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Lower-GWP Non-Flammable Refrigerant Blends to Replace HFC-134a

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ABSTRACT

Non-flammable, lower global-warming-potential (GWP) refrigerants are needed to replace HFC-134a (GWP=1300) in military equipment. We previously used thermodynamic cycle simulations to screen 100 000+ refrigerant blends and identified 23 candidate replacements. In the present study we narrowed the candidates to three "best" blends and measured their "drop-in" performance in a military environmental control unit (ECU) tested in environmental chambers. Through simulations, the laboratory-measured performance was extrapolated to that of ECUs equipped with a compressor modified for each blend to provide the same system capacity while maintaining the isentropic efficiency of the original HFC-134a compressor. R-513A (GWP=573) and Tern-1 [R-134a/1234yf/1234ze(E) (49.2/33.9/16.9 %mass), GWP=640] are good replacement blends for HFC-134a, offering a similar capacity and COP at GWP reductions of 66 % and 51 %, respectively. These fluids do not present significant application difficulties. For a greater reduction of GWP, R-515B (GWP=344) can be considered but it requires further development.

Keywords: Air conditioning; Coefficient of performance; Cycle simulation; Flammability; Low GWP; HFC-134a replacement

1. INTRODUCTION

Concerns about climate change resulted in regional (EU, 2014) and global (UN, 2016 and UNEP, 2019) regulations that limit the production and consumption of fluorinated refrigerants, which are the dominant fluids currently used in refrigeration and air-conditioning systems, including military equipment. In the United States (US), the use of high-GWP hydrofluorocarbon (HFC) refrigerants is regulated by the American Innovation and Manufacturing (AIM) Act (US Congress, 2021), which directed the U.S. Environmental Protection Agency (EPA) to establish a phasedown program and sector-based HFC restrictions to facilitate the transition to next-generation technologies.

The above concerns and regulations have spurred intensive global research for next generation hydrofluoroolefin (HFO) low-GWP fluids. These research efforts showed that the availability of low-GWP refrigerants varies between applications and is rather limited for medium- and high-pressure systems. Notable applications where HFC-134a has already been successfully replaced by low-GWP refrigerants are mobile air conditioners (HFO-1234yf, mildly flammable) and domestic refrigerators (isobutane, highly flammable); however, these fluids are not acceptable for military systems due to their flammability. Prior screening studies (McLinden et al., 2017) found that all single-component refrigerants that could serve with good performance as a replacement for HFC-134a (i.e., R-134a) are at least mildly flammable. For this reason, this search for non-flammable replacements for HFC-134a in military systems was focused on refrigerant blends.

2. OBJECTIVES AND TECHNICAL APROACH

The goal of this project was to identify lower-global-warming-potential (GWP), non-flammable refrigerants to replace HFC-134a (GWP=1300) in military equipment. The selection criteria also include coefficient of performance (COP), volumetric capacity (Q_{vol}), and toxicity. This work addressed the Statement of Need WPSON-17-02 "No/Low Global Warming Potential Alternatives to Ozone Depleting Refrigerants", issued by the US Strategic Environmental Research and Development Program (SERDP, 2023). This conference paper is a summary of a comprehensive report published for this project (Domanski et al., 2023), which contains more detailed descriptions of the experiments, models, and data.

This work is a follow-on of (Domanski et al., 2018), which screened over 100 000 refrigerant blends and identified over 20 promising HFC-134a replacements. The core objective of this project was to narrow the pool of blend candidates down to three "best" fluids, experimentally verify their non-flammability, and demonstrate their performance in a military ECU (designed for HFC-134a) tested in environmental chambers. Finally, the work estimated the performance potential of the candidate blends through simulations of the ECU with the compressor and heat exchangers optimized for each of the blends.

The starting point of this project was the outcome of Domanski et al. (2018), which identified over 20 candidate lower-GWP blends from an exhaustive, simulation-based search and evaluation of over 100 000 two- and three-component blends formed from 13 single-component refrigerants (Bell et al., 2019). At the outset of this project, we selected four blends as preliminary candidates, three of which were evaluated by testing in the ECU. The criteria for blend selection consisted of the following parameters:

- Non-flammability
- Minimum GWP
- Maximum COP
- Volumetric capacity (Q_{vol}) matching that of the baseline HFC-134a
- Market availability

The following four blends were selected:

1. **R-513A:** [R-134a/1234yf (44/56 %mass)], GWP = 573. R-513A was identified in (Domanski et al., 2018) (blend # 2). A1 ASHRAE safety classification.

2. **R-450A:** [R-134a/1234ze(E) (42/58 %mass)], GWP = 547. R-450A was not specifically identified in (Domanski et al., 2018); however, its make-up and performance are similar to those for blend # 9 [(R-134a/1234ze(E) (60/40 %mass)]. A1 ASHRAE safety classification.

3. **Tern-1:** [R-134a/1234yf/1234ze(E) (49.2/33.9/16.9 %mass)], GWP = 640. This blend was identified in (Domanski et al., 2018) (blend #4); it has not been classified by ASHRAE but is expected to be "A1" based on its toxicity and flammability.

4. **R-515B:** [R-1234ze(E)/227ea (91.1/8.9 %mass)], GWP = 344. R-515B was not identified in (Domanski et al., 2018); however, we subsequently applied our screening analyses to it and found it to be promising. A1 ASHRAE safety classification. It has a significantly lower GWP than those of other fluids.

This project involved preliminary experimental and analytical tasks prior to ECU testing in the environmental chambers. These tasks included measurements of thermodynamic and transport properties of the considered blends and improvements to the property modeling. Fundamental measurements and modeling were also conducted for: the flammability characteristics, the forced-convection heat transfer performance, and the cycle performance in a laboratory mini-breadboard heat pump (MBHP) apparatus, as the final qualification step of the "best" blends.

3. RESULTS AND DISCUSSION

3.1. Experimental Measurements of Blend Properties and Development of Mixture Equation of State

We measured thermophysical properties of refrigerant blends composed of next generation hydrofluoroolefins, HFO-1234yf and HFO-1234ze(E), mixed with traditional hydrofluorocarbons, HFC-134a, HFC-125, and HFC-227ea. These HFOs have very low GWP values (order of 1) but are slightly flammable; they were mixed with the non-flammable, but high-GWP, HFCs to obtain non-flammable blends with moderate values of GWP. Accurate property data are the backbone of any project to identify and verify new refrigerants; they are essential for cycle analysis, heat transfer analysis, and the analysis of system tests. These data allowed us to improve the refrigerant mixture models needed for conducting tests in the MBHP, refrigerant two-phase heat-transfer tests, ECU tests, and detailed simulations.

While the improved property models were a prerequisite for the subsequent tasks, no major deficiencies were identified in the models used for the screening (Domanski et al., 2018); therefore, the selection of “best” blends made in (Domanski et al., 2018) remained valid. These new property data, along with literature data, were used to develop a mixture model optimized for these HFO-containing blends; this optimized model was then used in the detailed ECU simulations.

For the blends R-1234yf/134a, R-134a/1234ze(E), and R-1234yf/1234ze(E) we carried out comprehensive measurements comprising vapor-liquid equilibria (VLE), density (p, ρ, T, x), speed of sound, thermal conductivity, and viscosity; these measurements (at two compositions for each blend) covered a combined temperature range of 230 K to 400 K, with pressures up to 50 MPa. For three additional blends (R-125/1234yf, R-1234ze(E)/227ea, and R-1234yf/152a, also at two compositions each) we carried out VLE measurements. The measurements were selected to provide an optimal data set for the purposes of fitting mixture property models. These models (Bell, 2022 and Bell, 2023) will be incorporated into future versions of REFPROP (Lemmon et al., 2018) and, thus, be made available to the entire HVAC industry.

3.2. Flammability Assessment

It is essential in military applications that any low-GWP replacement for HFC-134a be non-flammable. This is challenging, however, since for molecules containing only hydrogen, fluorine, and carbon, there is a trade-off between GWP and flammability. The common changes to the molecules (adding hydrogen atoms or double bonds) to make them more reactive in the troposphere and hence lower their atmospheric lifetime (which lowers GWP), also make them more flammable. A further challenge arises, in that flammability is not a distinct boundary but rather depends upon the environment to which the refrigerant is exposed.

In the preliminary work, an empirical model of flammability based on the adiabatic flame temperature and the fluorine to hydrogen ratio of the reactants was used to create a flammability index (Linteris et al. 2019) and rank the candidate blends according to their flammability. Only blends predicted to be non-flammable were considered for further study. Nonetheless, it was essential that these predictions be verified by tests. Thus, the primary goal of this refrigerant flammability work was to experimentally assess the flammability of the promising blends considered for performance testing in the ECU in the environmental chambers.

All four selected candidate blends are non-flame propagating in the modified ASTM E681 test (ASTM, 2015) specified in ASHRAE Standard 34 (ANSI/ASHRAE, 2019). We also used a more stringent test, a modified version of the Japanese high-pressure gas law test (JHPGL), in which the explosion pressure in a 2 L combustion chamber with a fused platinum wire ignition source is used as a metric for flammability. Figure 1 shows that three of the four candidate blends, Tern-1, R-513A, R-450A, had similar pressure rises of (0.0451, 0.0474, and 0.0262) MPa, respectively, while R-515B had a higher pressure rise of 0.156 MPa. Tests with binary blends of HFC-134a and HFO-1234yf with increasing fractions of HFC-134a showed that an HFC-134a mole fraction of 0.30 was required to pass the E681 tests, and at this composition, the explosion pressure in the JHPGL test was 0.127 MPa. Hence, it appears that R-515B is close to the edge of passing the E681 test, while the other blends pass the test more easily.

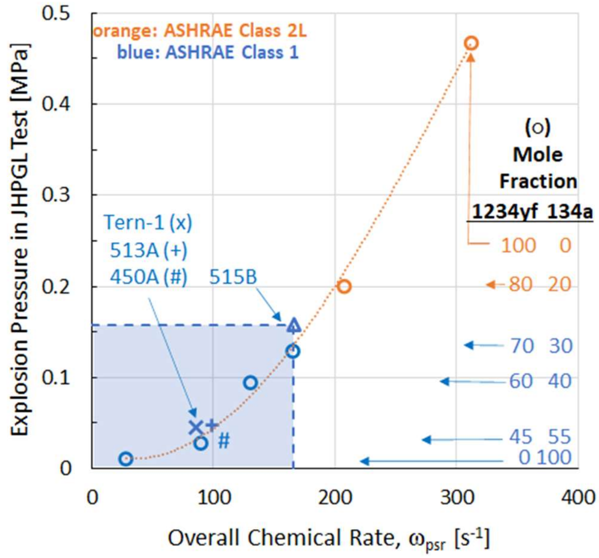


Figure 1: Explosion pressure in the JHPGL test vs. overall chemical reaction for R-513A (+), R-450A (#), R-515B, Tern-1 (X), and the R-1234yf/134a blends (O). Dotted line is a polynomial fit to all the data.

A new parameter has been developed for characterizing the flammability. The overall reaction rate, ω_{psr}, is a fundamentally-based parameter that can be used to correlate experimental flammability results between test methods or with full-scale test results. It is readily calculated for any arbitrary mixture of interest and can be used to predict its flammability. In the present work, a detailed kinetic model was developed and validated, and used to estimate the overall chemical reaction rate of the candidate blends. Both the E681 flame propagating/non-propagating boundary, as well as the JHPGL test explosion pressure were well correlated with the calculated overall reaction rate for each blend. Moreover, the calculated overall reaction rate predicts that for the candidate blends the effect of humidity in the air will be small for an increase from 0 % to 50 % relative humidity (r.h.), but large for an increase from 50 % r.h. to 100 % r.h. (all r.h. evaluated at 23 °C), as shown in Figure 2. Thus, levels of humidity above 0.014 moles H_2O/mole air (50 % r.h. at 23 °C) may have large effects on the flammability of the blends and should be considered in any full-scale tests to be used to specify the degree of non-flammability required in military applications. For example, Figure 2 illustrates the effect of humidity with data for the nominal blend (Nom), worst-case fractionation WCF (from uncertainty in the blend components), and worst-case fractionation for flammability WCFF (from different vaporization rates for leaking blend components of liquid agent at the WCF). As indicated, for most blends, the differences in Nom., WCF, and WCFF are small, except for the case of R-450A, for which the WCFF is quite different from the WCF (although the Class 1 rating is still maintained for the WCFF). In the military ECU application, the concern is with rapid loss of refrigerant charge, so WCF is the mixture of interest.

3.3. Testing Selected Blends in a Mini-Breadboard Heat Pump

The Mini-Breadboard Heat Pump (MBHP) was used to experimentally evaluate HFC-134a and the four candidate low-GWP blends: R-513A, R-450A, R-515B, and Tern-1. The purpose of these tests was to: (1) validate the CYCLE_D-HX simulation model (Brown et al., 2021, and Brignoli et al., 2017) used in Domanski et al. (2018), and (2) qualify the three "best" blends for testing in a military ECU. Performance of each fluid was measured over a range of capacity including (1.3, 1.5, and 1.7) kW, where 1.5 kW was the rating point. The varying capacity provided measurements to verify the model's predictive ability over a range of mass and heat fluxes. The test-to-test variation, largely driven by compressor efficiency, yielded representative average COP and Q_{vol} values with (0.5 to 1.0) % confidence intervals. In total, 121 tests were conducted.

All experimental tests were then simulated using CYCLE_D-HX. For R-513A, R-450A, and R-515B in the basic cycle (tests without the liquid-line/suction-line heat exchanger, LLSL-HX), the model predicted values were within the confidence intervals of the experimental results. For Tern-1, the model overpredicted the experimental COP and Q_{vol} by about 3 %. Importantly, the CYCLE_D-HX model provided the same relative COP and Q_{vol} ranking as the experimental data, giving confidence to the HFC-134a replacement candidate

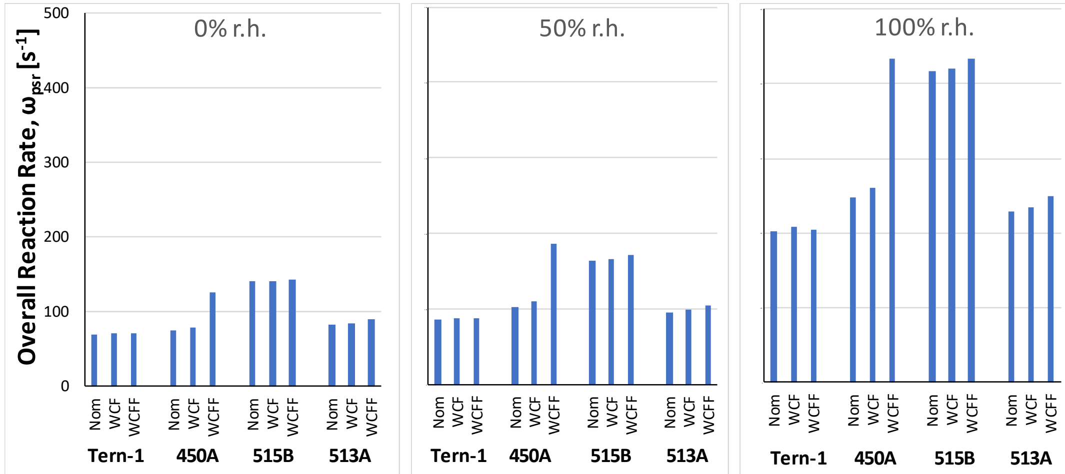


Figure 2: Peak chemical reaction rate for the candiate blends. Data are shown for the Nominal, WCF, and WCFF compositions in air (T = 296 K) and 0 %, 50 %, and 100 % r.h.

screening performed in Domanski et al. (2018). All four low-GWP candidates were deemed acceptable for testing in the ECU as none had significant deviations from modeled performance, excessive discharge temperatures, or other hardware-related problems.

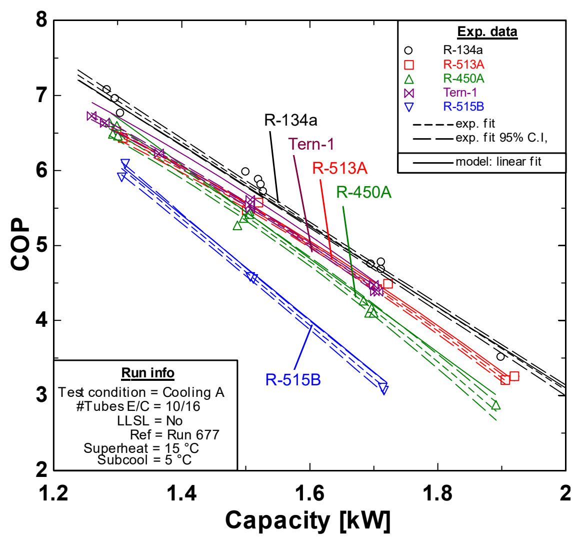


Figure 3: Measured and simulated Cooling COP for HFC-134a and the replacement candidates.

3.4. Refrigerant Forced-Convection Heat-Transfer Testing

An experimental apparatus was used to measure 432 convective-boiling local heat-transfer coefficients for R-515B, R-450A, R-513A, and HFC-134a in a micro-fin tube. These data were used to develop an improved correlation for the local Nusselt number, Eq. (1):

$$\mathrm{Nu_p} = 242.5\,\mathrm{Re}^{0.26(1-x_q)}\,\mathrm{Bo}^{0.28}\,\mathrm{B_{nd}}^{-0.61x_q} \qquad \text{Eq. (1)}$$

where B_{nd} is the dimensionless Bond number (Kedzierski et al., 2018), which includes fin geometry parameters and the surface tension. The correlation is valid for Reynolds numbers (Re) between 1000 and 14 000, boiling numbers (Bo) between 0.000 002 and 0.001, and B_{nd} between 0.002 and 0.05. Eq. (1) was developed with data where the refrigerant reduced temperature ranged between approximately 0.71 and 0.94. The dimensionless parameters and symbols are defined in the nomenclature of Domanski et al. (2023). This correlation predicted 82.8 % of the measured convective boiling Nusselt numbers within ± 20 %. The new correlation was used in the simulations of the ECU system, Section 3.6.

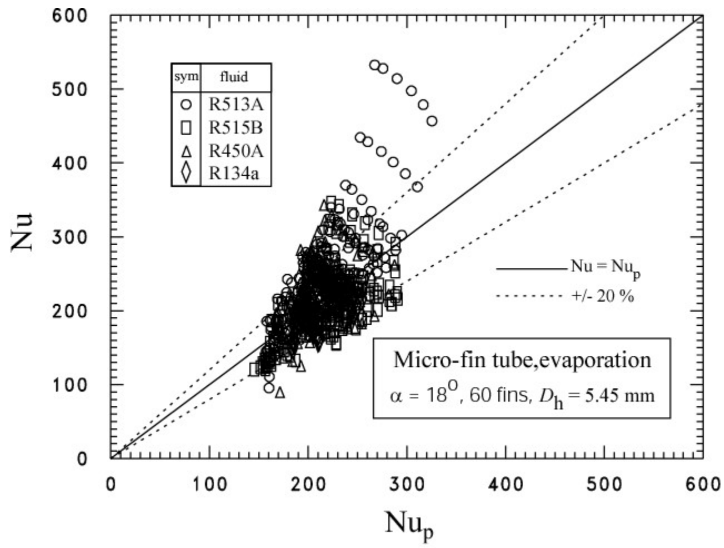


Figure 4: Comparison between measured Nusselt numbers and those predicted by the new correlation in Eq. (1)

3.5. Selection of Three Blends for Testing in Military ECU

We selected R-513A, Tern-1, and R-515B for ECU testing in the NIST environmental chambers. Each of these blends has the potential of being the fluid of choice depending on the weights applied to the selection criteria (GWP, COP, Q_{vol}, flammability). The main merits of R-513A (GWP = 573) and Tern-1 (GWP = 640) were their good COP and Q_{vol} performance. We selected R-515B (GWP = 344) to provide an assessment of performance of this lower-GWP and lower-pressure blend should lower GWP values be mandated in the future.

Regarding safety characteristics, R-513A, R-450A, and R-515B have the ASHRAE safety designation A1 (lower toxicity, no flame propagation). While Tern-1 does not have ASHRAE classification, it can also be considered an A1 blend, since its ‘non-flammability’ was confirmed by the ASTM E681 test prescribed in ASHRAE Standard 34, and its three components are classified as ‘lower-toxicity’ fluids by this standard. It is uncertain at this time whether the ASTM E681 test is stringent enough for military requirements; since this issue has not been determined yet, we decided to use the ASHRAE flammability criteria in this study.

Table 1 provides select properties of the blends tested in the ECU. The ratios of COP/COP$_{R-134a}$ and $Q_{vol}/Q_{vol,R-134a}$ were obtained from CYCLE_D-HX simulations with optimized heat exchangers. The table also provides selected thermophysical data, which complement the COP and Q_{vol} information. The normal boiling point correlates with Q_{vol}: R-515B has the highest NBP and the lowest volumetric capacity. The molar heat capacity of vapor ($C_{p,v}$) affects the shape of the two-phase dome and the slope of the saturated vapor line on the temperature-entropy diagram, and higher values of $C_{p,v}$ correspond to a less steep slope and larger throttling loses in the expansion device (Morrison, 1994). In this respect, HFC-134a has a slight advantage over the blends. Regarding thermal conductivity and viscosity, HFC-134a also has an advantage in a better conductivity although its higher viscosity is a disadvantage.

Table 1. Selected properties of blends tested in ECU

Fluid	NBP (°C)	COP/ COP$_{R-134a}$	Q_{vol}/ $Q_{vol,\ R-134a}$	GWP	$C_{p,v}$ * (J mol^{-1} K^{-1})	k_l * (W m^{-1} K^{-1})	μ_l * (mPa s)
HFC-134a	**-26.1**	**1**	**1**	**1300**	**91.6**	**0.092**	**0.266**
R-513A	-29.6	0.988	1.027	573	99.8	0.067	0.226
Tern-1	-27.8	0.987	0.989	640	98.1	0.079	0.239
R-515B	-19.0	0.974	0.738	344	103.0	0.080	0.250

* at 0.0 °C from REFPROP

Summary of characteristics of blends selected for testing in the ECU:

R-513A: possesses a very good combination of three important attributes: its GWP is second to the lowest on our list (Table 1); its COP is 1.2 % below $COP_{R\text{-}134a}$, which makes it the second top COP of blends with GWP < 750; and its volumetric capacity is the highest on our list, 2.7 % better than that of HFC-134a. In addition, this blend is an azeotrope and is commercially available.

Tern-1: compared to R-513A, Tern-1 contains 5.2 % more HFC-134a and includes 16.9 % HFO-1234ze(E), which is less flammable (lower burning velocity) than HFO-1234yf. As a result, Tern-1 is expected to be farther below the flammability boundary than R-513A (Section 4.2.4 of Domanski, 2023) and is a more conservative choice should military flammability criteria be more stringent (see Section 4.2.5 of Domanski et al., 2023). The simulated COP of Tern-1 is 1.3 % below $COP_{R\text{-}134a}$, and its volumetric capacity is lower by 1.1 % , both of which are insignificant differences.

R-515B: was selected because it has significantly lower GWP than the other chosen blends. Per CYCLE_D-HX simulations with optimized heat exchangers, the COP of this blend is 2.6 % lower than that of HFC-134a, and the volumetric capacity is lower by 26.2 %, which will have to be mitigated by a larger compressor and some efficiency enhancing features. The data presented in (Section 4.2.4 of Domanski, 2023) indicate that R-515B is closer to the flammability boundary than the other blends (see Figure 1). Despite these shortfalls, it is of interest to explore the performance potential of this low-pressure blend in case even lower GWP fluids become strongly preferred in the future. R-515B is an azeotrope and is commercially available.

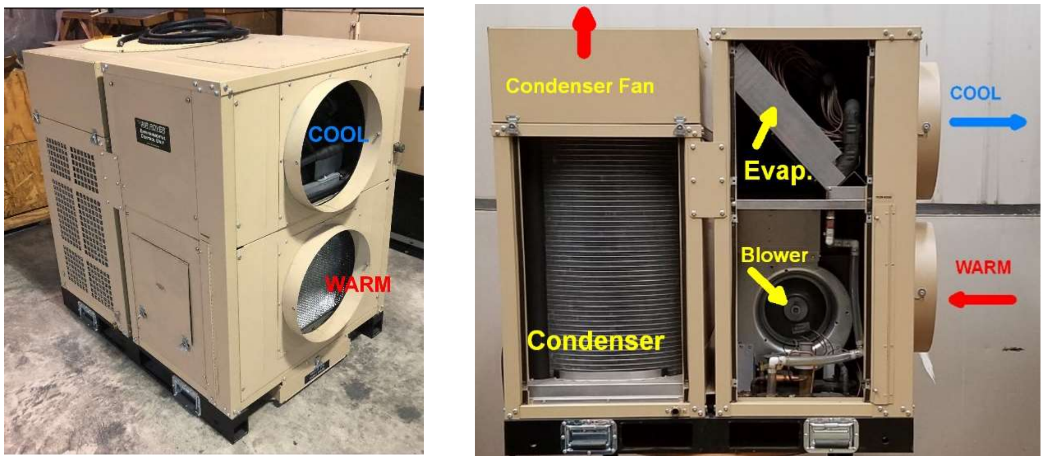
By the above selection of three blends, we dropped R-450A from further testing, though it could be a viable option for the ECU. The volumetric capacity of R-450A is 13.3 % lower than that of HFC-134a, or about half the difference between that of HFC-134a and R-515B. Testing R-515B instead of R-450A provides more useful data for validating the ECU model with a broad spectrum of measurements (R-515B gave performance of a low-pressure fluid). Moreover, the ECU model can be used for predicting performance of other fluids that were not included in the tests, e.g., R-450A.

3.6. Evaluation of Blend Performance in ECU

Military ECU Specifications and Test Facility

The tested system was a military HFC-134a-based air conditioner with a 19.9 kW rated cooling capacity (Figure 5). It was comprised of a 3-phase electrically-powered scroll compressor, finned-tube evaporator, evaporator blower, microchannel condenser, condenser fan, and controls. The unit was designed to run continuously at part load by modulating its capacity using a hot-gas bypass with a tempering expansion valve and an evaporator pressure regulating (EPR) valve. This arrangement of components and controls would have made it impossible to execute a test program with different refrigerants. Therefore, for the purpose of this study, we disabled the hot-gas bypass and fully opened the EPR valve to produce a basic vapor-compression cycle.

The test facility consisted of two adjacent environmental chambers. The ECU was installed in the outdoor chamber and supplied the conditioned air to the indoor chamber through the attached ductwork. Figure 6 shows the nozzle chamber setup used to measure the volumetric flow rate of air.



(a) (b)

Figure 5: (a) Complete ECU before installation. (b) ECU with protective grids removed.

Figure 6: Connecting ducts and nozzle chamber located in the indoor environmental chamber

The primary measurement of ECU capacity was the air enthalpy method, and the refrigerant enthalpy method served as the secondary measurement. All ductwork was thoroughly insulated and leak-tested before testing began. For standard rating points, the air-side and refrigerant-side measurements closed the energy balance within 6 %.

The tests used the indoor condition of 26.7 °C drybulb and 15.8 °C dewpoint, and four outdoor drybulb conditions: (27.8, 35.0, 46.1, and 51.7) °C. For each refrigerant, the ECU was charged with refrigerant according to the procedure recommended by the manufacturer while operating at 26.7 °C indoor drybulb, 15.8 °C indoor dewpoint, and 35.0 °C outdoor drybulb. In this process, the thermostatic expansion valve (TXV) and refrigerant charge were adjusted to produce an evaporator exit superheat and condenser subcooling per manufacturer's instruction. We refer to these tests as "drop-in" tests.

Experimental Performance of Candidate Replacement Refrigerants

Figure 7 and 8 show "drop in" capacity and COP for the tested blends with respect to the values for HFC-134a. R-513A provides a somewhat higher capacity at all test conditions. Its COP is below that of HFC-134a at outdoor temperatures of 27.8 °C and 35.0 °C; however, its COP is better at the higher outdoor temperature even as it delivers a higher capacity. The performance of Tern-1 was similar to that of HFC-134a, both in terms of capacity and COP. On the other hand, R-515B yielded capacity lower by (17 to 23) % because it is a lower pressure fluid. With this lower capacity the heat exchanger area/capacity ratio was larger, so the "drop-in" COP of R-515B was comparable to that of HFC-134a.

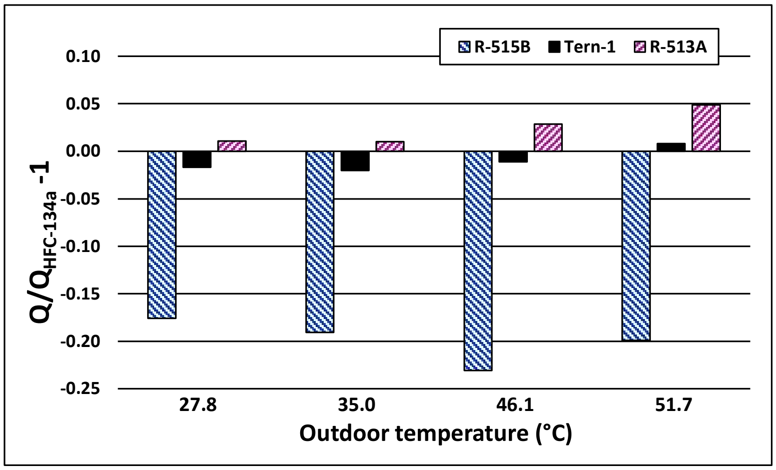


Figure 7: Capacity difference for R-515B, Tern-1, and R-513A relative to HFC-134a, based on ECU "drop-in" tests at outdoor temperatures (27.8, 35.0, 46.1, 51.7) °C

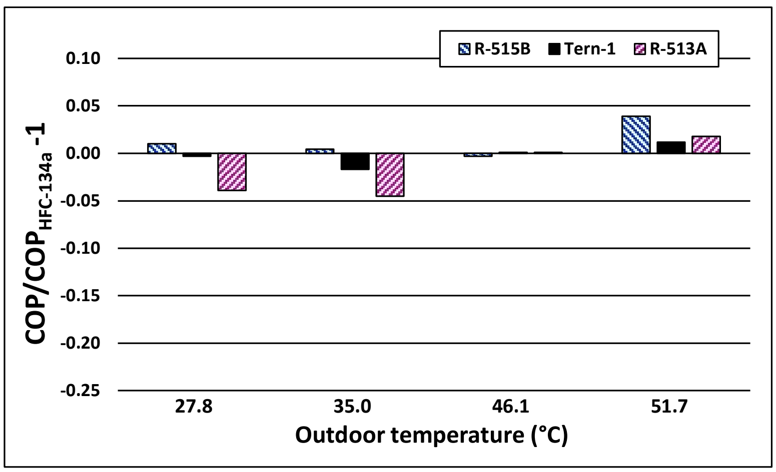


Figure 8. COP of R-515B, Tern-1, and R-513A relative to HFC-134a, based on ECU "drop-in" tests at outdoor temperatures (27.8, 35.0, 46.1, 51.7) °C.

<u>Simulation of Performance of Candidate Replacement Refrigerants</u>

The ECU tests conducted in the environmental chambers provided information on the ECU performance with tested refrigerants producing different capacities. To determine performance merits equitably for each fluid, performance comparisons need to be carried out at the same capacity produced by each fluid (McLinden and Radermacher, 1987). It would be a rather complex task to carry out experimentally, but it is practical to execute it using simulation models. In this work, we used an in-house system model, ACSIM, and the heat exchanger model EVAP-COND (Domanski et al., 2021), to simulate the refrigerants' ECU performance with the same capacity imposed at the 35.0 °C rating point. Compressor isentropic efficiencies for these simulations were calculated by the HFC-134a compressor map using the suction and discharge saturation temperatures established in a cycle for a given individual blend. Figure 9 and 10 show that under these conditions, the R-513A and Tern-1 blends still provide the best performance compared to HFC-134a.

ACSIM is the NIST in-house model of an air conditioner. It includes models of a compressor, evaporator, condenser, TXV, and connecting tubing. Further, it uses the EVAP-COND routines for simulating performance of the evaporator and condenser. EVAP-COND is a software package that contains NIST's simulation models EVAP and COND for finned-tube evaporators and condensers. The "tube-by-tube" simulation scheme used in these models allows for specifying complex refrigerant circuits, modeling refrigerant distribution between these circuits, and accounting for one-dimensional air maldistribution. EVAP-COND includes a computationalintelligence-based module for optimizing a heat exchanger's refrigerant circuitry. For Figure 9 and 10 we used the existing ECU tube circuit configurations. We explored using EVAP-COND to determine optimal tube circuitry for the evaporator and condenser in the ECU, but the COP only improved about (1 to 2) % and didn't change the relative performance of the fluids.

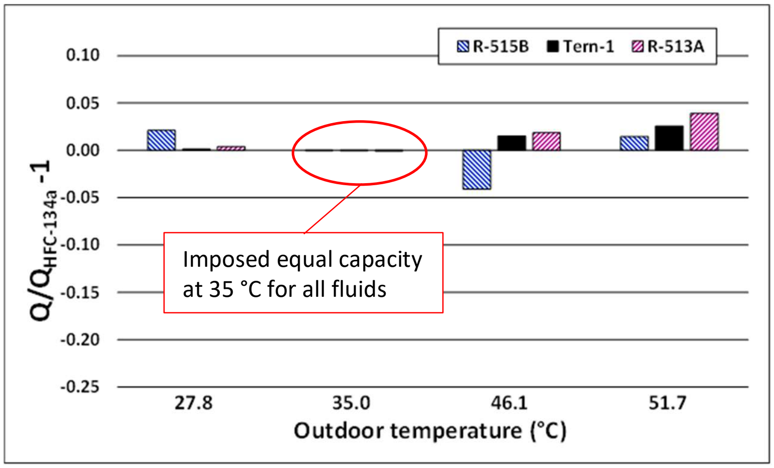


Figure 9: Capacity for R-515B, Tern-1, and R-513A relative to HFC-134a, for ECUs with equal capacity at the 35.0 °C test condition; based on ACSIM simulations at outdoor temperatures (27.8, 35.0, 46.1, and 51.7) °C

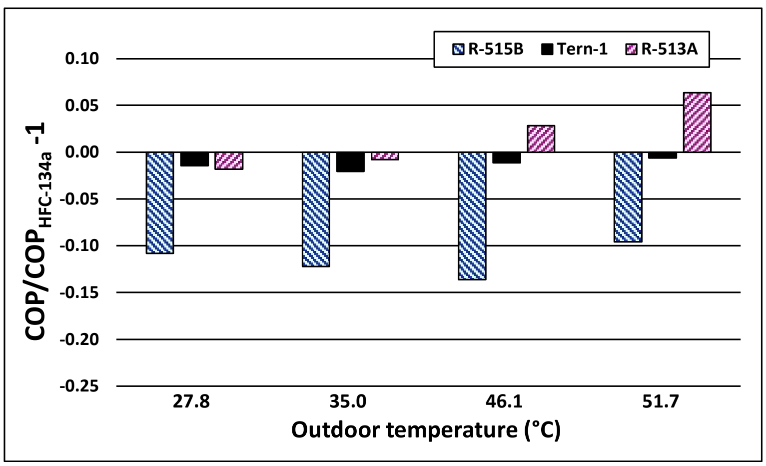


Figure 10: COP for R-515B, Tern-1, and R-513A relative to HFC-134a, for ECUs with equal capacity at the 35.0 °C test condition; based on ACSIM simulations at outdoor temperatures (27.8, 35.0, 46.1, and 51.7) °C

4. CONCLUSIONS

This study developed new measurements and data on non-flammable, low-GWP candidate replacements for HFC-134a, which included thermophysical properties, flammability characteristics, two-phase heat transfer performance, and cycle performance. This information will assist the HVAC industry in its transition to low-GWP systems.

For the studied ECU system, the R-513A and Tern-1 blends provide comparable capacity and COP to that of HFC-134a and offer GWP reductions of 66 % and 51 %, respectively. They can be implemented without major redesign of currently used components or other difficulties. If greater reduction in GWP is desirable, R-515B (74 % GWP reduction) can be considered, but its use requires further research and developmental work.

While the tested blends pass the ASTM E681 test as stipulated by ASHRAE Standard 34 for qualifying 'non-flammability' of refrigerants, some pass more easily than others, as determined from the other tests and modeling. In the present blends, there is a trade-off between 'non-flammability' and GWP. If military requirements for 'non-flammability' are more stringent than the E681 standard, the less flammable of the three (Tern-1 and R-513A) might still pass a more stringent criterion while R-515B would likely fail. If better flammability behavior than Tern-1 and R-513A is required, the less flammable blends identified in (Domanski et al., 2018) would need to be selected, and then evaluated experimentally to verify their predicted performance and flammability. These less-flammable fluids would have a reduction of GWP of about 50 % as compared to HFC-134a.

A live-fire test program in conjunction with flammability modeling should be carried out to establish a representative test for assessing 'non-flammability' for the military environment. We recommend HFC-134a to be tested at high ambient temperature and high humidity as a benchmark. We suggest live-fire tests of HFC-134a with increasing amounts of added HFO-1234yf to enable correlation to the small-scale experimental and numerical results.

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NOMENCLATURE

COP	coefficient of performance	GWP	global-warming potential
p	pressure (kPa)	Q_{vol}	volumetric capacity (kJ×m^{-3})
T	temperature (K)	x	mixture composition
ρ	density (kg×m^{-3})	ω_{psr}	perfect-stirred-reactor overall chemical rate (s^{-1})

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