief valves used to protect the autoclaves failed frequently, and improved maintenance procedures were implemented. It was also determined that the SSU excitation current should be set at 20.0 amps.

Four valid SSU trials were completed in baseline refrigerant lubricant (virgin R-22/mineral oil installed using recognized good refrigeration practice). Four additional valid trials were completed in aggressive refrigerant/lubricant (R-22/mineral oil deliberately

contaminated with air, moisture, and acid). The test results developed during this phase of development of the Improved Accelerated Hermetic Motor Insulation Life Test (the SSU test) show that the method can distinguish a life difference between baseline R-22/mineral oil and a known aggressive refrigerant/lubricant.

It was determined that inherent in the design of the AC capacitance and dissipation factor instrumentation is a systematic error in the determination of the capacitance, the measured value of which appears to change with variations in the circuit resistance. Radian developed a deconvolution algorithm allowing mathematical separation of the true capacitance, the circuit series resistance (R_s), and the circuit parallel resistance (R_p). Application of this algorithm to the prior Phase 2 results was not possible, because the method requires additional measurements which were not made in Phase 2. The method was useful, however, in evaluating the results of Phase 3 insulation property measurements.

Once capacitance and power dissipation factor data were deconvoluted, the IPM tests were found not to provide a predictive tool for surges-to-failure of the SSUs, though the data from the IPMs showed that the dielectric and resistive properties of the varnish exposed to the aggressive refrigerant/lubricant underwent changes suggestive of increasing amounts of polar species within the varnish. In all cases, SSU failure was signaled by high wire-to-wire, coil-to-coil, and/or coil-to-ground currents.

The daily determination of insulation properties is both time-consuming and costly. In future tests, the daily monitoring of insulation properties could reasonably be replaced by automatic wire-to-wire, coil-to-coil, and coil-to-ground fault trips, with insulation property measurements being used to determine the initial SSU condition and the causes of high fault current trips.

Evaluation of the specific patterns of SSU failure suggests that the winding core temperature thermocouple concentrates electrical stresses within the primary loop where this thermocouple is imbedded. For future tests, it is recommended that the winding core temperature thermocouple be replaced with a surface-contact thermocouple bonded to the upper end-turns of the SSU (this would correspond to the actual design of hermetic motor thermal protectors).

2.0 OVERVIEW OF THE SSU TEST

This section provides a summary description of the SSU test for the convenience of the reader. Detailed discussions of the development of the concept and the as-constructed apparatus have been reported separately (1,2). Figure 2-1 shows the SSU and autoclave as constructed.

2.1 The SSU

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);
- Coil-to-coil voltage stress; and
- Transient voltage stresses resulting from simulated starting cycles.

Figure 2-2 is an isometric drawing of the SSU. The SSU consists of a laminated electrical steel core simulating the stator stack of a 7.5 hp, 460 V, three-phase hermetic motor. The laminated core of 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 were designed to simulate the slot geometry of a typical motor. When the unit is assembled, the "I" lamination rests on top of the custom "E" lamination and forms an air gap over the center leg, which simulates 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.

The slots contain a slot liner, two 38-turn coils of #19 wire separated by mid-stick insulation, and top-stick electrical insulation. Each 38-turn coil is wound with 19 bifilar (two-in-hand) turns of #19 wire. Bifilar winding increases turn-to-turn voltage stress during testing and allows determination of wire-to-wire dielectric properties. In electric motor construction, 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

Figure 2-1. SSU Test Assembly

Figure 2-2. Isometric Drawing of the SSU

phase." In the SSU device, the slot coil is referred to as the primary coil, while the wedge coil is referred to as the secondary coil.

2.2 The Autoclave

The autoclave pressure vessel shown in Figure 2-1 was custom-fabricated by Parr Instrument Company. The autoclave has an internal capacity of 2.2 L. The autoclave head contains 11 pass-through penetrations: eight power/sensor terminals, two chilled water ports, and a port for thermocouple pass-throughs. The power/sensor terminals are Fusite single-lead ceramic pass-throughs, while the thermocouple pass-through is a multi-lead device manufactured by Pave Technologies. Both devices are designed and sold for use with hermetic motors.

The siphon cup located between the cooling coil (condenser) and the top winding of the SSU fills with condensing refrigerant until siphon action is triggered, at which time it dumps 119 ± 1 mL (7.26 ± 0.06 in³) of liquid refrigerant onto the top windings of the SSU. The cooling coil of each test unit is supplied with chilled water at 13.3°C (56°F). During Phase 2, the flow rate was set at 12.6 mL/s (0.2 gpm). Early in Phase 3, it was determined that reducing flow to 6.3 mL/s (0.1 gpm) had no apparent effect on condensation rates as indicated by either the interval between siphon dumps or the temperature rise across the cooling coil. The flow rate of 12.6 mL/s (0.2 gpm) per autoclave was maintained during Phase 3 testing.

During the pilot testing, the need for headspace heating to prevent condensation on the outside of the autoclave head became apparent. Condensation is potentially a problem, because the head is cooled somewhat by conduction through the chilled water ports. Condensation, at this point, is very undesirable given the proximity to high-voltage connectors. The condensation problem was eliminated by externally insulating the chilled water connections at the autoclave head and by installing a wraparound heat-tape headspace heater. Heat input from this heater is sufficient to produce a head temperature of approximately 38 to 43°C (100 to 110°F).

2.3 Electrical Excitation and Data Acquisition

The SSU is excited by 60 Hz current pulses of nominal one-second duration, separated by nominal one-second nuls. Pulse current is 20.0 ± 0.2 amps at the peak SSU temperature. Excitation is under digital control by a programmable logic controller (PLC). Figure 2-3 illustrates the permissive logic used to control excitation.

The macrocycle generator enables excitation for 18 hours and prohibits excitation for 6 hours (one macrocycle). Insulation property measurements (IPMs) are made during this macrocycle-disabled period.

Figure 2-3. Permissive Logic for Excitation Surge Generation

The mesocycle generator continuously generates mesocycles, consisting of 30-minute enabled periods during which the microcycle generator is energized, separated by 10-minute nul periods (one enabled period plus one nul period equals one mesocycle). Nominally, 27 mesocycles occur during each 24-hour day.

The next permissive link is the thermal limit control (TLC), the function to prevent thermal runaway. The TLC senses SSU winding core temperature (WCT) via the imbedded thermocouple. If the WCT exceeds a preset maximum temperature, the TLC *inhibits* the microcycle generator; otherwise, the TLC enables the microcycle generator.

The microcycle generator simulates plug reversal or locked rotor events by applying high current (nominally 20 amps rms) to the SSU windings for one second, followed by a one-second off (nul) period. The high current pulses are referred to in this report as surges, and one surge equals one simulated plug reversal or locked rotor event.

Phase-to-phase voltage stress is simulated by applying a 540 VAC RMS impressed potential between the primary and secondary (slot and wedge) coils.

Each time the microcycle generator creates a surge, it triggers a cumulative pulse counter. Four channels of temperature data are potentially available. During the current work, only the WCT was monitored continuously. These are winding core temperature, top end-turn surface temperature, vapor temperature, and liquid pool temperature. During the proof-of-concept tests, these parameters were monitored by strip-chart recorder, and the number of refrigerant dumps was determined by examination of the resulting strip charts. The PLC-based controllers automatically analyze thermal data and provide a cumulative count of the number of quenches (refrigerant dumps).

2.4 Insulation Property Measurements (IPMs)

Insulation properties are measured manually, using off-the-shelf instrumentation. Table 2-1 lists the insulation property measurements and the potentials used.

2.5 Test Conditions

During the Phase 2 testing, an SSU was equipped with a thermocouple to directly measure the surface temperature of the top end windings. Pressures were recorded at 15 second intervals from 12.75 minutes through 31.0 minutes of a typical mesocycle and correlated with lubricant temperature, vapor temperature, end-turn surface temperature, and winding core temperature. The results are shown in Figure 2-4. 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 ($T_{(sat)}$).

Table 2-1

Instrument Property Measurements

Property Test	Instrument	Where Measured	Test Potential	Purpose
Hipot	Baker ST112R/ MTA4.5 Software	Wire-to-wire within each bifilar coil	360 VDC	DC electrical resistance of wire varnish insulation
		Coil-to-coil	1450 VDC	DC electrical resistance of phase insulation
		Coil-to-ground	1450 VDC	DC electrical resistance of slot insulation.
Surge Test	Baker ST112R/ MTA4.5 Software	Primary coil	1000 VDC	Test for wire-to- wire arcing within primary coil
		Secondary coil	1000 VDC	Test for wire-to- wire arcing within secondary winding
Capacitance and Dissipation Factor	Biddle Tester	Wire-to-wire between bifilar coil	250 VAC RMS	Dissipation Factor and apparent capacitance ¹ of wire varnish insulation.
		Primary coil-to- ground	1000 VAC RMS	Dissipation Factor and apparent capacitance between primary coil and ground
		Secondary coil-to- ground	1000 VAC RMS	Dissipation Factor and apparent capacitance between primary coil and ground

¹ The capacitance is referred to as apparent because Radian discovered, during Phase 2 testing, that the capacitance measured by the Biddle Tester contains errors resulting from both series and parallel resistive elements in the circuit. The error varies with changes in the values of the resistive elements and is apparently inherent in the design of the Biddle Tester. During the course of the Phase 3 work, Radian developed a mathematical method for deconvoluting the hipot, dissipation factor, and apparent capacitance data, extracting correct values for the capacitance, as well as the series and parallel resistances.

MPa = Refrigerant Pressure; $T(\text{core})$ = Winding Core Temperature; $T(\text{liq})$ = Liquid Temperature; $T(\text{vap})$ = Vapor Temperature; $T(\text{surf})$ = Top End-turn Surface Temperature; $T(\text{vap})$ = Vapor Saturation Temperature (dew point)

Figure 2-4. Plot of SSU Temperature and Pressure Data from Minute 12.25 through Minute 31.00 of a Typical Mesocycle of Operation

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 119 mL (7.26 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 from continued microcycle surges.

The amplitude of the winding core temperature oscillation is 110 Celsius degrees (C°) [198 Fahrenheit degrees (F°)], while the amplitude of the surface end-turn temperature oscillation is about 60 C° (108 F°). 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 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).

The measured temperature of the refrigerant vapor, ($T_{(vap)}$) in Figure 2-4, 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 2-4 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 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 2-5 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 Point 6 while pressure rises due to flashing of the liquid refrigerant on the hot SSU and 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 equals 30 minutes in Figure 2-4. The extremely rapid decay of SSU core temperature to approximately 35°C (95°F) in the absence of current pulses is clearly evident.

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 six-hour resting period.

Points 0-2, siphon cup discharge; Points 2-6, refrigerant boil-off from SSU; Points 6-11, isothermal boil-off from lubricant pool; Point 12, peak pressure; Points 12-0, siphon cup refill

Figure 2-5. Refrigerant vapor-pressure/temperature cycle during a typical siphon cup cycle. Each point indicates an increment of 15 seconds in the cycle.

3.0 PHASE 3 RESULTS

3.1 Objectives and Plan for Phase 3

The objectives of Phase 3 were to:

- Conduct eight baseline SSU trials in virgin R-22/mineral oil;
- Conduct eight aggressive refrigerant trials in R-22/mineral oil deliberately contaminated with moisture, hydrochloric acid, and air;
- Assess the reproducibility of the SSU test; and
- Assess the discrimination of the test.

3.2 Preparatory Activities

Several steps necessarily occurred prior to the beginning of actual testing. Based on experience gained from the prototype testing in Phase 2, the specification for the SSU was tightened. An additional 20 units were ordered from Jasper Electric.

Two additional custom autoclaves were constructed, providing a total of four test stations. Two new sequencers were constructed, using programmable logic controllers rather than the analog timers of the Phase 2 sequencers. The Phase 2 sequencers were also converted to digital (PLC) control.

The chilled water system was also expanded to service four test stations in parallel, each with independently metered chilled water flow.

Both the Biddle Tester and the Baker Hipot/Surge Tester were returned to the manufacturers for recalibration. To provide a daily check of instrument calibration, Radian also constructed a number of calibration check circuits. These calibration check circuits were constructed from precision capacitors and resistors and have precisely defined resistance, capacitance, and dissipation factors.

3.3 Improved Interpretation of Capacitance and Power Dissipation Factor Results

As discussed in the Phase 2 report (2), the power dissipation factor is a measure of the "lossiness" of the wire-to-wire insulation. The power factor term includes contributions from both capacitance and ohmic resistance. The instrument manufacturer (Biddle) provided formulas for extracting the ohmic resistance component from the power factor, given the capacitance. At the conclusion of Phase 2, Radian interpreted the capacitance and power

dissipation factor data generated during the prototype type test using the formulas provided by Biddle.

At the beginning of Phase 3, Radian began a dual-track effort to improve interpretation and understanding of the capacitance and power dissipation factors. This effort was motivated by two considerations:

1. Uncertainty that the "equivalent circuit" models offered by Biddle reflected the actual SSU behavior; and
2. Discrepancies between the "ohmic resistance" calculated by the Biddle interpretation and the ohmic resistance measured by hipot (DC) tests.

Equivalent circuits are widely used in the interpretation of electrical test data from physical systems (in this case the SSU). The actual physical system is treated as a black box which can be replaced with a circuit of resistors and capacitors which mimic the response of the physical system under investigation over a wide range of AC frequencies (typically 0.1 to 10,000 Hz). Once the form of the equivalent circuit is defined, one can attempt to identify the physical phenomena which contribute to each component.

The Biddle interpretation offered two simulated circuits, a series circuit and a parallel circuit, shown in Figure 3-1. The series circuit will exhibit both capacitance and power dissipation under AC excitation but should show infinite resistance under DC excitation once the capacitor has fully polarized. The parallel circuit will show both power dissipation and capacitance under AC excitation but will also show a finite resistance under DC excitation due to current flow through R_p .

Based on a review of the technical literature, Radian concluded that the series/parallel simulated circuit shown in Figure 3-1(c) was most probably representative of the actual SSU resistances and capacitance. Under AC excitation, this circuit, like the SSU, will show both capacitance and power dissipation. Under DC excitation, the resistance of the capacitor becomes infinite, and the hipot test simply measures the cumulative DC resistance of the circuit.

In the SSU, wire-to-wire capacitance (C_{w-w}) is proportional to wire surface area (A) and the permittivity of the insulation (ϵ_i), and inversely proportional to the wire-to-wire separation (d).

$$C_{w-w} \propto A\epsilon_i/d$$

Wire area is constant. Increases in ϵ_i , or decreases in d, will increase capacitance. R_p represents the resistance to current leakage through the insulation. Interpretation of R_s is more problematic, and this term could easily represent a number of separate resistances.

(a) Series

(b) Parallel

(c) SSU (empirical)

Figure 3-1. Simulated or Equivalent Circuits for Real-World Capacitive-Resistive Systems

All insulation property measurements (IPMs) were made at least two hours into the macrocycle rest periods, by which times the SSU devices had reached steady-state temperatures. Consequently, electrical property variations due to temperature variations should be minimal.

Results obtained with the recalibrated Biddle Tester, using series and parallel calibration circuits (i.e., Figure 3-1, a and b), showed that the measured capacitance changed with changing values of R_s or R_p . The dissipation factor should change with changing values of the resistors, but ideally the capacitance should not change.

The instrument was recalibrated again by Biddle with no change in performance. It was concluded that the error was inherent in the operation of the Tester¹. The fact that the capacitance measured by the Biddle Tester contains a systematic error, which changes with changing values of R_s and R_p , coupled with the fact that the simulated circuit which models the SSU behavior is more complex than the simulated circuits of the Biddle interpretation, means that both the capacitance and ohmic resistance values reported for the Phase 2 work are in error.

Radian has developed a unique deconvolution algorithm which requires the apparent (measured) capacitance, the dissipation factor, and the hipot resistance. The AC and DC measurements must be made at comparable peak voltages (i.e., 1 VDC = 1.414 VAC RMS). Testing of this algorithm with simulated circuits of precision capacitors and resistors verifies that it yields accurate values for the actual capacitance, R_s , and R_p for series/parallel circuits which mimic SSU behavior.

Radian has applied this deconvolution algorithm in the interpretation of test data from Phase 3. Unfortunately, concurrent wire-to-wire hipot measurements at suitable voltages were not made in conjunction with AC measurements during Phase 2. Consequently, it is not possible to reanalyze the wire-to-wire data from those tests.

3.4 Test Environments

Baseline trials were conducted in an environment of virgin R-22 and mineral oil with care to exclude moisture and oxygen contamination. At the direction of ARTI, the "contaminated refrigerant" trials were conducted in virgin R-22/mineral oil deliberately spiked with air, hydrochloric acid, and water to five times the levels allowed by ARI Standard 700-93. Table 3-1 compares the two charging procedures. The derivation of the formula for the spike solution is given in Appendix A.

¹ Radian notes that the Biddle Tester was designed to perform quality control checks on electric motors, not to look for subtle changes in insulation properties. The magnitude of the errors in capacitance measurement is probably not significant in the application for which the instrument was designed.

Table 3-1

Charging Procedures

Baseline Trials		Aggressive Refrigerant Trials	
Description	Virgin R-22/mineral oil	Description	R-22/mineral oil 7.5 v% air in the vapor phase at 25°C (77°F) 50 ppmw water in the liquid phase at 25°C (77°F) 5 ppmw acidity (hydrochloric acid) in the liquid phase at 25°C (77°F).
Procedure		Procedure	
1.	Assemble SSU and test chamber.	1.	Assemble SSU and test chamber.
2.	Perform electrical continuity tests.	2.	Perform electrical continuity tests.
3.	Instill 350 mL (21.4 in ³) virgin mineral oil.	3.	Instill 350 mL (21.4 in ³) virgin mineral oil.
4.	Seal autoclave.	4.	Instill 30 µL of spike solution (see note 1).
5.	Evacuate to less than 13.3 Pa (0.1 mm Hg).	5.	Seal autoclave.
6.	Pressurize with R-22 and leak test.	6.	Evacuate to 5.0 inches (12.7 cm) Hg below atmospheric on compound refrigeration gauge. Absolute pressure of 84.8 kPa (12.3 psia).
7.	Evacuate to less than 13.3 Pa (0.1 mm Hg).	7.	Charge with 11.75 oz (333.1 g) R-22, using a standard Dial-A-Charge refrigeration apparatus calibrated in quarter-ounce increments.
8.	Bake overnight at 140°C (284°F).	Note 1. The spike solution is prepared by diluting 24.53 g of concentrated analytical grade hydrochloric acid to a final weight of 100.00 grams with deionized water. The final solution is 9.2 w/w% HCl.	
9.	Cool to ambient temperature.		
10.	Double purge and trap, evacuating to less than 13.3 Pa (0.1 mm Hg) on each cycle.		
11.	Charge with 11.75 oz (333.1 g) R-22, using a standard Dial-A-Charge refrigeration apparatus calibrated in quarter-ounce increments.		

3.5 Trial Results

Table 3-2 summarizes the results of the Phase 3 trials. Each trial was designated with an alphanumeric C (number), with C indicating Phase 3, and the number being the trial number. The individual SSUs were also identified by this label.

3.5.1 Rejected Trials

A total of 14 trials were conducted. Of these, three were rejected due to equipment failures which were judged to have compromised the results. The most recurrent problem was repeated leaking of the O-ring seal of the autoclave pressure relief valves after some period of exposure to refrigerant/lubricant. Other problems included failure of one of the thermocouple pass-throughs and loss of chilled water circulation. There were no operational problems involving the PLC-based sequence controllers.

Three early trials were rejected on the suspicion that higher-than-originally-planned impressed currents may have caused rapid and unrepresentative SSU failure. At the conclusion of Phase 2, it was agreed that the target winding core temperature would be increased from 180 to 200°C (356 to 392°F). However, during the first few trials of Phase 3, it was observed that, while WCTs of 180°C (356°F) could be readily obtained at impressed currents of 20 amps, the winding core temperatures of some SSUs did not reach the 200°C (392°F) target temperature, even at impressed currents of 24 amps (a 20% increase in impressed current and 44% increase in heat dissipation).

Winding core temperature is sensed by a thermocouple (the WCT-TC) imbedded in the slot winding nominally at the vertical midpoint of the SSU (midway between the top and bottom end turns). This WCT-TC supplies a signal to a peak core temperature limiter. When the peak core temperature reaches the preset limit, the limiter interrupts power pulses to the SSU until the peak temperature falls a degree or two below the preset peak temperature limit. For some of the SSUs, a power input of 20 amps, which corresponds to a power input of approximately 450 watts, produced a peak WCT of 200°C with only occasional tripping of the peak temperature limiter. This was the desired operating condition. However, application of even significantly higher currents, up to 24 amps, did not produce the target temperatures for a few SSUs. Despite the 44% increase in energy dissipation represented by these current increases, a few SSUs still failed to register the 200°C (392°F) target temperature.

Variations in SSU electrical and magnetic properties were eliminated as a source of the discrepant behavior as were calibration and measurement errors. It was concluded that the problem resulted from probable mis-positioning of the WCT-TC in some of the SSUs. If the true core winding temperature is 200°C (392°F) while the liquid and vapor temperatures are around 40°C (104°F), as demonstrated during Phase 2, the thermal gradient in the copper core as one moves away from the vertical midpoint of the SSU is approximately 3.2 C°/mm (146.3 F°/in) moving toward the bottom of the SSU. Moving toward the top,

Table 3-2

Summary of Phase 3 Test Results

Trial	Surges to Failure	Quenches to Failure	Quenches/Mesocycle	Amps @ Peak Temp	Post-Failure Condition	Comments
Rejected Runs						
C3	13,771	36	Test terminated due to equipment malfunction.			
C7	7,576	107				
C10	2,937	0				
C1	137,558	2,277	15	24.0	Primary bifilar short. No discoloration.	It was concluded that errors in thermocouple placement lead to overpowering of the SSUs to reach the target WCT of 200°C (392°F), resulting in unrealistic test conditions. Power input for subsequent SSUs was set at 20 ± 0.2 amps at peak core winding temperature.
C2	194,904	2,534	12	22.8	Primary bifilar short. No discoloration.	
C5	21,179	350	15	23.0	Primary-to-secondary coil short. No bifilar shorts. No discoloration.	
Accepted Tests in Baseline Refrigerant (Uncontaminated R-22/Mineral Oil)						
C4	1,509,915	20,498	12	19.9	Primary bifilar hipot overcurrent trip.	While this SSU did not short out, a hermetic motor with similar hipot response would be considered to have failed.
C6	161,048	2,544	14	20 est	Primary-to-secondary coil short. No bifilar shorts. No discoloration.	
C13	274,829	3,681	12	20.0	Primary-to-secondary coil short and secondary bifilar short. No discoloration.	
C14	1,231,230	5,769	4	20.0	Primary bifilar short. Primary-to-secondary short. No discoloration.	

Table 3-2

(Continued)

Trial	Surges to Failure	Quenches to Failure	Quenches/Mesocycle	Amps @ Peak Temp	Post-Failure Condition	Comments
Accepted Tests in Aggressive Refrigerant (Contaminated R-22/Mineral Oil)						
C8	122,915	1,311	10	20.0	Primary-to-secondary coil short. Top end-turns of primary coil charred.	
C9	175,320	1,727	9	20.0	Primary bifilar short and primary-to-ground short. Top end-turns and leads charred.	
C11	23,928	119	5	20.0	Top end of primary coil charred.	
C12	262,272	2,360	8	20	Top end of primary coil charred. Insulation charred from leads.	

the gradient could be even higher as the temperature of the refrigerant dump is about 15°C (59°F). This could create a vertical thermal gradient in the core winding of approximately 3.6 C°/mm (164.6 F°/in) toward the top end-turns. While this analysis is very simplified, it is evident that small variations in the placement of the WCT thermocouple could result in an apparent failure to reach the target temperature.

Impressed current can be measured with great accuracy, and review of the Phase 2 and early Phase 3 results indicated that a setting of 20 amps (approximately 450 watts applied power) at peak temperature normally provided the desired peak WCT. After the first few trials in Phase 3, the impressed current was set at 20 ± 0.2 amps when the WCT was at its peak (because the electrical resistance of the copper wire is at a maximum and current is at a minimum at the peak winding core temperature; currents are higher when the SSU is cooled by liquid refrigerant dumps). Setting the impressed current fixes the amount of heat to be dissipated by the SSU. The peak core temperature limiter remains in the control circuit to prevent any possible thermal runaway. All of the accepted trials in Table 3-2 were run at this impressed current.

3.5.2 Analysis of Events-to-Failure Data

The statistical results of the accepted Phase 3 trials are shown in Table 3-2. Four acceptable trials were performed in the baseline refrigerant lubricant. Only one of the baseline trials ended in less than 270,000 surges. All four of the SSUs tested in aggressive refrigerant/lubricant failed in less than 270,000 surges. Table 3-3 provides a summary of the surges-to-failure data for the two data sets. The results in Table 3-3 are ranked by quartile. This table also gives the arithmetic and geometric means of the two data sets, as well as their estimated Weibull parameters.

The Wilcoxon Significance Test was selected as the most appropriate method to test the hypothesis that the apparent difference in surges-to-failure between the baseline and aggressive refrigerant/lubricants was a statistical fluke. The probability that the apparent difference is a statistical fluke was determined to be 7%.

Figures 3-2 and 3-3 show the estimated Weibull probability density functions and cumulative distribution functions, respectively. The Weibull distributions confirm that the behavior in the aggressive refrigerant/lubricant was very different than the behavior in the baseline refrigerant.

The medians estimated from the Weibull distributions were approximately 15% lower than the medians interpolated directly from the data (without a distributional assumption) for both the baseline and aggressive refrigerant/lubricant mixtures. Given that the data sets are small and the two statistical methods are quite different in approach, this variation is not surprising.

Table 3-3

Summary of Surge-to-Failure Statistics

Parameter	Units	Baseline	Aggressive
Statistical Parameters			
Minimum observed value	Surge-to-failure	161,048	23,928
1st quartile	Surge-to-failure	217,939	73,422
Median	Surge-to-failure	753,030	149,118
3rd quartile	Surge-to-failure	1,370,573	218,796
Maximum observed value	Surge-to-failure	1,509,915	262,272
Arithmetic mean	Surge-to-failure	794,256	146,109
Standard error of the mean	Surge-to-failure	338,363	49,844
Geometric mean	Surge-to-failure	535,584	107,838
Weibull Statistics			
α^1		900,769	168,416
β^1		1.11	1.29
Median ²	Surge-to-failure	647,700	126,978

¹ Defined by the Weibull Probability Density Function, $f(t)$, taking t to be the surges-to-failure,

$$f(t) = (\beta/\alpha)(t/\alpha)^{\beta-1} \exp[-(t/\alpha)^\beta], t \geq 0$$

² Extracted from the Weibull Cumulative Probability Function, Figure 3-3.

Figure 3-2. Estimated Weibull Probability Density Function for Baseline and Aggressive Refrigerant/Lubricant Mixtures

Figure 3-3. Estimated Weibull Cumulative Distribution Functions for Baseline and Aggressive Refrigerant/Lubricant Mixtures

The traditional method of comparing plug-reversal test results has been comparison of the median surges-to-failure in the Weibull cumulative distribution plot. Based on a comparison of median surges-to-failure estimated by the Weibull method, the aggressive refrigerant/lubricant caused an 80% decrease in SSU endurance compared to the baseline refrigerant/lubricant. The same result is obtained using the medians interpolated directly from the experimental data.

3.5.3 Analysis of Post-Failure Condition

The SSUs tested in the baseline refrigerant showed no gross visible damage after failure, and the locations of the failures were determined by analysis for electrical shorts. The SSUs exposed to the aggressive environment showed pronounced charring of the top end of the primary coils. The insulation was also burned from the electrical leads of some of these units.

A few of the SSUs showed coil-to-coil shorts without bifilar (wire-to-wire within the coil) shorts. Visual inspection of these units suggests that the leads of the two phases were not separated by phase insulation where the leads emerge from the armature slots.

Most interestingly, there were no bifilar shorts in the secondary coils. Consideration of capacitor physics suggests that the placement of the WCT thermocouple within the primary winding would greatly intensify the electrical stress along the thermocouple and probably lead to preferential failure of the primary coils. This effect could also have contributed to the scatter in surges-to-failure data. Based on these considerations, it would probably be better to monitor temperature with surface thermocouples applied to the top end-turns of the SSU. This would be analogous to the practice in hermetic motors, where the bimetallic safety switches or thermocouples are bonded to the motor end-turns.

3.5.4 Analysis of Insulation Property Measurement (IPM) Data

The development of a deconvolution algorithm for hipot resistance, apparent capacitance, and dissipation factor data was discussed in Section 3.3. Figures 3-4 through 3-7 illustrate the results of application of this algorithm to the wire-to-wire insulation property measurements from Trials C8 and C12, the shortest and longest runs in the aggressive refrigerant/lubricant, respectively. Figures 3-8 through 3-11 present the corresponding results from the shortest and longest runs in the baseline refrigerant/lubricant. The 10,000 megohm upper limit shown in these figures represents the upper limit of resistance measurable by the Hipot Tester at the impressed voltages used in this study. Points plotted along the 10,000 megohm line thus indicate "greater than 10,000 megohms."

In all figures, the final data points are the post-failure values. Any examination for trends should not consider the final data points in these graphs.

Figure 3-4. IPM Results for SSU C8 Primary Coil Wire-to-Wire Insulation

Figure 3-5. IPM Results for SSU C8 Secondary Coil Wire-to-Wire Insulation

Figure 3-6. IPM Results for SSU C12 Primary Coil Wire-to-Wire Insulation

Figure 3-7. IPM Results for SSU C12 Secondary Coil Wire-to-Wire Insulation

Figure 3-8. IPM Results for SSU C6 Primary Coil Wire-to-Wire Insulation

Figure 3-9. IPM Results for SSU C6 Secondary Coil Wire-to-Wire Insulation

Figure 3-10. IPM Results for SSU C4 Primary Coil Wire-to-Wire Insulation

Figure 3-11. IPM Results for SSU C4 Secondary Coil Wire-to-Wire Insulation

In all cases, the agreement between the sum of R_s and R_p , determined by deconvolution of the capacitance and dissipation factor data and the total resistance measured by DC hipot, was excellent.

SSU C8, the shortest run in aggressive refrigerant/lubricant, showed no discernable changes in wire-to-wire resistive properties prior to failure, though there was a clear increase in capacitance, suggestive of an increase in polar and/or ionic molecules within the varnish dielectric. SSU C8 showed a decline in R_p and an increase in capacitance for several days prior to failure. A decrease in R_p indicates a decrease in resistance to current leakage through the varnish insulation.

Like SSU C8, SSU C6, the shortest-lived of the baseline SSUs, showed a clearly discernable increase in varnish capacitance prior to failure. There was no detectable decrease in R_p prior to failure.

SSU C4 endured more than 1.5 million surges. The capacitance of this SSU actually declined during the first 100 kilosurges. After that point, the capacitance data became quite noisy but showed no clear trend. The value of R_p remained off scale (greater than 10,000 megohms) until more than 500 kilosurges had been applied. Beyond that point, the R_p data also shows a high degree of noise.

4.0

CONCLUSIONS AND RECOMMENDATIONS

A total of 14 trials were completed in Phase 3. Six of these trials were judged to be invalid due to a variety of equipment problems which were resolved during this phase of work. Four SSUs were tested in baseline refrigerant lubricant (virgin R-22/mineral oil installed using recognized good refrigeration practice). Four additional SSUs were tested in aggressive refrigerant/lubricant (R-22/mineral oil deliberately contaminated with air, moisture, and acid). The test results developed during this phase of development of the Improved Accelerated Hermetic Motor Insulation Life Test (the SSU test) show that the method can distinguish a life difference between baseline R-22/mineral oil and a known aggressive refrigerant/lubricant, based on comparison of the median surges-to-failure (MSTF).

It was determined that inherent in the design of the AC capacitance and dissipation factor instrumentation is a systematic error in the determination of the capacitance, the measured value of which appears to change with variations in the circuit resistance. Radian developed a deconvolution algorithm allowing mathematical separation of the true capacitance, the circuit series resistance (R_s), and the circuit parallel resistance (R_p). Application of this algorithm to the prior Phase 2 results was not possible, because the method requires additional measurements which were not made in Phase 2. The method was useful, however, in evaluating the results of Phase 3 insulation property measurements.

Once capacitance and power dissipation factor data were deconvoluted, the insulation property measurement (IPM) tests were found not to provide a predictive tool for surges-to-failure of the SSUs, though the data from the IPMs showed that the dielectric and resistive properties of the varnish exposed to the aggressive refrigerant/lubricant underwent changes suggestive of increasing amounts of polar species within the varnish. In all cases, SSU failure was signaled by high wire-to-wire, coil-to-coil, and/or coil-to-ground currents.

The daily determination of insulation properties is both time-consuming and costly. In future tests, the daily monitoring of insulation properties could reasonably be replaced by automatic wire-to-wire, coil-to-coil, and coil-to-ground fault trips, with insulation property measurements being used to determine the initial SSU condition and the causes of high fault current trips.

Evaluation of the specific patterns of SSU failure suggests that the winding core temperature thermocouple concentrates electrical stresses within the primary loop where this thermocouple is imbedded. For future tests, it is recommended that the winding core temperature thermocouple be replaced with a surface-contact thermocouple bonded to the upper end-turns of the SSU (this would correspond to the actual design of hermetic motor thermal protectors).

APPENDIX A

COMPUTATION OF RECIPE FOR AGGRESSIVE REFRIGERANT

ASSUMPTIONS

ARTI directed that the aggressive refrigerant to be used in the Phase 3 testing was to be R-22/mineral oil contaminated with five times the maximum allowable levels of air, moisture, and acid specified by ARI 700.

ARI 700 establishes the purity requirements for refrigerants. ARI 700 Appendix 93 describes the measurement techniques. Neither document describes how to generate specific contaminant levels. Both are concerned only with measurement.

The target contamination levels are defined in Table A-1.

Table A-1. Target Contaminant Levels

Contaminant	Concentration	Measured in
Air	7.5 vol%	Vapor at 25°C
Water	50 ppm wt	Liquid at 25°C
Acid (HCl)	5 ppm wt	Liquid at 25°C

R-22 has the following properties at 25°C:

Vapor pressure	151.5 psia
Liquid density	1.10 g/mL
Vapor density	0.044 g/mL

The formulation is based on the assumption that the virgin R-22 is air-free and that the virgin refrigeration-grade mineral oil is dry.

VAPOR PHASE

The vol% air in refrigerant vapor (expressed as a fraction) is the partial pressure of the air divided by the total gas pressure. For an air fraction of 0.075, the relationship is:

$$0.075 = P_{\text{air}} / (P_{\text{air}} + P_{\text{R}})$$

Where P_{air} and P_{R} are the pressures of the air and refrigerant, respectively.

This equation is solved iteratively. For R-22, $P_{R22} = 151.5$ psia, and $P_{air} = 12.3$ psia.

The equivalent reading on a compound refrigeration gauge would be -5.0 inches Hg.

LIQUID PHASE

Total Liquid Mass

Computation of the air and water charge requires determination of the total liquid volume of the autoclave at 25°C.

The total refrigerant charge for R-22 is 335 g. The vapor space with mineral oil in place is 1760 mL. The vapor density at 25°C is 0.044 g/mL. Thus the mass of R-22 in the vapor state at 25°C is given by:

$$\begin{aligned} R22_v &= (1760 \text{ mL})(0.044 \text{ g/mL}) \\ &= 77.4 \text{ g.} \end{aligned}$$

Given that the total refrigerant charge is 335 g, the liquid residual is 258 g. The oil charge is 350 mL, with a mass of 315 g. The total liquid mass at 25°C is 0.573 kg.

Acid Mass Requirement

ARI 700 Appendix 93 states that acidity is determined by mixing the liquid refrigerant with toluene, isopropanol, and water with a thymol blue indicator, then titrating to the indicator endpoint with standardized KOH. Results are reported as parts-per-million HCl. Using dilute HCl as an acidification agent is justified by this definition of acidity.

The pure HCl required for a final liquid-phase concentration of 5 ppm (5 mg/kg) is given by:

$$\begin{aligned} \text{mg HCl} &= (5 \text{ mg HCl/kg liq})(0.573 \text{ kg liq}) \\ &= 2.9 \text{ mg HCl (pure).} \end{aligned}$$

Water Mass Requirement

The water addition required for a final liquid-phase concentration of 50 ppm (50 mg/kg) is given by:

$$\begin{aligned} \text{mg H}_2\text{O} &= (50 \text{ mg H}_2\text{O/kg liq})(0.573 \text{ kg liq}) \\ &= 28.6 \text{ mg H}_2\text{O.} \end{aligned}$$

Water Derived from Hydrochloric Acid

The source of HCl is concentrated AR-grade hydrochloric acid:

$$\text{Con HCl} = 37.5 \text{ wt\%}$$

$$= 37.5 \text{ g HCl}/100 \text{ g soln}$$

$$= 37.5 \text{ g HCl}/(37.5 \text{ g HCl} + 62.5 \text{ g H}_2\text{O}).$$

The water contribution from Con HCl is given by:

$$\text{HCl water contribution} = (2.9 \text{ mg HCl})(62.5 \text{ g H}_2\text{O}/37.5 \text{ mg HCl})$$

$$= 4.8 \text{ mg H}_2\text{O from HCl}.$$

DI Water Contribution

The DI H₂O addition required to obtain the desired total water mass is given by:

$$\text{DI H}_2\text{O addition} = \text{Total H}_2\text{O} - \text{H}_2\text{O from Con HCl}$$

$$= 28.6 \text{ mg H}_2\text{O} - 4.8 \text{ mg H}_2\text{O}$$

$$= 23.8 \text{ mg H}_2\text{O addition}.$$

Spike Solution Generation

The final HCl concentration of the spike solution is given by:

$$\text{Spike concentration} = (100)(2.9 \text{ mg HCl})/(2.9 \text{ mg HCl} + 28.6 \text{ mg H}_2\text{O})$$

$$= 9.2 \text{ wt\%}.$$

Concentrated HCl is diluted to make 100 g spike solution as follows:

$$M_1C_1 = M_2C_2$$

$$M_1 = M_2C_2/C_1$$

$$= (100 \text{ g})(9.2 \text{ wt\%})/(37.5 \text{ wt\%})$$

$$= 24.53 \text{ g Con HCl}.$$

The spike is prepared by weighing 24.53 g Con HCl into a beaker and diluting with DI water to a final weight of 100 g.

Spike Volume

The spike mass is given by:

$$\begin{aligned}\text{Spike wt} &= 2.9 \text{ mg HCl} + 28.6 \text{ mg H}_2\text{O} \\ &= 31.5 \text{ mg spike.}\end{aligned}$$

The density of 9.2 wt% HCl is $1.04 \text{ mg}/\mu\text{L}$.

The spike volume is given by:

$$\begin{aligned}\text{Spike vol} &= (31.5 \text{ mg spike})(1 \mu\text{L}/\text{mg spike}) \\ &= 30.3 \mu\text{L.}\end{aligned}$$

The spike charge is delivered by the use of a $30 \mu\text{L}$ micropipette.