Survey of Available Literature on the Use of Hydrocarbon Refrigerants in Heating, Air-Conditioning, and Refrigeration Equipment

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Executive Summary

Industry experts worked together to review available information on the relative performance of hydrocarbon and hydrofluorocarbon refrigerants in heating, air-conditioning and refrigeration equipment. Twenty-seven papers were selected that related to this topic. The purpose of the review was to determine whether good information was available to compare the performance of hydrocarbon and hydrofluorocarbon refrigerants in several types of equipment under proper conditions; that is, that the equipment was optimally prepared for each type of refrigerant.

The industry volunteer reviewers were divided into five groups, nominally identified by product categories: Compressors and Condensing Units (CCU)/ Commercial Refrigeration Equipment (CRE); Industrial Refrigeration and Heat Transfer (IRHT) / CRE; and three (3) general heating, ventilation, and air-conditioning (HVAC) groups.

Papers were reviewed using several criteria.

- Was information provided to allow quantitative comparison of the performance of hydrocarbon and HFC refrigerants in compressors or systems optimized for each refrigerant tested?
- Was information provided to allow the reviewer to evaluate the uncertainty levels of the data (in the case of experimental work) or the computer model predictions (in the case of theoretical studies)?
- Was the methodology of the work explained sufficiently that it could be duplicated by others?
- Did the work appear to have a bias because of limitations of the protocol (e.g., drop-in of a test refrigerant in a system designed for a different

refrigerant, without re-optimization)? Or – was there an evident “political” bias?

- In the case of papers on domestic refrigerators, did the results appear to have some applicability to refrigerant options for HVACR equipment – e.g., small commercial refrigeration systems?

While data from tests of complete systems was favored, the reviewers agreed that computer models exist which are capable of providing good comparisons of the performance of different refrigerants in optimized systems. Thus, papers based exclusively on analysis rather than experiment, were included in the review but the nature of the computer models was an important evaluation item.

As a sidelight, the reviewers noted whether information was provided about how safety requirements were addressed in systems using flammable or toxic refrigerants – particularly information about the design features employed and estimates of the costs associated with them. The review panel was aware that costs associated with safety requirements can be determined only when reference is made to a specific safety standard or code.

Some valuable information was identified, mainly in several papers that used residential heat pumps as the test equipment (HVAC1). However, overall the information gathered was incomplete, not relevant, or not verified by other studies. Panel members expressed significant concerns regarding some research methodologies and the arbitrary assignment of priority to various environmental and thermal performance parameters. None of the information in the reviewed papers provided data on the performance of systems optimized for each of the refrigerants they employed. Based on this body of work, the evidence does not show a significant performance advantage for either hydrocarbon or hydrofluorocarbon refrigerants. Further study is recommended in residential and small commercial air-conditioning and refrigeration.

CCU/CRE Group

Experimental Results and Theoretical Investigations with Alternative Refrigerants

Authors: T. Engler, F. Mobner, L.R. Oellrich

Published: 19th International Congress of Refrigeration 1995, Proceedings Vol. IVb

This paper describes a systematic investigation of mixtures containing chlorine-free refrigerants using compressor calorimeters and provides an evaluation of the Total Equivalent Warming Potential (TEWI). In examining the TEWI approach, a number of assumptions have to be made with respect to such issues as refrigerant leakage and refrigerant recovery. The authors did not detail where their values come from, specifically the value of 5% annually for α_L (leakage loss) and 75% for α_R (recycling rate). The authors chose a range of values of "filling ratios" for the refrigerant - the amount of refrigerant charge per unit of cooling capacity. They selected a value of 0.6 kg CO_2/kWh for β, characteristic of Germany, for the energy conversion factor used to determine the amount of greenhouse gases emitted by a utility plant generating the electricity required to operate the equipment in question.

For the purpose of the study, the authors looked at a small commercial refrigeration plant with a nominal refrigeration capacity of 2 kW at -30° C. A theoretical analysis was conducted first using the Berlin-Process-Package with the Peng-Robinson equation of state, followed by a laboratory study. It was assumed in calculating TEWI values that "use is made of the temperature change during phase transition" (temperature glide). The laboratory tests were conducted utilizing a single-stage semihermetic reciprocating compressor with a 22.4 m^3/h swept volume, condenser and evaporator pipe bundles, and two expansion valves (one thermostatic and one manual). The tests were run on a laboratory test rig, not a typical refrigeration system.

The authors report that the filling ratio of the system greatly affects the TEWI values of the halogenated refrigerants and mixtures at the leakage rate assumed. At low filling ratios, the zero global warming potential of hydrocarbons results in no significant reduction in TEWI compared to fluorocarbons because the hydrocarbons exhibit lower COPs.

The authors suggest a change from flooded to dry evaporators with their lower filling ratios to lower the TEWI significantly, However, a robust evaporator design which allows for significant swings in operating conditions is needed to avoid operation at reduced effectiveness under different operating conditions – thus leading to decreased efficiency, higher energy consumption and, ultimately, increased TEWI.

Graphic results of the experiments indicate that R-290 and an R-290/R-600a blend (70%/30% by weight) have the lowest calculated TEWI values by approximately 1,000 kg CO_2 per year lower than the nearest HFC-based blend (R-32/R-125/R-134A), and approximately 1,500 kg CO_2 per year lower than R-22 for the system chosen, running 3000 hours per year. At -10^o C, the TEWI with R-290 is about 40% of that of R-22.

At -10^0 C evaporating temperature, the COP with R-290 is about 3.3 vs 3.1 for R-22, a difference of about 6%. This difference narrows at lower evaporating temperatures. The authors note that "the future reduction of TEWI in refrigeration plants will thus be achieved mainly by plant construction details minimizing the filling ratio, employing the refrigerant with the maximum COP, and, if applicable, by taking advantage of the temperature change during phase transition ("glide") when using mixtures." The authors focused on filling ratio as a major design issue, and did not note the benefits of designing to minimize leakage.

IRHT/CRE Group Report

<u>Refrigerant Use in Europe</u>
Author: Kruse, H.
Published: AHRAE Journal, September 2000

Dr. Kruse's paper, "Refrigerant Use in Europe," identifies various European research projects that were conducted in response to regulations such as the Montreal Protocol, the European Council Directive 3093/94, and the Kyoto Protocol, that call for the phase-out and/or reduction of the use of hydrochloroflurocarbons (HCFCs), hydrofluorocarbons (HFCs), and greenhouse gases. These research projects involved assessing the impacts of various refrigeration systems, based on system and refrigerant type, on the Total Equivalent Warming Impact (TEWI) and theorizing upon, and developing potential refrigeration systems, specifically tested in supermarkets or similar laboratory environments, that efficiently and safely use alternative, non-chlorinated, refrigerants such as ammonia and CO_2. Although none of the research projects were performed in conjunction with the writing of this paper, Dr. Kruse examines the conclusions of these projects to suggest ways to fulfill the requirements of the Kyoto Protocol concerning greenhouse gas emissions.

Dr. Kruse summarizes the results of energy consumption measured in a German Research Center's calorimeter tests of substitutes for R-22 and R-502 under refrigeration conditions varying from -10^o C to -40^o C. Substitutes tested include R-404A, R-407A, R-407B, R-407C, R-507, R-410A, and R-290. Only R-410A and R-290 have energy efficiencies comparable to R-22, whereas the other fluids show a 5% to 15% higher energy consumption. R-410A is advantageous at low evaporation temperatures while R-290 has a small advantage (about 4%) over R-410A in the higher temperature range (-10^o C).

Dr. Kruse recommends tightening refrigerant systems to reduce the leakage of HFC refrigerants. In 1991, new systems consumed one-third of refrigerants used worldwide, while systems requiring after-market service consumed two-thirds of refrigerants. Leakage may have been an important reason for the after-market refrigerant consumption and thus higher greenhouse gas emissions.

For commercial refrigeration as in supermarkets, Dr. Kruse recommends using fluids with very low Global Warming Potentials (GWP). Examples are indirect refrigeration systems that implement a secondary loop of CO_2, or use of CO_2 in direct expansion systems. Ammonia and hydrocarbons can not be used in direct refrigeration systems because of their flammability and toxicity, but can be used in indirect systems. Indirect refrigerant systems have a lower TEWI than direct refrigerant supermarket systems with high leakage rates, however with the use of a secondary loop, require high pumping power.

Referring to a Swedish design of an ammonia system employing CO_2 as the secondary loop coolant, Dr. Kruse concludes that a secondary loop using CO_2, because of its desirable heat transfer characteristics at low temperatures, low viscosity, and high heat of vaporization, can lower the pumping power needed, thus reducing energy consumption compared to conventional single-phase fluids such as calcium chloride brines. A disadvantage to using CO_2 is its high pressure. Dr. Kruse identifies the cost-effectiveness of using an inherently-safe direct expansion CO_2 system.

Dr. Kruse notes that liquid chillers for indirect systems can be made at the manufacturer's site with control of tightness, so the choice of refrigerant between the environmentally or locally dangerous types, i.e., the synthetic and natural fluids respectively, is not important from the aspects of the environmental problems of refrigerant systems. The choice of refrigerant can be made on the basis of costs of the complete system.

<u>Cooling of a Bulk Milk Tank with R-290/R-600A in the Netherlands</u>

Authors: E. Dijkstra, C. Machielsen, D. Menard

Published: Proceedings of the International Conference on Ozone Protection Technologies, 1996

This paper by Dijkstra et al. presents the results of a test in which an existing bulk milk cooling tank (BMT), typically cooled with R-12, R-22, or R-134A refrigerant, was tested with ECOOL-PIB, a hydrocarbon mixture of R-290 and R-600a. The BMT was of a particular design with over 350,000 units sold. The purpose of the test was to determine whether ECOOL-PIB can be used as a ‘drop-in’ substitute, meaning no hardware changes, for tanks typically cooled with the previously mentioned refrigerants. Because the system tested was not optimized for the hydrocarbon refrigerant mixture, it is difficult to generalize the results from this limited field test.

The authors claim similarity in the thermodynamic properties of milk and water, and use water in the experiment in lieu of milk, however data is not presented in the report to support the similarity. The tests, using only one sample tank, were executed in a laboratory environment in which water was cooled from an ambient temperature, 35°C (normal initial temperature of milk extracted from cows and transferred to BMT) to 4°C (normal conservation temperature of milk at farm) and at another test condition, from an ambient temperature, 25°C, to 4°C. Refrigerant phase, mass flow, temperature, and pressure were monitored at various points in the refrigeration cycle, and electric power consumption was determined when both types of refrigerants were used to cool the tanks.

At both test conditions, and without any modifications to the cooling cycle of the system, the authors claim that while maintaining similar lab conditions as those on a real dairy farm, there is a decrease in overall electric consumption of 7.8% at 25° C ambient and 3.9% at 35° C ambient when using ECOOL-PIB in lieu of R-12. However, the tests do not mention whether sunlight could potentially shine on the condenser or storage tanks, affecting the operating efficiencies. The authors do not speak to how the test results varied when ambient temperatures are different. In the cycling tests that determine energy consumption, the stored milk may not cooled to the appropriate temperature prior to the next batch of milk being delivered to the tank, thus unrealistically improving efficiency. While showing that the pressure ratio values indicate no significant change in the functioning of the compressor when cooling with the two different refrigerants or operating the compressor at the two different ambient temperatures, the authors do not speak to the compatibility of the compressor lubricant and ECOOL-PIB.

<u>Experimental Investigation on the Performance of Commercial Freezers Using Refrigerant HC-600a</u>

Authors: R. Peixoto, S. Epof, Diogo Parra
IIF-IIR Commission B1, B2, E1, and E2, Purdue University USA - 2000

This paper presents a comparative study of the performance of a commercial bottle cooler/ice cream freezer cabinet when cooled with R-134a and R-600a. Pull down and energy consumption tests were performed on an R-134a unit and on a prototype model cooled with R-600a. The R-134a and R-600a units were comparable in design with the exception of the compressors used. The R-134a unit implemented a 95 W compressor, and while the authors identify that another compressor was used in the R-600a unit, the size of this compressor and its efficiency compared to the R-134a compressor is not listed. The R-134a unit was charged with 120 grams of refrigerant, and the R-600a unit was charged with 60 grams of refrigerant. The tests were performed in a monitored climate chamber, with controlled humidity, temperature, and air velocity. Temperature was monitored within the freezer cabinet and at various points in the refrigeration cycle.

A seven-hour pull down test showed that the R-600a unit, though slightly slower in pull down, was capable of achieving a lower internal temperature by several degrees at the -20^{o} C level than the R-134a unit. The authors planned to explore these results in order to optimize the heat exchangers and capillary tube design.

Energy consumption tests were run with the appliance loaded with test packages. These cycling tests showed that the R-600a unit consumed about 13% less energy than the R-134a unit. The authors conclude, based on the tests, the R-600A prototype "presented a better performance than the similar HFC-134a appliance." These conclusions were drawn from one particular set of tests. The degree of optimization of the system as an R-134a unit and the degree of optimization of the system (other than finding the proper amount of R-600a charge) when it was converted to use the R-600a compressor are not explained in the paper.

Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/Isobutane

Author: G.D. Mathur

Proceedings of the1996 International Conference on Ozone Protection Technologies, Washington, DC, USA 1996. Pages 835-844

This paper presents the results of a theoretical investigation conducted to compare the coefficient of performance (COP) of vapor compression refrigeration systems using various refrigerants. Refrigerants examined are propane (R-290), isobutane (R-600A), a 50/50 mixture (by weight) of R-290 and R-600A, R-12, and R-134A. The COP for each refrigeration system assuming isentropic compression is calculated for a set of operating conditions in which the evaporator temperature is varied, in 20 degree increments, from –40°F to 40°F, and the condenser temperature is varied, in 20 degree increments, from 100°F to 200°F. Dr. Mathur uses ASHRAE published data and the REFPROP computer program (1992 version) to determine the refrigerant properties at each operating condition. He calculates the COP for each cycle by assuming the vapor is saturated at the compressor inlet and no subcooling occurs at the condenser outlet.

His calculations show that the COPs of the hydrocarbons are from 6% to 9% higher than for R-134A under conditions of 20^{o} F evaporator and 120^{o} F condenser temperatures as in an automotive air conditioning system. However, his charts show that the hydrocarbon performance advantage is lost at a higher evaporator temperature of 40^{o} F except for the highest condenser temperature condition, 200^{o} F. Dr. Mathur concludes from his charts that the performance of hydrocarbons is marginally better than R-134a and R-12 under some operating conditions.

Dr. Mathur acknowledges that in real world applications, performance is affected by other parameters not taken into account in these ideal simulations. Examples include the presence of lubricant, moisture, efficiency of the compressor which may differ for each refrigerant, superheat at the compressor inlet, subcooling at the condenser outlet, and heat transfer characteristics of each refrigerant. The author states that the theoretical COPs he has determined are higher than those that could be derived through actual testing.

HVAC1 Report

Experimental Evaluation of Five Refrigerants as Replacements for R-22

Author: Joshua P. Meyer, Ph.D., P.E.
ASHRAE Transactions 2000, V.106, Pt. 2

The paper by Meyer presents a comparative analysis of the performance and environmental effects of R-134a, R-290, R-404A, R-407C, R-410A, and R-22 in a vapor compression experimental setup. The evaporator and condenser in the system were tube-in-tube heat exchangers with water in counterflow to the refrigerant. The compressor was a hermetic reciprocating compressor with a nominal cooling capacity of 4 kW. The measurements were taken over a wide range of evaporating temperatures from -20° C to 20° C at a condensing temperature of 55° C on the same experimental setup. The research technique and data are sound, following standard test practices for laboratory systems.

The paper concludes that "not one of the refrigerants outperformed all of the other refrigerants on all the criteria considered." The COP was highest in the experimental system for R-134a, although the differences in cooling COP between R-134a, R-290, and R-22 are on average less than 2%. It is followed by R-404A and R-410A which have cooling COPs approximately 12% lower than that of R-134a for this high condensing temperature condition. The cooling COP of R-407C is the lowest, on average 17% below that of R-134a. The paper further concludes that R-290 is marginally better than the alternatives due to its low global warming potential (GWP) and zero ozone depletion potential (ODP).

The paper did not address the cost of modifying equipment to meet safety standards for a highly flammable refrigerant, comparing only the costs of the refrigerants themselves. In addition, the article does not address the equipment sizing and charging issues, although stating that R-410A has a significantly higher volumetric cooling capacity than the alternatives.

Screening of Single Component Fluids for Compression Heat Pump Applications

Authors: T. Engler, L.R. Oellrich, G. Venkatarathnam, S. Srinivasa Murthy
20th International Congress of Refrigeration, IIR/IIF, Sydney, 1999

The paper by Engler et al. utilizes computer modeling methods to compare several single-component refrigerant alternatives for heating-only heat pump applications. Performance was evaluated at a range of -10° C to +60° C evaporator temperature and +50° C to +140° C condenser temperature. The COP, pressure ratio, and volumetric capacity for natural fluids (HC) are compared with HFC, HFE, and other organic fluids. No HCFCs were included in the evaluations. The calculations were made using the computer simulation package K-BP[2] using cubic equations of state (Peng-Robinson). The results are limited to R-12, R-11, and R-114 replacements.

The paper presents a wealth of comparisons for more than 80 single-component refrigerants and potential candidates.

The comparisons in the paper are based upon a 60^o K temperature lift in the heat pump for all fluids. At a condensing temperature level of 50^o C, the R-12 substitutes with highest COP performance are ammonia, R-600a, R-245cb, R-134a, R-290, R-227ea, and R-1270. The COPs for all are within 5% of that of R-12 except for R-600a which is slightly higher.

At a condensing temperature of 70^o C, the best COPs compared to R-11 were shown by R-152 followed by the amines, particularly ethyl amine, and R-143. All showed COPs within 5%, but lower than that of R-11.

At a condensing temperature of 100^o C, alternatives to R-114 included R-600, neo-pentane, HFC-245fa, HFC-254cb, and the HFC-236xx series. All of these candidates had COPs within 5% of that of R-114, but the first four were higher. Cyclo-butane has a COP nearly 8% higher than R-114 but yields very high compressor discharge temperatures.

The paper does not comment on the total equivalent warming impact (TEWI) of the alternatives but does provide a basic summary of all hydrocarbon refrigerants available.

<u>Evaluation of Flammable Refrigerants for Use in a Water-to-Water Residential Heat Pump</u>
Authors: D.K. Choi, P.A. Domanski, D.A. Didion
IIF-IIR Commissions B1, B2, E1 and E2 – Aarhus, Denmark -1996

The paper by Choi et al. compares the performance of R-22 to R-290 and flammable zeotropic mixtures R-290/600a and R-32/R152a in a test apparatus that simulates a residential ground-source water-to-water heat pump designed to keep the flammable refrigerants outdoors. Tube-in-tube heat exchangers were used for the evaporator and condenser to allow for counter-flow heat transfer between the refrigerant and indoor-loop and outdoor-loop heat transfer fluids. Counter-flow in the heat exchangers was used in order to effectively employ zeotropic mixtures with temperature glide, attempting to match the glide with the temperature rise of the water through the heat exchanger. The secondary heat transfer fluid was a 60/40 mixture of water and ethylene glycol. Some tests employed a liquid-line/suction-line heat exchanger. The test equipment included a reciprocating compressor and a manually adjustable expansion device. An explosion proof motor drove the compressor with a variable frequency drive to control the compressor speed.

Performance characteristics of the hydrocarbon refrigerants in the water-to-water system were compared to the performance of R-22 in a system with a direct-expansion air-side indoor heat exchanger and the outdoor water loop. This is called the “reference system”.

One set of tests were conducted at a fixed compressor speed, simulating a "drop-in" refrigerant change in an existing system. In the cooling mode, the COPs of the hydrocarbon systems were more than 10% lower than that of the reference system. In the heating mode, all COPs were essentially the same. The R-290/600a system exhibited large capacity reductions (50% in cooling and 30% in heating) compared to the reference system. The authors noted that this drop-in comparison method does not provide a fair comparison of the fluids' potentials since different refrigerant/secondary fluid temperature differences and secondary fluid heat transfer coefficients blur the merits due to the refrigerants' properties.

Other tests were run with constant heating or cooling capacity ("constant heat flux") for all refrigerants. In the cooling mode at a capacity of 2 kW, COPs of all fluids were below the reference system (21% for R-290, 27% for R-290/600a, and 16% for R-32/152a). In the heating mode at a capacity of 1.7 kW, the COPs were more uniform (1%-3% below the reference system for R-290 and R-32/152a) except for R-290/600a which was 10% below the reference COP. The addition of a suction line heat exchanger had an important effect on the heating mode tests, allowing R-290 to exceed the reference COP by 3% and bringing R-290/600a up to 3% below the reference COP.

The good performance of R-32/152a in the constant capacity tests was stated by the authors to be due to good glide matching in the heat exchangers and it excellent thermodynamic and transport properties.

Analysis of the test data and comparison with previous analytical modeling led the authors to conclude that the poor test performance of R-290/600a was handicapped in the constant capacity comparisons. The test COP with R-290/600a was 11% lower than the analytical model indicated it should be. This mixture required a higher compressor speed and was subject to higher pressure drops in a number of components in the system. The authors believed that the performance or R-290/600a would be significantly better in a system with compressor and heat exchangers optimized for this mixture.

The authors note "the study demonstrates the need for both simulations and laboratory methods in evaluating alternative refrigerants" to provide a balanced comparison since it is unlikely that a single laboratory apparatus could fairly compare the performance potentials of different fluids.

A Study of a Water-to-Water Heat Pump Using Flammable Refrigerants

Authors: W. V. Payne, P. A. Domanski, J. Muller
IIR Commission B2 Report, Oslo, Norway - 1998

The paper by Payne et al. compares the performance of R-22 to R-290 and flammable zeotropic mixtures R-32/R-290 and R-32/R152a in a test apparatus that simulates a residential ground-source water-to-water heat pump designed to keep the flammable refrigerants outdoors. Brazed plate heat exchangers were used for the evaporator and condenser to allow for counter-flow heat transfer between the refrigerant and indoor-loop and outdoor-loop heat transfer fluids.

Counter-flow in the heat exchangers was used in order to effectively employ zeotropic mixtures with temperature glide, attempting to match the glide with the temperature rise of the water through the heat exchanger. The performance of the system was characterized by the coefficient of performance (COP) at different compressor speeds and the capacity of the indoor air-side heat exchanger. The test equipment included a reciprocating compressor, manually adjustable expansion device, and an accumulator. An explosion proof motor drove the compressor with a variable frequency drive to control the compressor speed.

The goal of the study was to compare COPs of different refrigerants at the same duty which, in this case, meant the same air-side capacity (same heat exchanger heat flux). At a cooling capacity of 8.5 kW, the COP with R-22 was 0.79. The COP with R-290 was 0.81, R-32/290 was 0.87, and R-32/152a was 0.81.At a heating capacity of 6.5 kW, the COP with R-22 was 0.95. The COP with R-290 was 1.01, R-32/290 was 0.95, and R-32/152a was 0.93. These figures should be compared to the performance of the system operating with R-22 in a water-to-air direct expansion heat pump. In the cooling mode the COP of the best hydrocarbon refrigerant, R32/290, was 13% lower than the COP of the R-22 water-to-air system. In the heating mode, the COP of the best refrigerant, R-290, was within 1% of the water-to-air system. The COP of the R-32/290 mixture probably could be made to exceed that of R-22 by 5% if the mass flows of the secondary heat transfer fluid were optimized for the heating mode.

The results presented do not include the COP penalty associated with the pump for the secondary heat transfer fluid, a 70/30 (mass) mixture of water and ethylene glycol. The percent degradation of COP for the hydrocarbon systems due to pumping was estimated at 5.5%.

Theoretical Analysis of Hydrocarbon Refrigerant Mixtures as a Replacement for HCFC-22 for Residential Uses

Authors: S. Chen, J.F. Judge, E.A. Groll, R. Radermacher
Proceedings of the 194 International Refrigeration Conference at Perdue, Perdue University, West Lafayette, IN, USA, 1994. Pages 225-230

The paper by Chen et al. investigates the feasibility of hydrocarbon refrigerant mixtures as replacements for R-22 in residential air-conditioning and heat pump systems using computer modeling methods. The COP and the seasonal performance factor (SPF) were calculated for R-290 and mixtures of R-290/R-600, R-290/R-600a, and R-290/isopentane. The simulation results were compared to results for R-22, R-410A, and R-407C. The simulations were run using a steady state UA model called HPCYCLE and refrigerant properties from the NIST software REFPROP version 4.0. For the simulation the authors assumed that all heat exchangers are counterflow and that part-load performance is identical to steady-state performance.

The paper concludes that the mixture of R-290 and R-600 (25%/75%) showed the best performance, with “a higher COP than either one of the currently proposed HFC replacement refrigerants" at 4.27, compared to the COP of 3.66 achieved with R-22, 3.44 with R-410A, and 3.86 with R-407C. The paper points out "the disadvantage of R-290/R-600 is the low volumetric capacity which results in a larger, more expensive compressor."

Comparison of R-410A, R407C, and Propane in Heat Pump Applications
Author: H. Konig
IlF-IIR Commission E2, with E1 and B2 – Linz, Austria – 1997

The primary focus of the paper by Konig is a comparison of R-410A and a number of HFC mixtures as possible replacements for R-22. The author includes a theoretical analysis of R-22, R-290, R-407C, and R-410A, comparing COPs for a heat pump cycle with an evaporating temperature of –5^{o} C, superheat of 7^{o} C, and a condensing temperature of 40^{o} C. The COP for R-290 and R-407C was found to be 2% less than that with R-22, while R-410A was 4% lower than R-22. The heating capacity of the four refrigerants ranges from 100% for R-22 (the baseline) to 102% for R-410A, although the analysis assumes "a fixed heating effect of 1 kW" for all refrigerants.

HVAC2 Report

Comparative Assessment of CO_2 for Window Air Conditioners
Authors: S. Devotta, A.S. Padalkar, S.N. Joshi, N.N. Swant, and N.K. Sane
IlF-IIR Commission B1, B2, E1, and E2, Purdue University USA - 2000

The paper by Devotta et al. presents a comparative assessment of different refrigerants such as R-134a, R-290, R-407C, R-410A and CO_2 for use in window air-conditioners. The assessment is based on predicted values of compressor pressure ratio, coefficient of performance, compressor power, and specific compressor displacement. These values are generated by utilizing a theoretical thermodynamic cycle analysis using EES (Engineering Equation Solver) software (F-Chart Software, 1996) and REFPROP (NIST, 1996). The analysis cycle parameters were 7.2 ^{o}C evaporating temperature and a condensing temperature of 44^{o} C, with a superheat of 5^{o} C and 2^{o} C of liquid subcooling. The compression process was taken to be isentropic. The authors' results show that there is no alternative clearly superior to R-22 when considering performance and system cost. The COP for R-134a and R-407C were the greatest of the alternative refrigerants analyzed at 6.31 and 6.25 respectively, compared to the 6.29 COP achieved with R-22. The COP for R-290 was 6.21. However, the author comments that system cost with R-134a will be increased due to the increase in compressor size required to achieve the cooling capacity.

The COP of CO_2 was very low compared with R-22 since the condensing temperature of 44 ^{o}C is above the critical temperature of CO_2. The author goes on to point out that R-134A and R-407C have the disadvantage of high GWP while "R-290 offers comparable characteristics like COP, specific compressor displacement, and pressure ratio with R-22" without the high GWP. The safety against flammability will limit its use in high charge systems".

Practical Application of Hydrocarbon Refrigerants: Production Costs and Operational Performance

Author: D. Colbourne

20th International Congress of Refrigeration, IIR/IIF, Sydney, 1999

The paper by Colbourne describes the safety conversions and necessary air conditioning system changes when the existing system fluorocarbon refrigerants were replaced with a flammable blend of R-290/R-170. Application safety, associated costs, and performance issues are also discussed. The safety requirements necessary to conform to British Standard BS4434: 1995, 'Safety and environmental aspects in the design, construction and installation of refrigerating appliances and systems' are listed. These requirements include modifications to electrical components, minimization of leakage, and elimination of refrigerant/air accumulation.

Colbourne details the results of comparative performance tests using a chiller, split air-conditioner, and an air handling unit using HCFC, HFC blend, and HC blend. The author states "Following safety conversions and any necessary system changes such as lubricant and expansion valve setting, each piece of equipment was tested under typical operating conditions".

Identical chillers were tested using R-407C and R-290/R-170. The two chillers were installed on a bank rooftop and monitored during the months of July and August, 1998 with "each control leading during one of the months". Capacity was based on water flow rate and system power consumption was time averaged for each chiller. The COP for R-290/R-170 was reported to be 19% higher than for R-407C. This is said to be due to a 2.3% increase in capacity and 14% decrease in power for the HC unit.

Three refrigerants, R-22, R-290, and R-290/R-170 were tested in a split air-conditioner "under a number of ambient conditions" from 25^{o} C to 45^{o} C. Compared with R-22, R-290 gave equal capacity at low ambient temperatures, rising to an increase of 5% at the higher temperature. COP was up to 3% below that of R-22. R-290/R-170 exhibited negligible capacity increase but was reported to provide up to an 11% increase in COP over R-22.

Initial data at 'standard conditions' for a packaged air handling unit show an increase of 8% in COP for R-290/R-170 blend when compared with R-407C. However, the COP calculation for the R-290/R-170 system did not take into account the additional power needed to run a secondary heat transfer loop required for the flammable refrigerant. The COP was actually slightly higher (3.17 vs. 3.15) for R-407C when the pumping power of the secondary loop is factored in.

In all three case studies the author refers to unpublished data obtained though private communications. Thus, it is difficult to know whether these results would be duplicated by other tests and other laboratories.

<u>Ecological and Energetical Aspects of Changing-Over Refrigerant Equipment of Joint-Stock Company "NORD" to Alternative Refrigerants</u>

Authors: Zhidkov, V. V., Zhelezny, V. P., Butner, A. G.

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Zhidkov et al. presented a methodology to evaluate alternative refrigerants in household appliances such as domestic refrigerators manufactured by NORD. The methodology takes into account parameters such as energy consumption of the appliance, energy required to manufacture new components, and Total Equivalent Warming Impact (TEWI). The authors calculated parameters for a number of refrigerants including R-134a, R-600a, R-290/R-600a, R-152a/R-600a, R-134a/R-152a, and R-401A. The authors reported that R-600a has a favorable COP when compared with R-12 (5% higher for a $-23^{o}/40^{o}$ C cycle and 8% higher for a $-15^{o}/55^{o}$ cycle) but requires a "significant increase of the compressor volume and hence its metal consumption." The authors did not consider R-600A a viable replacement using the modified TEWI comparison because of additional manufacturing costs that would be incurred in order to make the equipment safer.

The authors presented data, previously published in Russian, from drop-in tests using a Russian domestic refrigerator and recommend the R-134a/R-152a blend (80%/20%) as the best choice for household refrigerators since the blend is non flammable, a near-azeotrope, and has cooling properties very close to R-12. Tested in one refrigerator model, the R-134a/R-152a mixture had 1-2% higher COP than with R-134a alone. Drop-in tests in another refrigerator model showed the R-134a/R-152a mixture outperformed R-134a but had an 18% capacity shortfall and a 5% lower COP than R-12.

The TEWI calculation methods in this paper are instructive, and the concept of life cycle evaluation is not found in most other papers. Although this paper focuses on domestic appliances, these features are beneficial to those studying HVACR applications as well.

HVAC3 Report

<u>Assessment of Propane in North American Residential Air Conditioning</u>

Authors: F.J.Keller, L.Sullivan, H.Liang

Proceedings, 1996 International Refrigeration Conference at Purdue University, USA

The paper details a computer model evaluation of unitary split systems with a capacity of 3 tons utilizing alternative refrigerants. The systems modeled used refrigerants R-22, R-410A, R-290 with safety measures, R-290 with flame suppressant R-227EA, and R-290 with a secondary heat transfer loop. Three different propane systems were compared to a base system with R-22 and a zero-ozone-depletion refrigerant system with R-410A to analyze the performance and environmental impact within the North American region. Of the three R-290 systems, the version with safety features had the best performance and the lowest Total Equivalent Warming Impact (TEWI). The authors stated that the safety features would require a 30 percent increase in the system cost based on information described below.

The authors point out that adding the same cost to the highest efficiency R-410A system would result in an even more efficient R-410A system that would have a lower TEWI than the R-290 system with safety features. The paper concludes that R-290 does not provide the optimum environmental solution for unitary split systems in the North American market. The authors recommended more experimental work for further evaluation.

The SEER for the baseline R-22 system for the analysis was not stated in the paper. The SEER for the R-290 system with safety features was predicted to be 2% higher than for R-22. The R-290/227ea system had an SEER 8% lower than for R-22, and the R-290 secondary heat transfer loop had an SEER 16% lower than for R-22. The R-410A system was predicted to have an SEER 7% higher than for R-22.

Overall, the comparison methodologies exemplify a reasonable approach for comparing split systems with different refrigerants because the tradeoffs of performance, safety, and cost are present. The criterion of "TEWI reduction per unit of cost" appears to provide a solid basis for comparison. However, the paper does not provide enough information about the computer model (presumably a proprietary program) to allow the reader to evaluate the accuracy of the results nor to expand the analysis to systems operating in other regions of the country or at different design levels of performance. For example, a description of the inputs to the computer model was not provided, (e.g., refrigerant pressure drop effects, method by which the compressor efficiency was modeled to allow for the effects of changing refrigerants, baseline efficiency of the R-22 compressor, superheat, and subcooling.) In addition, the referenced Treadwell paper does not include discussion of the sources of the extra 30 percent cost to add safety features for use with propane. Anecdotal information indicates that a study at UL commissioned by Lennox reported a 30 percent cost figure at 1994 cost levels for design changes to make propane systems safe for residential applications.

The source and accuracy of the refrigerant properties used in the computer model should be reviewed for accuracy by 2002 standards. There are questions about how the compressor size was adjusted to maintain the same capacity while using the same heat exchangers. This is a rather coarse approximation as it omits the differences in heat transfer coefficients among the various refrigerants. If the R-290/R-227EA blend is a zeotrope, it would require larger heat exchangers at a higher cost. Documentation was omitted on key assumptions made by the authors, such as the basis for the assumed leakage rates of 4 percent used in the TEWI calculation and the improved efficiency of the R-410A system with a 30 percent cost adder such that the indirect CO_2 contribution would be decreased more than 2000 kg (6%) for a system under 13 SEER.

Evaluation of Propane as an Alternative to HCFC-22 in Residential Applications

Authors: J.D. Douglas, E.A. Groll, J.E. Braun, D.R. Tree
Proceedings, 1996 International Refrigeration Conference at Purdue University, USA

The paper by Douglas et al. on window air conditioners chronicles the development of a simple analytical method to compare the minimum manufacturing cost for a simplified system with a specified capacity and efficiency when alternate refrigerants are used. An R-22 system was compared to systems with propane having added safety features and propane mixed with a non-flammable refrigerant (R-227ea). Assuming an additional cost of 30 percent to make systems with flammable refrigerants safe, flammable refrigerants are not cost competitive with non-flammable refrigerants. However, the additional flammable refrigerant cost of 30 percent is only an approximate number with an unknown degree of uncertainty. The risks due to the use of a flammable refrigerant are very dependent upon application.

The authors used a "cost-based evaluation method", the analytical model ACOPT, developed at the Ray W. Herrick Laboratories at Purdue University to evaluate the optimal cost ratio using the R-22 system as the baseline. The method evaluates refrigerants based on the "manufacturing cost of systems which are optimally designed to meet specified capacity and efficiency constraints." The optimal design of a typical window unit was too complex for this study, so the problem was simplified by modeling a water-to-water heat pump configuration having counterflow heat exchangers.

The optimal cost ratio of pure propane is about 5 percent less than that of R-22. The authors conclude that it is currently unlikely that safety features could be installed for less than that amount. Optimal cost ratios were calculated also for an R-32/134a mixture, R-407C and other mixing ratios of the same components, R-410A, and R-134a. R-410A and R-407C had costs within 1% of the baseline system while R-134a was about 3% higher than R-22.

Due to the many simplifying assumptions made to develop the results in this paper, the results are interesting in a qualitative sense only. The acceptability of mixing R-227ea with a hydrocarbon to create a non-flammable mixture is questionable as R-227ea has a very high GWP when compared with other hydrofluorocarbons that are currently being reviewed for possible phase-out. In addition, it is a rough approximation to assume, as the authors do, that the cost of the heat exchanger scales linearly with the weight of the tubing. To optimize for different refrigerants, fins-per-inch may change (e.g., for the R-227ea mixture) and tube diameter may change (e.g., for R-410A). The cost impact of return bends and assembly labor/overhead may not scale with tube length that was used to calculate tube weight. It was not stated if the heat exchanger modeling accounted for the possibility that the propane/R-227ea mixture has a temperature-glide, or accounted for the reduced heat transfer coefficients of zeotropes. Information was not provided regarding the accuracy, source, or other details of the thermal property information for the four mixtures used to model the system performance.

<u>Thermodynamik, Energy-Efficiency, and Economic Criteria for Evaluation of Alternative Refrigerants for Heat Pumps</u>

Authors: G. Kazachki, C. Gage

IIF-IIR Commission E2, with E1 and B2 – Linz, Austria –1997/4

The paper by Kazachki and Gage evaluates refrigerant alternatives based on the cost of heat-pump heat. The cost of the heat serves as a way to take into account both of the key refrigerant characteristics - specific volumetric capacity (SVC), and the coefficient of performance (COP). SVC determines the size of the equipment and COP reflects the energy efficiency of the system. The refrigerants considered in the analysis are R-32, R-410A, R-125, R-507, R-407A, R-143A, R-407B, R-407C, R-407E, R-290, R-407D, R-134a, R-270, R-12, R-152a, and an unnamed blend of R-32/R-134a (22%/78% by weight).

The authors evaluated the "cost of heat" produced by a heat pump by deriving equations relating the cost of heat to the COP and volumetric capacity of the refrigerants being considered, as well as utilizing the volumetric and isentropic efficiencies of the compressor. The operating conditions assumed for the analyses were 7^{o} C evaporating, 18^{o} C entering the compressor, 50^{o} C or 65^{o} C condensing, and 7^{o} C subcooling.

The authors conclude that the heat-cost method supplemented by design criteria is a viable tool for refrigerant evaluation and screening. The authors also state that R-410A was identified as a replacement for R-22 for temperatures up to 55° C with a cost relative to R-22 of about 0.9 at 50^{o} C condensing. R-32 had a similarly low cost ratio but is flammable. Refrigerants R-407E and R-407C had a cost ratio of about 1.02 and could be used for temperatures up to 75° C. R-290 had a cost ratio of about 1.06 without considering extra costs associated with flammable refrigerant applications. R-134a had a cost ratio of about 1.18 because of its low volumetric capacity which significantly increased capital costs based on the calculation methods employed.

The results are of qualitative value only due to the limitations from the simplifying assumptions. For example, capital cost was varied only with compressor displacement. Capital cost was amortized over a 30,000 hour operating life. The costs of other components such as coils, controls, assembly labor and overhead, compressor motor and fan motors, depend on system capacity more than compressor displacement. Electricity cost was specified at $.10/kWh. There was no inclusion of estimated costs associated with safeguarding systems with flammable refrigerants.

Hydro Carbon Refrigerants Performance in an Air Conditioning Unit
Authors: M. Hammad, R. Tarawnah
IIF-IIR Commission B1, B2, E1, and E2, Purdue University, USA - 2000

The paper by Hammad and Tarawnah presents the results of drop-in testing of mixtures of propane and butane in a 2.5 ton capacity split air conditioning unit designed to operate with R-22. The COP of the original R-22 system at a standard rating condition is not given. The unit had a 2-cylinder reciprocating compressor. The percentage of propane mixed with butane was varied in the tests.

All experiments were carried out at a constant entering evaporator temperature of 1^{o} C but the method of maintaining the same conditions was not noted. The expansion device was not described although the type affects the performance measurements reported. The test results indicate that the hydrocarbon mixtures produce COP values varying between about 2.0 to 4.0, with the highest COP value produced with 100 percent propane. The COP with R-22 was below 3.0. However, it is hard to know what to make of the results because the test conditions that generated the data are unclear. For example, the paper does not show how the cooling capacity of the system was affected when R-22 was replaced by the different hydrocarbon mixtures.

The nature of the test setup did not permit heat balance checks to verify the accuracy of the test results. It is likely that the instrumentation and data reduction resulted in significant levels of uncertainty in the final results. The figures in the paper are not completely explained. It is not clear what parameters were being held constant, nor at what levels, for the data displayed.

The authors selected the 90 percent propane mixture as the most suitable alternative refrigerant to R-22, based on both a higher COP value and equal saturated pressure match.

The authors do not indicate any modifications or adjustments to the original equipment and reported no problems were encountered with the compressor. Following approximately 1000 hours of equipment operation with the same lubricating oil, no lubricating oil degradation could be detected.

Propane as a Refrigerant for Heat Pump Applications in Southern Europe
Author: Jaun de Blas
IEA Heat Pump Centre Newsletter. Volume 18 - No.4/2000

This article reports on the development of an improved air-to-water heat pump developed for the southern European market in a two-year project. Universities, manufacturers, and government laboratories collaborated on the project which was funded in part by the European Commission.

The starting point was an existing commercially-available R-22 heat pump with a heating capacity of 21.1 kW (COP of 2.8) and cooling capacity of 19.2 kW (COP of 2.5). The goal of the project was to develop a propane heat pump with 10% higher energy efficiency and 40% reduction in the amount of refrigerant charge.

The original heat pump was tested carefully in a climate chamber. A number of compressors were tested separately on a compressor test bench. A mathematical model was developed for each of the main heat pump components and for the complete system. The model was applied to optimize the component selection for the new propane heat pump. The first prototype for the propane heat pump incorporated many changes including improved heat exchangers. This prototype achieved the 10% increase in energy efficiency compared to the original R-22 heat pump.

A final prototype was built using special heat exchangers, a scroll compressor, and a standard expansion valve. This prototype operated with a propane charge 66% less than the R-22 charge in the original R-22 heat pump. The final propane heat pump had a cooling capacity within +/- 5% of the R22 unit but the compressor energy consumption was 9% to 13% lower. The increase in cooling COP was 10 - 19%. In heating mode, the COP was 15% to 20% higher than for the R-22 unit because capacity increased 11-23% with propane and the new design features.

The project met the design goals for the new propane heat pump. However, the project did not address the extent to which performance of a heat pump employing R-22 or HFC refrigerants could be improved if the same optimization techniques were applied.

Domestic Refrigerators

Hydrocarbons as Substitutes for Halogenated Refrigerants in Refrigerating Systems.
Authors: R. Camporese, S. Bobbo, F. Rozza
Proceedings of the 194 International Refrigeration Conference at Perdue, Perdue University, West Lafayette, IN, USA, 1994. Pages 231-236

This paper examines the use of an R-290/600a (50/50) zeotropic mixture and R-600a by itself as alternatives to R-12 for domestic refrigerators. A theoretical comparison of performance characteristics of the refrigerants was conducted for a cycle with a 55^o C condensing temperature and two different evaporating temperatures, -23.3^o C and –30^o C. The subcooled liquid temperature from the condenser and the superheated vapor temperature into the compressor both were 32^o C. The R-290/600a mixture has a temperature glide of about 7^o C in the condenser and about 6^o C in the evaporator. Refrigerant properties for the analyses were determined using REFPROP 4.0. The evaporating pressure, condensing pressure, volumetric capacity, and COP were predicted to be nearly identical for this hydrocarbon mixture and R-12. Compressor discharge temperatures were about 20^o C lower for the mixture.

The theoretical analysis indicated that the COP of the cycle would be 2.79 for R-600a vs. 2.70 for R-12 at the -23.3^o C evaporating condition. At the -30^o C evaporating condition, the COP was predicted to be 2.53 for R-600a and 2.36 for R-12. However, R-600a requires a compressor displacement nearly twice that of R-12, and has a subatmospheric evaporator pressure which causes concerns about noncondensables leaking into the system. Long-term tests of refrigerators operating with R-600a were recommended by the authors in order to assess the risks of problems with noncondensables.

The authors tested several hermetic compressors on calorimeter test stands at the same conditions used for the theoretical cycle analyses. The compressor test results supported the conclusions of the theoretical analyses for the two hydrocarbon-based refrigerants. Compressor tests were run also with R-134a, and an EER reduction of around 10% at -23.3^o C and 6% at -30^o C relative to R-12 was observed. The theoretical analyses predicted that R-134a would have slightly higher COPs (and EERs) than R-12. The reason for the discrepancy between the predictions and test results for R-134a is not clear.

The authors conclude that isobutane/propane can be considered a replacement for R-12 due to the similar capacity of the compressor that is needed. In the US, however, the hydrocarbon mixture would be replacing R-134A in today's refrigerator designs, which would require a different lubricant to accommodate the hydrocarbon refrigerant. The heat exchangers probably have to be redesigned to accommodate the temperature glide of the mixture.

Design Modifications Needed in the Compressor for Using Alternate Refrigerants to R-12

Authors: T. P. Ashok Babu, C. P. Arora

IIF-IIR Commissions B1, B2, E1, and E2, New Delhi, India - 1998

This paper compares refrigerants R-290, R-22, R-134a, R-152a, R-600a, and R-290/600a (50/50) to R-12 based on theoretical evaluations of system performance in domestic refrigerators. The cycle used in the evaluations is a standard refrigerator cycle with 55^o C condensing temperature, 32^o C into the expansion device and into the compressor inlet, and a -25^o C evaporating temperature.

The authors included allowances for the variation in compressor volumetric efficiency for the different refrigerants. Assumed pressure drops in the compressor valves also were adjusted for each refrigerant. The pressure drops in the condenser and evaporator were assumed to be the same for all refrigerants. For each refrigerant, the authors sought to predict the required displacement volume for an 88 W capacity, the starting torque, the motor winding temperature, and the rating of the motor.

If alternative refrigerants are used with the same compressor as for R-12, the calculations predict a COP of 1.91 for R-134a, 1.75 for R-152a, 1.85 for R-600a, and 1.70 for R-290/600a vs. 1.84 for R-12.

Tests were conducted with all refrigerants except R-290 and R-22 which were not considered attractive for domestic refrigerators. The test procedures and test setup are not described. Only motor winding temperature data from the tests and a few qualitative observations are presented in the paper.

The authors conclude that there are very few drop-in replacements for the current CFC and HCFC refrigerants. In Section 8, a paragraph states: "If the oil used is mineral oil with all refrigerants, then the oil effects on starting torque also remain." This statement is inconsistent with common practice, where mineral oil is not used with HFCs, and conflicts with the actual test data where synthetic oils were used for R134a and R152a. The conclusions section should have noted that, based on the test data, R-134A is the most efficient R-12 replacement refrigerant.

<u>Three Years Experience with Hydrocarbon Technology in Domestic Refrigeration</u>
Author: Udo G. Wenning
International Conference on Ozone Protection Technologies, Oct 21-23,1996

Wenning provides observations on the use of hydrocarbons as a replacement for CFCs in domestic refrigerators by a German refrigerator manufacturer. The author discusses the hydrocarbon foaming technologies and hydrocarbon refrigerants as they are used in domestic refrigerator manufacturing. The author's data shows that cyclopentane, the hydrocarbon blowing agent generally used, has a thermal conductivity ~5% worse then R-141b. According to the author, theoretical calculations show that the COP for R-600a is 5% higher than that of R-134a. The author added a statistical evaluation of "R-134a and R-600a refrigerators of different sizes with identical refrigeration circuit and cabinets but with adjusted compressors." The author's data showed R-600a refrigerators with 4-5% lower energy consumption than R-134a refrigerators, but there was no measurable difference between freezers utilizing these refrigerants. It is not clear how the compressors were "adjusted" and whether the cooling capacity of the systems was affected – which would change power consumption.

Insulation Selection and Effects

<u>Influence of Blowing Agent Selection and Foam Aging on Energy Consumption and TEWI of Refrigerators</u>
Authors: W. Deeg, M. Hayslett, K. Hortin, R. Johnson
The Earth Technologies Forum Conference Proceedings, Washington, DC, USA 1998. Pages 270-278

This paper documents the results of aged refrigerator energy tests and cabinet reverse heat leak tests to determine the influence of blowing agents and foam aging on the energy consumption and Total Environmental Warming Impact (TEWI) of refrigerators insulated with polyurethane foam blown with various agents. The purpose of the experiment was to find a suitable replacement for R-141b, a commonly used blowing agent for refrigerators and freezers. The blowing agents tested were R-141b, R-245fa, R-236ea, cyclopentane, and R-365mfc. Two companies carried out the experimentation by acquiring refrigerators that had been foamed with various refrigerants and performing 38-month studies to determine the effect aging has on a product's energy consumption. The rate of cabinet heat leakage for refrigerators blown with various foam types was monitored over a 27-month period. TEWI calculations were performed for refrigerators blown with HFC-245fa and cyclopentane, with a set of calculations taking into account product aging and another set of calculations disregarding product aging.

The authors conclude "R-245fa provides superior long-term aging performance relative to that of foam blown with R-141b," whereas blowing agents such as cyclopentane, R-134a, and R-365mfc aged more rapidly. Data indicates that the polyurethane foam's insulating performance degrades due to product aging which results in product energy consumption increasing 2-5% per year. In terms of energy consumption and aging rate, the authors conclude that R-245fa seems to be the best replacement for R-141b. The TEWI of refrigerators foamed with R-245fa are calculated to be less than those foamed with c-pentane.

The test methodology may have affected the test results, perhaps reducing their accuracy. The refrigerators used in this study were stored non-operating in a warehouse at an unknown ambient temperature, potentially affecting the foam aging, and hence energy consumption rate. Neither the aged refrigerator energy tests nor the reverse heat leak tests simulate actual customer usage. Very little information is presented regarding the controlled test conditions and setup. Individual data sets were not shown for both participating companies, and therefore the repeatability claimed by the authors was not demonstrated. Several assumptions are made in performing the TEWI calculations and the authors do not give reasons for these assumptions. Not having a basis for these assumptions, the relative difference between TEWIs established for products foamed with R-245fa and those foamed with c-pentane were not confirmed or placed in perspective by absolute TEWI values for each product.

Conclusions

These survey findings are similar to those reached by Arthur D. Little, Inc. in their report "Assessment of the Commercial Implications of ASHRAE A3 Flammable Refrigerants in Air Conditioning and Refrigeration Systems" prepared for the Air Conditioning and Refrigeration Technology Institute, May 3, 2001. The following is taken from this report's Executive Summary.

> "The second phase of our study involved an evaluation of A3 refrigerant performance, benefits, risks, and costs. An extensive literature review suggested that A3 refrigerants such as propane offer similar or slightly superior efficiency to R-22 in air conditioning systems. Unfortunately, few rigorous "apples to apples" comparisons of fluorocarbon and hydrocarbon systems have been reported publicly. However, the data that is available suggests that efficiency increases of about 2-5% were common in drop-in or "soft-optimized" system tests. In a system specially optimized for hydrocarbons, one might be able to achieve efficiency increases somewhat greater than 5% by using propane rather than R-22, assuming that no other fire safety measures need to be taken which reduce efficiency. For example, if a secondary loop is required in order to keep all the refrigerant outdoors for safety reasons, the hydrocarbon system would suffer a large reduction in efficiency and increase in cost compared to the R-22 system. It should also be recognized that modest efficiency increases can also be achieved without much difficulty, using HFC refrigerants, so the real dilemma faced by industry is to determine how the costs of safety improvements required for hydrocarbon systems compare with those necessary to raise efficiency of fluorocarbon systems in other ways.
>
> In commercial refrigeration, a literature review suggests that the use of hydrocarbon refrigerants could offer efficiency increases close to 10% compared to fluorocarbons. Once again, such improvements need to be analyzed in the context of cost-efficiency tradeoffs which account for safety improvements needed in hydrocarbon systems.
>
> The most important benefit of hydrocarbon refrigerants is their near zero direct global warming impact. However, to put the potential warming effect of refrigerant emissions into context, it is important to consider both direct and indirect effects, using concepts such as Total Equivalent Warming Impact (TEWI) of Life Cycle Climate Performance (LCCP). Using TEWI or LCCP as metrics, hydrocarbons would offer a modest improvement over fluorocarbon systems in most air conditioning systems, assuming that leak rates were maintained at low levels using the best available technology. Even with leak rates that were 2-3 times the best practice, the direct warming impact would be less than 15% of the total warming impact. In traditional direct expansion supermarket systems where large leakage losses are typical, the direct warming impact of the

refrigerant is large, so use of hydrocarbons could, in theory, decrease total warming impact substantially. However, the safety issues associated with distributing hundreds of kilograms of flammable refrigerant throughout the store would likely require that a secondary loop be used, in which case the direct warming impact of the refrigerant would be minimal regardless of which refrigerant was used.

Very little information has been published that attempts to estimate the actual cost savings that can be obtained from the lower cost hydrocarbons, compatibility with low cost mineral oil, and superior transport properties. For equivalent performance, aside from the costs associated with fire safety design requirements, it is likely that the cost of a hydrocarbon system would be similar or slightly lower than that of a fluorocarbon system. The critical unknown is the cost of design changes needed to ensure an acceptable safety level, which could drive costs up substantially.

Because the publicly available information about hydrocarbon-based air conditioning and commercial refrigeration systems is so fragmented, there appear to be several fertile areas for further research that could help enhance the understanding of the benefits and drawbacks of such systems. One critical area for further work is a rigorous analysis of the cost impact of achieving acceptable safety levels when hydrocarbon refrigerants are used. Since there is no consensus on what safety level is acceptable. It might be appropriate to use the requirements of IEC standard 60335-2-40 as the basis for such as cost study. Another area for further work would be rigorous "apples to apples" comparative testing of fluorocarbons and hydrocarbons in a variety of real world equipment. This might resolve the differences in performance reported by various researchers who tested fluorocarbon and hydrocarbon systems. Finally, the key driver for considering hydrocarbon refrigerants is their potential for reducing the global warming impact of air conditioning and refrigeration systems. The key area of uncertainty in evaluating global warming impact of such systems is the actual field leakage rate. Therefore, a large-scale field survey of actual current practices and refrigerant losses would help provide a sound basis for making accurate judgments about the true global warming impact of various refrigerant options."

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