2006

Converting a Military Environmental Control Unit to Propylene Refrigerant

Detlef Westphalen
TIAX LLC

Converting a Military Environmental Control Unit to Propylene Refrigerant

Detlef Westphalen
TIAX LLC
15 Acorn Park, Cambridge, MA 02140
Tel: 617-498-5821, Fax: 617-498-7250
Email: westphalen.d@tiaxllc.com

ABSTRACT

Conversion of a military environmental control unit from R-407C to hydrocarbon refrigerant was investigated. The key objective was reduction of size/weight while maintaining capacity and power input. Initial analysis indicated that propylene would be the most promising hydrocarbon refrigerant. Testing was done with a prototype unit charged with R-407C and subsequently with propylene. Capacity was 12% higher and COP was 10% higher when operating with propylene. Analysis showed that the condenser could have 8.5% less face area, and that initial 32 inch (813 mm) unit height could be reduced 2 inches (51 mm). Tracer gas testing was done to determine refrigerant concentrations generated due to leakage rates of 1 lb/hr (0.5 kg/hr) and 20 lb/hr (9 kg/hr). The testing showed that some locations could build up concentration levels above the LFL. However, locations with likely ignition sources (i.e. the interior of electric boxes) did not experience levels close to the LFL.

1. INTRODUCTION

Air-conditioning and heating for aircraft hangars/shelters is currently provided by the Field-Deployable Environmental Control Unit (FDECU), shown in Figure 1 below. The FDECU was developed with U.S. Air Force funding in the 1990s and is used by all branches of the U.S. military. The need for smaller, lighter equipment has led to development of a smaller design, the Lightweight Environmental Control Unit (LECU), also shown in Figure 1. The two unit's key characteristics are summarized in Table 1 below.

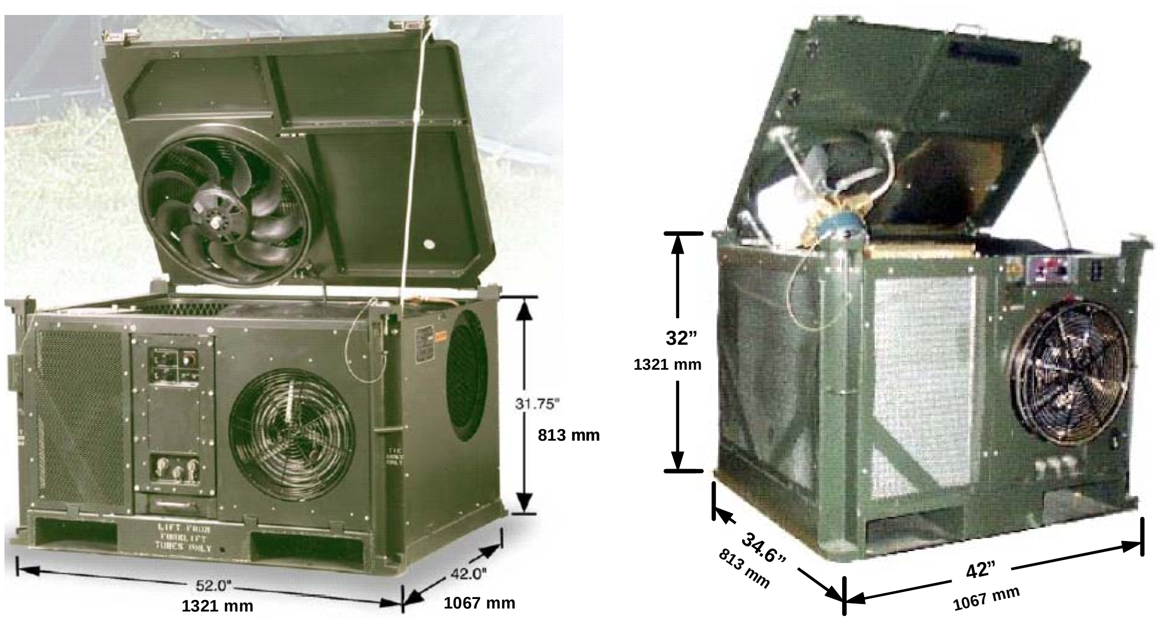

Figure 1: Field-Deployable Environmental Control Unit (FDECU, left) and Lightweight Environmental Control Unit (LECU, right)

Table 1: Comparison of Lightweight ECU and FDECU

Parameter	FDECU	LECU
Cooling Capacity (Btu/hr [kW])	54,300 [15.9][1]	60,000 [17.6][3]
Heating Capacity (Btu/hr [kW])[2] Heat Pump Only Heat Pump and Auxiliary Heat	 68,000 [19.9] 82,000 [24.0]	 66,500 [19.5]
Evaporator Air Flow (cfm [m^3/min]) at 1.0 in wg [250 Pa] static pressure	2,100 [59.5]	1,700 [48.1]
Power consumption (kW)	14	14
External Dimensions (inches [mm], W x D x H)	52 x 42 x 32 [1321x1067x813]	42 x 34.6 x 32 [1067x879x813]
Weight (lb [kg])	695 [316]	475 [216]
Refrigerant	HFC-134a	R-407C
Refrigerant Charge (lb [kg])	14 [6.4]	5 [2.3]

[1]For 125 ºF [51.7 °C] ambient, 80 ºF [26.7 °C] dry bulb / 67 ºF [19.4 °C] wet bulb evaporator air return, 60Hz power input, 1.0 inch water gauge [250 Pa] external static pressure.
[2]For 47 ºF [8.3 °C] ambient and 70 ºF [21.1 °C] interior, 60Hz power input, 1.0 inch water gauge [250 Pa] external static pressure.
[3]For 125 ºF [51.7 °C] ambient, 90 ºF [32.2 °C] dry bulb / 75 ºF [23.9 °C] wet bulb evaporator air return, 60Hz power input, 1.0 inch water gauge [250 Pa] external static pressure. Note that there is no available performance data for the same operating conditions for the two units.

The FDECU, designed in the 1990s, uses HFC-134a refrigerant, the only HFC refrigerant widely available at that time. The more recent LECU design is based on use of R-407C refrigerant. Another key difference between the units is the use of microchannel heat exchangers in the LECU, for both the "outside" and "inside" coils.

Further development was desired by the U.S. Air Force to determine whether more reduction in size and weight is possible if a unit were designed for use with hydrocarbon refrigerant. The key objectives of this project have been to investigate conversion of the LECU design to hydrocarbon refrigerant, determine the size reduction possible with such a design change, address fire/explosion risk, and identify necessary design changes.

2. REFRIGERANT ASSESSMENT

Hydrocarbon (HC) refrigerant options were investigated to determine which of the options would be the best choice for the hydrocarbon LECU. The HC refrigerants which received the most attention in this assessment are listed in Table 2 below. The refrigerant eventually chosen was propylene (R-1270).

Table 2: Relevant Hydrocarbon Refrigerants for Military ECU Applications

Refrigerant	Description	General Conclusions
R-1270	Propylene (C_3H_6)	Refrigerant Selected for the project.
R-290	Propane (C_3H_8)	Good alternative, but requires higher-displacement compressor to equal HCFC-22 or R-407C capacity.
CARE50	Mixture of 94% Propane and 6% Ethane (C_2H_6)	Good match of HCFC-22 Pressure/ Temperature characteristics, but has high glide (10 ºF [5.5 °C] in evaporator, 6 ºF [3.3 °C] in condenser).
HC-22a/502	Mixture of 87% Propane and 13% Propylene	Performance very similar to pure propane.

Some of the refrigerant characteristics analyzed include the following.

- Saturated Pressure/Temperature curves
- Volumetric Capacity
- Coefficient of Performance
- Properties which predict heat transfer in both the evaporator and the condenser
- Temperature Glide

- Compressor Pressure Ratio
- Flammability Limits and Combustion Energy

Refrigerant properties were calculated using REFPROP Version 7.0 (Lemmon *et al.*, 2002). Calculations were done primarily for cooling system performance for typical military operating conditions: 125 ºF [51.7 °C] ambient temperature with 90 ºF [32.2 °C] Dry-Bulb / 75 ºF [23.8 °C] Wet-Bulb evaporator return air. For a typical design, this would result in a condensing temperature of 150 ºF [65.6 °C] and an evaporating temperature of 55 ºF [12.8 °C]. For refrigerants with glide, these condensing and evaporating temperatures were selected as the midpoints of the glide range.

Volumetric Capacity and COP for the analyzed refrigerants is shown in Figure 2 below. Among the HCs, propylene has the highest volumetric capacity, the closest match to that of HCFC-22 or R-407C. The COP's of the hydrocarbons with sufficient volumetric capacity to be of interest are all very similar.

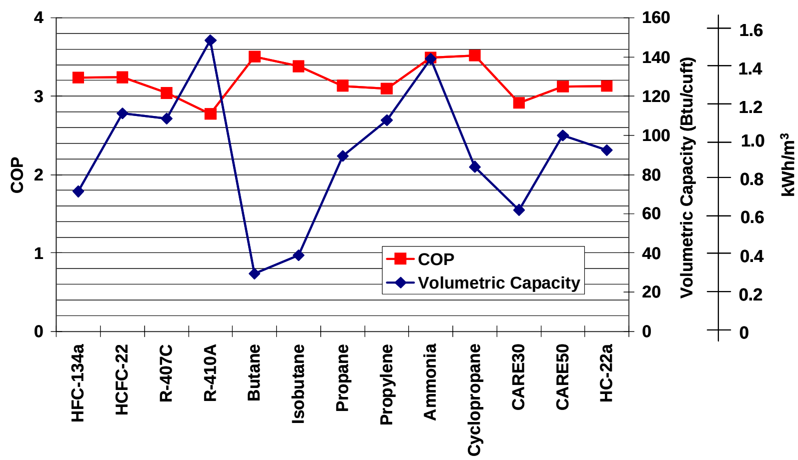

Figure 2: Refrigerant COP and Volumetric Capacity

Heat transfer parameters, which appear in heat transfer correlations for the refrigerants and provide an indication of the level of achievable heat transfer, were defined as follows.

- Condensing Parameter 1: $(k\,\rho^{2/3})/\mu$, liquid properties
- Condensing Parameter 2: $(k^{0.6}\,\rho^{0.8}\,c_p^{0.4})/\mu^{0.4}$, liquid properties
- Evaporating Parameter 1: $(k\,h_{fg}^{0.5})/\mu$, liquid properties
- Evaporating Parameter 1A: Evaporating Parameter 1 times vapor density
- Evaporating Parameter 2: $(k^{0.6}\,c_p^{0.4})/\mu^{0.29}$, liquid properties
- Evaporating Parameter 3: $(k^{0.6}\,c_p^{0.4})/\mu^{0.4}$, vapor properties

These parameters, calculated for the analyzed refrigerants, are compared in the charts in Figure 3 below. Among the hydrocarbon refrigerants, the heat transfer parameters for propylene are generally the highest.

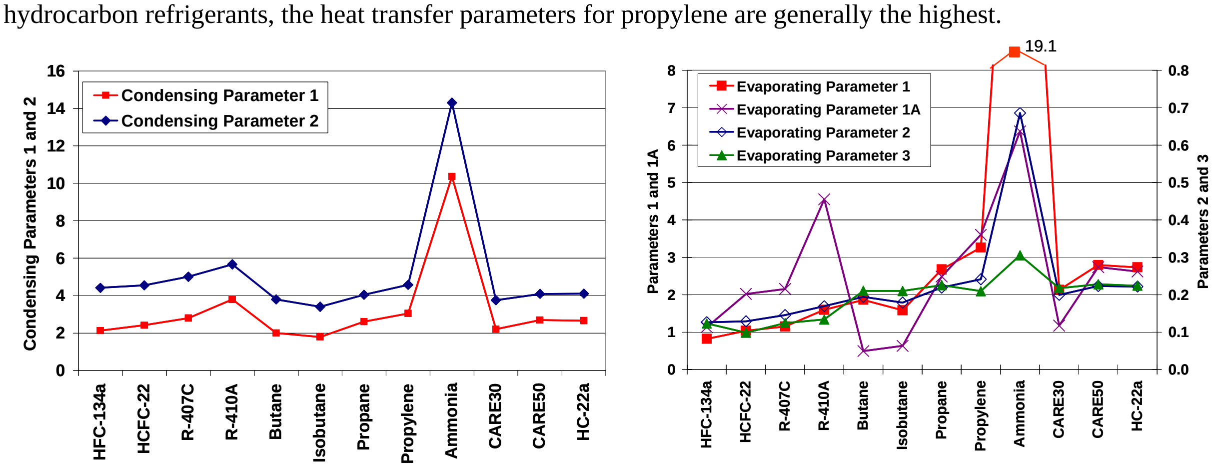

Figure 3: Refrigerant Condensing and Evaporating Heat Transfer Parameters

Based on the investigation of refrigerant characteristics (only some of which have been presented in detail), a decision was made to pursue propylene for the hydrocarbon-refrigerant ECU work. While propane has more commonly been the subject of testing and development of air-conditioning units using hydrocarbon refrigerants, we consider propylene to be a better selection because (1) the volumetric capacity of propylene is higher and much closer to that of HCFC-22, (2) limited test data, for example that presented by Chang *et al.* (2000), Colbourne and Suen (2000), and Lee *et al.* (2005), suggest propylene is better, and (3) refrigerant properties influencing heat transfer suggest that propylene has better heat transfer.

3. PERFORMANCE TESTING

Testing was done with the LECU prototype both with its as-designed charge of R-407C and with propylene. The tests were carried out in TIAX's air-conditioning test facility, which is set up for testing in accordance with ASHRAE Standard 37 using an enthalpy loop for capacity measurements. The unit was tested in sensible-only cooling mode, to simplify establishment of the same conditions for both tests. Operating temperatures were consistent with military cooling design operating conditions: 125 ºF [51.7 °C] condenser inlet air temperature and 90 ºF [32.2 °C] Dry-Bulb evaporator return air. Evaporator air flow was 2,200 scfm [62 m^3/min]. The propylene tests were done without hardware changes, although the refrigerant charge and the thermostatic expansion valves were adjusted to give appropriate performance. Test results are shown in Figure 4 below.

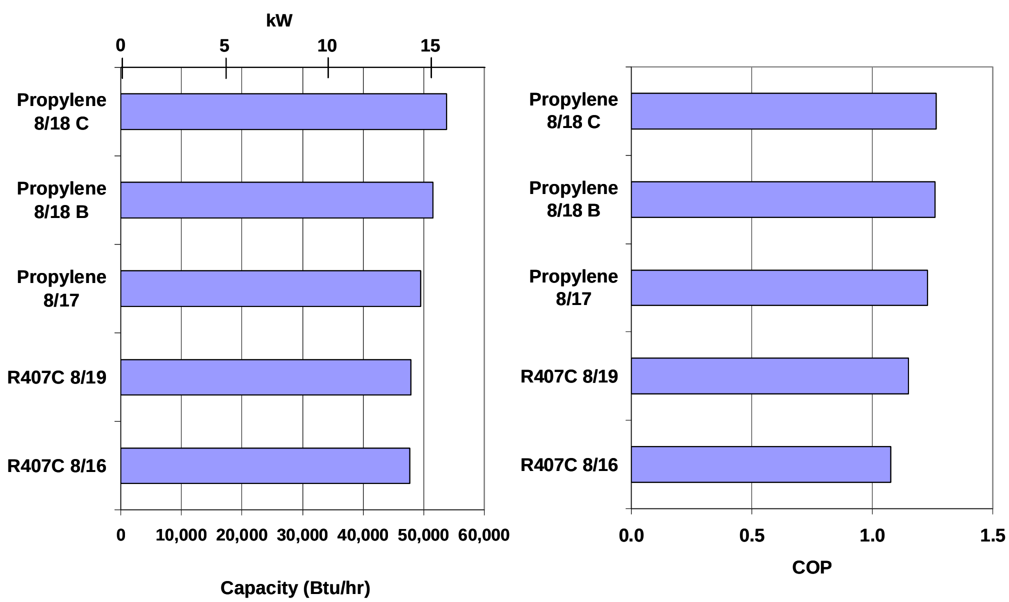

Figure 4: Performance Test Data: Capacity and COP

Some notes regarding differences between the test runs are as follows.

1. Refrigerant charge was probably high for the 8/16 R-407C run (leading to high discharge pressure and high power input), and some liquid may have been escaping the evaporator (since discharge temperature was relatively low for this test). For this reason a retest with R-407C was done on 8/19.
2. Differences between the propylene tests include (a) increase in charge from 2.2 lb [1 kg] for the 8/17 test to about 2.5 lb [1.1 kg] for the 8/18 tests, (b) additional tightening of the thrermostatic expansion valves to reduce suction pressure for the 8/18 C test as compared with the 8/18 B test.

The results show 12% better capacity and 10% better COP for propylene as compared with the conventional refrigerant, R-407C. This is slightly better improvement than is suggested by literature. However, part of the improvement gained with the use of propylene is probably due to the fact that it is a single-constituent refrigerant with no glide, while R-407C has about 7 ºF [3.8 °C] of glide in the condenser and about 10 ºF [5.5 °C] in the evaporator. The unit has microchannel heat exchangers, which do not allow counterflow circuiting to take advantage of this glide. Hence, the R-407C is not being used to its maximum potential in the LECU prototype.

4. ASSESSMENT OF POTENTIAL FOR LECU SIZE REDUCTION

Analysis based on the test data was done to determine what size reduction could be achieved for the propylene LECU if the same performance level as the R-407C LECU were maintained. A simplified analysis was done initially to determine what condenser size reduction would be possible. The following assumptions were made in carrying out this analysis.

- The current compressor would be used, and its performance was based on the manufacturer's performance data and the propylene-refrigerant test data.
- Simplified heat exchanger performance models were used. These were based on an assumption of constant refrigerant temperature in the heat exchanger (evaporating or condensing temperature) and the calculated air temperatures, with UA values determined based on the propylene test data. UA for the smaller condenser was assumed to be proportional to the condenser face area. Condenser air flow was assumed to be proportional to height (i.e. same face velocity). This is conservative, since fan pressure/flow characteristic will more likely lead to increased face velocity.

The analysis showed that the condenser height could be reduced from 23.5 to 21.5 inches (597 mm to 546 mm).

The condenser height reduction would result in reduction in height of the unit by the same amount. Some additional design modifications required to make this possible were identified during the investigation (Westphalen, 2005).

5. TRACER GAS TESTING

Tracer gas testing was done to assess the danger of reaching flammable concentrations of propylene refrigerant in the case of refrigerant leakage. CO_2 was used as a tracer gas, since it has nearly the same molecular weight as propylene (44 for CO_2, 42 for propylene, and ~29 for air). This approach has been used by other investigators to characterize the potential for flammable concentrations of hydrocarbon refrigerant to collect in the case of refrigerant leakage (i.e. Colbourne and Butler, 2000). The tracer was injected near the condenser liquid manifold and near the evaporator inlet to simulate leaks at the locations likely to result in the most rapid leakage rates. Concentration-time traces were recorded in five locations: (1) inside the electric box, (2) in the main circuit breaker compartment, (3) in the low spot of the condenser area between the fork lift tubes (the "sump"), (4) near the condenser fan, and (5) in the evaporator air supply duct. Tests were done with leakage rates of 1 lb/hr [0.45 kg/hr] and 20 lb/hr [9 kg], both very high rates of leakage representing unusual damage to the ECU. Testing was done indoors.

The tracer gas testing is illustrated in Figure 5 below. A nearly-empty cylinder filled with 4 lbs [1.8 kg] of CO_2 tracer gas was depleted down to 2 lbs [0.9 kg] at a rate equal to the desired leakage rate. The cylinder was placed horizontally on a scale so that the weight reduction could be observed during the course of the test. The "leaking" gas was supplied to the leak location through a ball valve and needle valve (right side of Figure 5) feeding a supply tube. A repeatable leakage flow rate was achieved by setting of the needle valve. The leakage event was simulated by opening the ball valve for the appropriate amount of time. CO_2 was resupplied to the horizontal cylinder between tests from a full cylinder of CO_2, shown on the cylinder cart.

The LECU arrangement for the tracer gas testing is shown in Figure 6 below. A short piece of supply ducting was attached to the evaporator air outlet. The figure shows the location of the concentration sampling tube for measurements in the supply duct. A filter was attached to the air inlet. Removal of any excess CO_2 within the test room was done with the room's exhaust system. Two metallic flexible ducts drawing air from the floor near the LECU were connected to the exhaust system to remove any CO_2 buildup in this area.

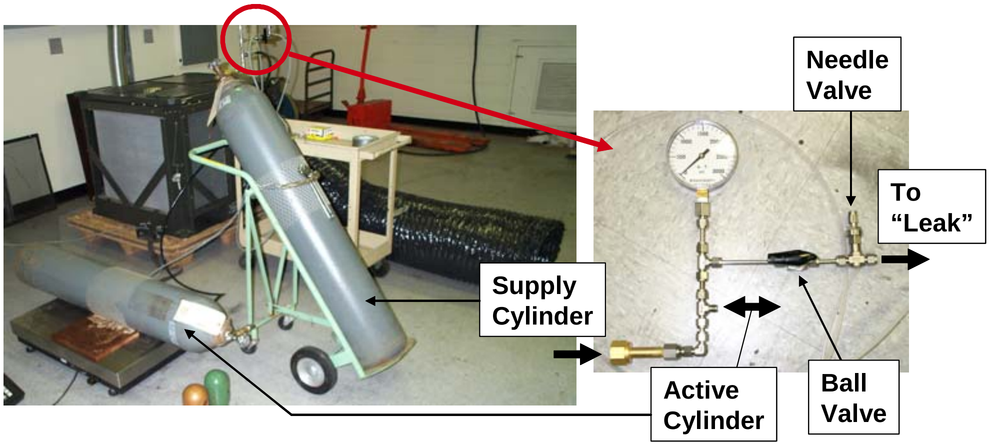

Figure 5: Tracer Gas Test Arrangement

Figure 6: LECU in Tracer Gas Test

CO_2 concentration was measured during the testing with an industrial gas sensor which had a 15-second recording interval. Response time for the instrument was quoted as being less than 40 seconds up to 100% of signal plus 0.7 seconds for each foot of sampling tubing. Measurements are reported in percent volume. Tracer gas was introduced at the condenser liquid outlet and the evaporator inlet. Concentration measurements were made in the Electric Box, at the Main Circuit Breaker location (separated from the electric box), the sump (the area on the condenser side between the fork lift tubes), near the condenser fan, and in the supply duct.

The concentration-time traces are shown in Figure 7 below. The plots are organized with the 1 lb/hr (0.5 kg/hr) flow rates in the first row and 20 lb/hr (9 kg/hr) flows in the second row. The left plots are for tests with the evaporator blower and condenser fan running, and the right plots are for tests with both the blower and fan turned off. At the lower leakage flow rate, no dangerous hydrocarbon concentrations develop when the blower and fan are operating. At the higher leakage flow rate, the sump area sees concentration levels above the lower flammability limit (LFL). LFL for propylene is 2.5%. Additional testing done with a vented sump (Westphalen, 2005), shows that this problem can be solved relatively easily.

When the blower and fan are not operating, higher concentrations of tracer gas are measured, but only in the sump area and in the evaporator air discharge duct. Both of these results are due to the density differences between the refrigerant (or tracer gas) and air. The tracer gas tends to fall, thus filling the low sump area.

When tracer gas is injected in the evaporator box without the blower operating, it collects in the low regions of this box. When enough tracer gas collects, it spills out of the discharge duct. With the supply duct arrangement used in the test (see Figure 6), the tracer gas spills to the concentration measurement location. The strong dependence of tracer gas concentration measurement for the test on height above the bottom of the supply duct (see the top right plot of Figure 7) shows that a limited amount of tracer gas is spilling out. In an actual field deployment, the supply duct would be connected to a shelter or tent at some height above the ground and it would be unlikely that the tracer gas would pass into the conditioned space when the blower is not operating.

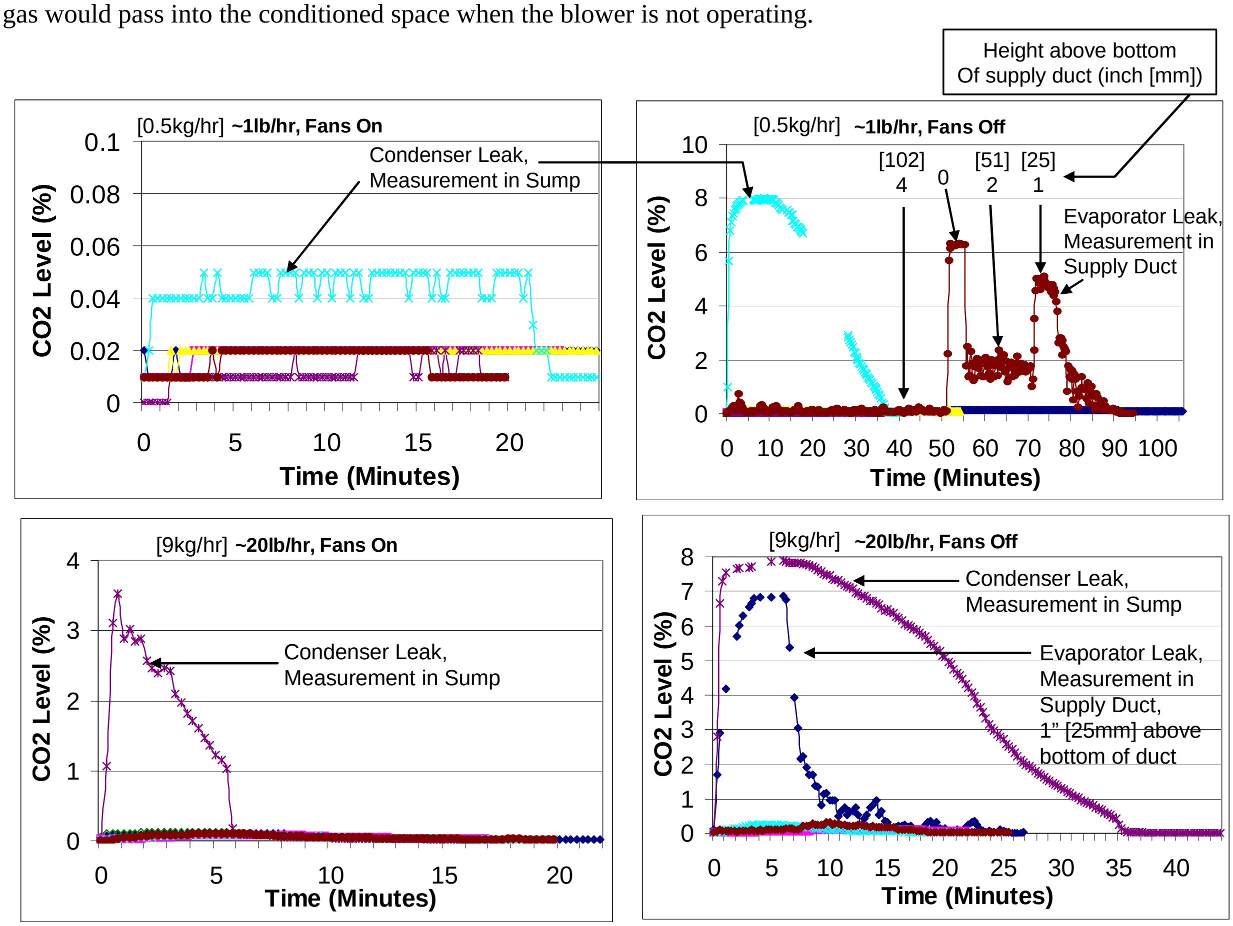

Figure 7: Simulated Refrigerant Leakage Test Results

Although the tests showed that ignitable concentrations of refrigerant can arise in some circumstances, these concentrations occur in areas with no likely ignition sources and are likely to be dispersed even more quickly in actual deployment, since the unit is generally located outdoors, where the ambient air movement helps further to disperse refrigerant. There are no ignition sources in the sump area of the LECU, and hence temporary buildup of ignitable refrigerant concentrations in this location is a low risk. The possible ignition sources in the evaporator box include the heater, the high-temperature cutout switch, and the evaporator blower motor. The blower motor is an enclosed induction motor and hence does not represent a high risk. The heater does not operate with surface temperatures high enough to ignite hydrocarbon refrigerants. Mitigation of risks in this area would be achieved by modifying the controls such that the blower motor starts prior to energizing the heater. This would assure that any leaked refrigerant would be dispersed prior to the heater being energized, thus reducing risk associated with a potential crack of the heater sheath and exposure of its heating element.

Refrigerant concentration levels in the electric box and main circuit breaker compartment stay well below LFL, even though these locations are not sealed according to typical European requirements for hydrocarbon units.

The results show that operation of the ECU blower and the condenser fan will easily dilute even large leaks to safe levels in areas of the ECU which have ignition sources, and that the risk associated with concentration levels which arise when the fan and blower are not operating either is small or can be mitigated. The low refrigerant charge required for the unit (2.5 pounds [1.1 kg]) helps to reduce risk.

6. CONCLUSIONS

Key conclusions of this investigation of converting a military ECU from conventional R-407C refrigerant to hydrocarbon refrigerant design are as follows.

- Refrigerant analysis shows that propylene, propane, CARE50 (94% propane, 6% ethane), and HC-22a/502 (87% propane, 13% propylene) are the most relevant for use in a military ECU. Our investigation led us to choose propylene as the best of these alternatives because it has the highest volumetric capacity and best match to that of R-407C, analysis and data which suggests it has the best heat transfer characteristics, data which suggests it has the best performance, and the fact that it has no glide. The last of these reasons is based on the use in the ECU design of microchannel heat exchangers, which don't easily allow optimization for high-glide refrigerants.
- Performance testing showed that as a drop-in refrigerant the ECU had 12% higher capacity and 10% higher COP with propylene than it did with R-407C. Some of this improvement is attributed to the elimination of refrigerant glide. Subsequent analysis based on these test results indicates that the unit size could be reduced by 2 inches (50 mm) with propylene and maintain the initial performance level. The size reduction is primarily associated with a reduction in condenser height.
- Tracer gas testing to simulate high rates of refrigerant leakage (1 lb/hr [0.45 g/hr] and 20 lb/hr [9 kg/hr]) shows that flammable concentrations of refrigerant can arise is some leakage situations but that risk levels do not appear unreasonably high. Further more detailed risk analysis considering more fully the range of possible leak scenarios and establishment of acceptable risk levels would have to be done to conclude that the risk of the use of hydrocarbon refrigerant in military ECUs is acceptable.

NOMENCLATURE

COP	Coefficient of Performance	LECU	Lightweight ECU
ECU	Environmental Control Unit	LFL	Lower Flammability Limit
FDECU	Field Deployable ECU		

REFERENCES

Chang, Y.S., M.S.Kim, S.T.Ro, 2000, "Performance and Heat Transfer Characteristics of Hydrocarbon Refrigerants in a Heat Pump System", *International Journal of Refrigeration*, 23, p.232-242.

Colbourne, D., K.O.Suen, 2000, "Assessment of Performance of Hydrocarbon Refrigerants", *Final Proceedings of the 4th IIR-Gustav Lorentzen Conference on Natural Working Fluids at Purdue*, July 25-28.

Colbourne, D., D.Butler, 2000, "Dispersion of Flammable Refrigerants from Split Air-Conditioners", Proceedings IIR Conference on Natural Working Fluids, Purdue University, USA.

Lee, H.S., J.I.Yoon, J.D.Kim, P.Bansal, 2005, "Evaporating Heat Transfer and Pressure Drop of Hydrocarbon Refrigerants in 9.52 and 12.70 mm Smooth Tube", *International Journal of Heat and Mass Transfer*, 48, p. 2351-2359.

Lemmon, E.W., M.O.McLinden, and M.L.Huber, 2002, "Reference Fluid Thermodynamic and Transport Properties (REFPROP)", NIST Standard Reference Database 23, Version 7.0, NIST Physical and Chemical Properties Division, Copyright 2002.

Westphalen, D., 2005, "Lightweight Environmental Control Unit", final report submitted to Air Force Research Laboratory, Deployed Base Systems Branch, Tyndall Air Force Base under contract FA8650-05-M-5818.

ACKNOWLEDGEMENT

This project was funded by the U.S.Air Force Air Force Research Laboratory Deployed Base Systems Branch at Tyndall Air Force Base through SBIR Purchase Order FA8650-05-M-5818.