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AN IMPROVED ACCELERATED HERMETIC MOTOR INSULATION LIFE TEST

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ABSTRACT

An improved accelerated hermetic motor insulation life test has been developed and validated to support the technology development required to replace CFC refrigerants for upper atmospheric ozone protection. This improved method, the Simulated Stator Unit (SSU) test, combines the best features of the IEEE Motorette test and the widely used but not standardized plug-reversal test, while avoiding some of the shortcomings of each of these methods. Validation testing of the SSU test method has been completed. The test showed clear differences in the life expectancies of a standard Class H hermetic motor insulation system in a known aggressive refrigerant/lubricant as compared to virgin R-22/mineral oil.

While the test was developed to evaluate the long-term effect of alternative refrigerant/lubricant mixtures on hermetic motor insulation, the test should also be potentially useful in validating decontamination requirements when converting existing equipment to alternative refrigerant/lubricants, for validating minimum purity requirements for reclaimed refrigerant, and for testing of new insulation systems.

INTRODUCTION

An insurance industry survey 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, defining the stator windings as the component to be simulated in an improved accelerated hermetic motor insulation life test (1).

A review of the literature pertaining to stator winding failure mechanisms found that stator life was proportional to the number of "hard-start" events (i.e., locked rotor starts, liquid refrigerant slugging, and any other condition which abnormally retards rotor rotation, increasing current). The following sequence of events to failure was identified as the typical "wear-out" mode: 1) operation at elevated temperature weakens the varnish/wire bond (thermochemical aging); 2) the combination of magnetic and differential thermal expansion forces created by in-rush surges under hard-start conditions and/or liquid refrigerant slugging exceeds the restraining strength of the varnish; 3) 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; 4) 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; 5) the low-power, intermittent arcing draws enough power to weld the conductors; and 6) high-induced currents in the shorted loops lead to rapid failure (2).

This magnetomechanical-thermochemical aging model appears to offer the most complete description of the factors affecting the intrinsic life of hermetic motor insulation materials. The magnetomechanical-thermochemical degradation model had significant implications for development of an improved accelerated test for hermetic motor insulation systems exposed to alternative refrigerant/lubricant mixtures. The most important of these implications are that attention should be focused on the stator windings, as these were the point of failure in the overwhelming majority of failures, and that the accelerated test should mimic the differential thermal expansion, thermochemical, and magnetomechanical forces operating on stator windings.

Prior to the development of the SSU test, the air-conditioning and refrigeration industry used three different methods of life testing of hermetic motor insulation systems. These were the IEEE Standard 117 Motorette test, the UL Standard 984 Motorette test, and the plug-reversal test, for which no standard existed. The IEEE Motorette test used motorettes containing a pair of coil windings to simulate the stators. The IEEE Motorette test simulated the electropotential and thermal aging aspects of hermetic motor service but did not simulate magnetodynamic and magnetostrictive forces, differential thermal expansion, locked-rotor current surges, and thermal excursions.

The UL Standard 984 Motorette test was similar to the IEEE Motorette test, except that the IEEE test was run to insulation failure to study time-to-failure while the UL Standard 984 test was run for a set period of time on a pass-fail safety criterion.

Conventional plug-reversal tests use an actual hermetic motor as the test component. The polarity of this test motor, inserted between the evaporator and suction of an auxiliary hermetic motor compressor in an actual refrigeration loop, was reversed every one to two seconds, simulating a stalled rotor event. While the plug-reversal test simulated the full range of forces acting on the stator windings, it would be cumbersome for comparative life testing in alternate refrigerant/lubricants since the auxiliary motor-compressor would have to be replaced for each mixture to avoid cross-contamination by residues of prior refrigerant/lubricant mixtures. This method would also require manufacture of a standardized hermetic motor with a variety of different insulation systems.

THE SSU TEST

The SSU test device, procedures, and apparatus have been described elsewhere (3,4). The heart of the apparatus is the simulated stator unit itself. The SSU emulates the electric, magnetic, and thermal environment of a typical 7.5 hp, three-phase, 460 VAC hermetic refrigeration motor. The SSU consists of a laminated steel core fitted with slot insulation, two coils separated by phase insulation, and top-stick or wedge insulation. The assembled SSU is vacuum-impregnated with varnish as in an actual hermetic motor stator. Each of the coils contains 19 bifilar (two-in-hand) random-wound turns. Use of bifilar coils allows measurement of wire-to-wire insulation performance. The prototype SSUs used in this study contained a thermocouple imbedded at the midpoint of the slot coil to measure winding core temperature (WCT). Film and wire insulation for the prototype SSUs conformed to Class H.

For testing, each SSU was positioned vertically in a custom 2.2 L autoclave equipped with a head-space condenser coil and siphon cup having a liquid refrigerant dump volume of approximately 120 mL. The liquid refrigerant was automatically delivered directly by siphon action onto the upper end-turns of the SSU, simulating liquid slugging events.

The lid of the autoclave contained two cooling water ports, electric pass-throughs for the eight leads from the two bifilar coils, and thermocouple pass-throughs for up to four thermocouples. Winding core temperature was monitored during all tests. Upper end-turn surface temperature, vapor temperature, and liquid refrigerant temperature were monitored for selected trials, along with autoclave pressure.

After SSU insertion and prior to sealing, 350 mL of lubricant was introduced to the autoclave, enough to immerse the bottom end-turns and approximately 1 cm of the core of the SSU. The autoclave was evacuated to less than 13 Pa and baked at 140°C overnight, cooled to ambient temperature, and purged using a triple purge-and-trap procedure, evacuating to less than 13 Pa for each purge. The refrigerant charge of 331 g (for R-22) was injected using a commercial refrigeration charging apparatus.

Excitation was digitally controlled with dedicated programmable logic controllers. Excitation was provided as 60 Hz current surges of nominal one-second duration, separated by nominal one-second nuls. Pulse current was set at 20 ± 0.2 amps at the peak WCT of 180 to 200°C. Phase-to-phase voltage stress were simulated by a 540 VAC RMS impressed potential between the slot and wedge coils. Excitation surges were applied for 30-minute intervals separated by 10-minute rest periods for a total of 18 hrs per 24-hr day. The SSU was allowed to cool and soak for the remaining six hours. Insulation property measurements (IPMs)—hipot, surge tests, and AC capacitance and dissipation factor measurements—were made near the end of the cool-soak period during the validation tests.

A peak temperature limiter temporarily interrupted current surges if the WCT exceeded 200°C, while fuses halted testing in the event of wire-to-wire, coil-to-coil, or coil-to-ground shorts. Automatic counting circuits tracked both the surges-to-failure and number of siphon cup dumps.

In the absence of head-space cooling, the peak allowable WCT of 200°C was reached within three minutes of initial excitation. Figure 1 shows the actual temperature-pressure regime resulting from superimposed siphon cup action.

Pressure minima occurred when the siphon cup was full and the moles of refrigerant vapor were at a minimum. Over the next 15 ± 5 seconds, the siphon cup discharged approximately 120 mL of liquid refrigerant at 13 to 18°C directly onto the exposed upper end-turns of the SSU. Extremely rapid cooling of the end-turns occurred while the pressure soared to peak values of 1.70 ± 0.1 MPa gauge as the liquid refrigerant boiled off. The quenching of the winding core trailed the cooling of the end-turns by about 25 seconds but was much more severe, with the WCT falling from between 180 and 200°C to between 75 and 80°C. Cooling rates exceeded 100 C°/minute for 15 to 30 seconds of each quench and peaked in the region of 133 C°/minute. The winding core temperatures reached their minima at about the same time that the pressure reached its maxima, indicating that much, if not all, of the liquid refrigerant had evaporated. The WCT then rebounded immediately due to the continued heat input. The rebound, once the siphon discharge ended, was even more rapid, with peak heating rates in the region of 150 C°/minute. These extreme rates imposed large differential thermal expansion stresses. The siphon cycle repeated approximately every 4.9 minutes during excitation.

VALIDATION TEST RESULTS

Two refrigerant/lubricant mixtures were used for the validation tests. The *baseline mixture* consisted of virgin R-22 and mineral oil. The *aggressive mixture* consisted of virgin R-22 and mineral oil deliberately contaminated with 7.5 vol% air, 50 ppm(wt) water, and 5 ppm(wt) hydrochloric acid (i.e., five times the maximum permissible contamination levels under ARI 700). The latter levels of contamination are known to be quite detrimental to hermetic motor insulation life.

Comparative quadruplicate tests of identical SSUs were performed in each mixture. All SSUs were tested to failure, defined as either a wire-to-wire, coil-to-coil, or coil-to-ground short or overcurrent result in the hipot test. The longest single test run was 76 days. The SSUs tested in the baseline mixture failed by bifilar wire-to-wire shorts or overcurrent hipot results, with coincident coil-to-coil shorts in some units. None of the baseline units showed visible damage after failure. All of the SSUs tested in the aggressive mixture were severely charred after failure, with both wire-to-wire and coil-to-coil shorts in each unit.

Table 1 provides a statistical analysis of the results of the validation test series. The probability-of-occurrence of the observed distributions by statistical fluke is 7%. In future tests, the number of replicate tests will likely be increased to six or eight to improve statistical confidence intervals. Figure 2, showing the probability density and cumulative probability functions of the Weibull distribution for the two mixtures, further illustrates that insulation performance was quite different in the two environments. Based on the median surges-to-failure, the relative life of the insulation system in the aggressive mixture was 0.20 relative to the baseline mixture.

These results validate the SSU test as an improved accelerated hermetic motor insulation life test capable of providing useful information with test periods of less than 90 days.

The insulation property measurement data over the course of each exposure were analyzed to determine if there was a measurable degenerative trend prior to failure. Such a trend might shorten future test durations, but no such trend was found. Insulation property measurements were useful, however, in identifying failure modes.

In future tests, the IPM tests will be performed only at the beginning of the exposure and diagnostically following failure. An additional trip circuit, added to the control logic to test for excessive wire-to-wire DC current leakage during each 10-minute rest period, will halt the test if excessive leakage occurs.

CONCLUSIONS

- The SSU test, an improved accelerated hermetic motor insulation life test combining the best attributes of the IEEE Standard 117 Motorette test and the unstandardized but widely used plug-reversal test, has been developed and validated as a relative life test to evaluate the effect of alternate (i.e, non-CFC) refrigerant/lubricant mixtures on hermetic motor insulation life.
- The SSU test is also potentially useful in validating decontamination requirements when converting existing equipment to alternative refrigerant/lubricants, for validating minimum purity requirements for reclaimed refrigerant, and for testing of new insulation systems.

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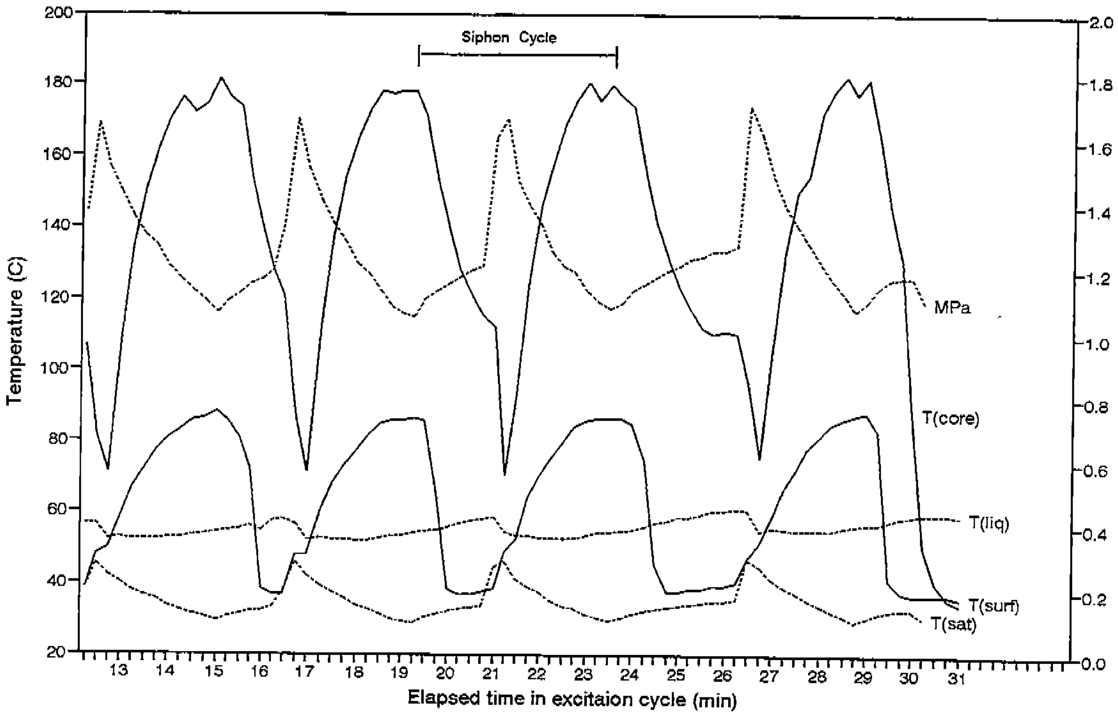
Table 1. Summary of Validation Test Results

Parameter	Units	Baseline	Aggressive
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
Weibull α[1]		900,769	168,416
Weibull β[1]		1.11	1.29
Weibull 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 2.



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

Figure 1. Plot of SSU Temperature and Pressure Data from Minute 12.25 through Minute 31.00 of a Typical Excitation Cycle.

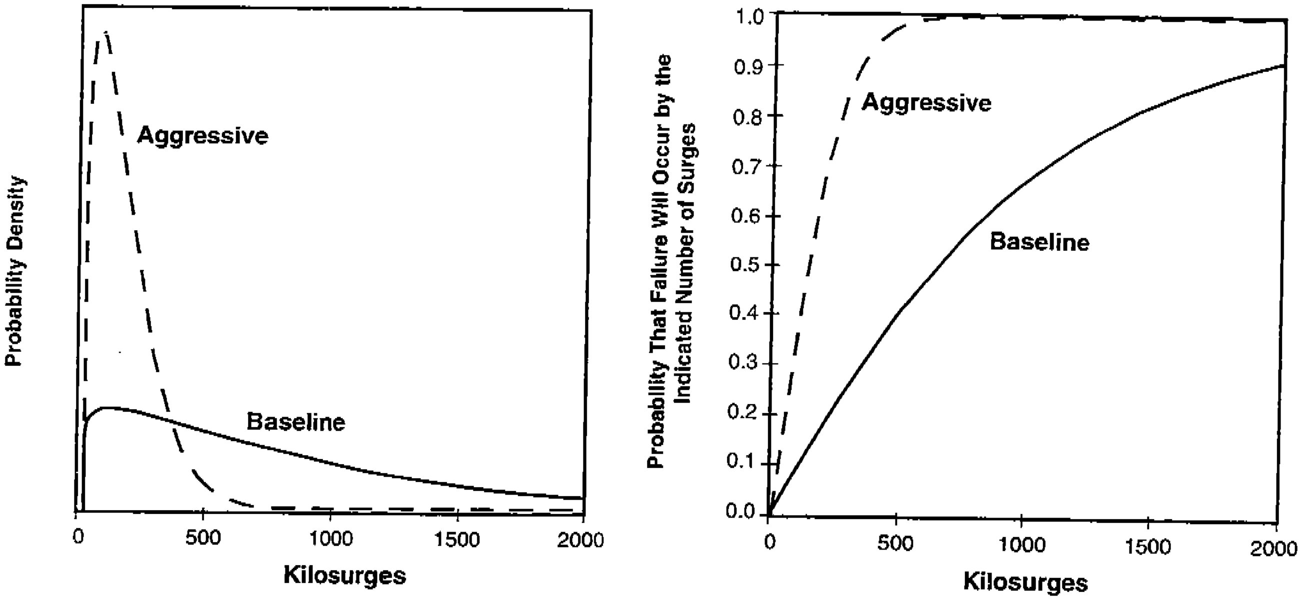


Figure 2. Probability Density (left) and Cumulative Probability (right) Functions of the Weibull Distributions of the Validation Test Results.