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Assessment of Life Cycle Climate Performance (LCCP) Tools for HVACR Applications with the Latest Next Generation Refrigerant Technology

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ABSTRACT

Societal demands to control climate change are driving the development of many Life Cycle Climate Performance (LCCP) tools to understand how to minimize the total environmental impacts of HVACR products. The LCCP models can be extremely detailed, accounting for all CO_2 contributions from CO_2 emissions from the use of energy (indirect) and CO_2 equivalent emissions from other operations (direct CO_{2eq}) from "cradle" (refrigerant and product manufacturing), through use (including servicing and potential leak rates by type of product), to "grave" (recycling and disposal) for a product. LCCP tools have been developed for a number of HVACR product segments and continue to grow in number (GREEN-MAC-LCCP; ORNL Supermarket LCCP; AHRI HP LCCP; Zhang, et al., 2011). However, there are few studies into understanding how the results from these various tools compare to each other against the latest available lower Global Warming Potential (GWP) next generation refrigerant technology.

Because global regulatory discussions currently are focusing on reducing direct GWP contributions of refrigerants and for the most part are ignoring their impact on indirect GWP contributions as refrigerant choices are considered, there is potential for regulators to reduce the available refrigerant choices that would allow manufacturers all the tools available to minimize the total environmental impact (lowest LCCP) through maximum efficiency and maintaining the maximum sustainability and safety for consumers. This paper will provide LCCP assessments with the latest available refrigerant technology for stationary refrigeration, transport refrigeration, unitary air conditioning, and chiller air conditioning product segments. This paper will suggest GWP limits for refrigerants by application, since direct GWP limits may need to be defined by application type based on the available refrigerant technology to minimize environmental impacts.

1. INTRODUCTION

Selecting the right refrigerant for the right application at the right time to meet uncertain regulatory policies in order to restrict and lower the direct GWP of fluorocarbons (F-gases) would seem to be an insurmountable challenge. When considering refrigerant alternatives for future policy makers, the public and manufacturers must select refrigerants with the best balance of:

- Safety for consumers and for service technicians (flammability, toxicity and high pressures)
- Indirect environmental concerns (reduced CO_2 emission through highest energy efficiency)
- Direct environmental concerns
    - de minimis[3] ozone depletion potential (ODP)

[3] *De minimis* is a Latin phrase denoting an item is so minor as to merit disregarding its importance. The author prefers this term to describe impacts of concerns rather than "zero" or "low" since these terms can be general in nature.

- de minimis direct GWP
- lowest emissions from leaks or emissions from foams used in the construction of products
- de minimis secondary environmental impacts like on water or local air pollution

• Product sustainability (long operational life, maximizing recyclable content and minimizing material use)

A manufacturer is further challenged to select a refrigerant that meets these requirements with various design technology options to provide the most competitive product for the application. Figure 1 depicts a number of the most important design requirements that are considered when selecting a refrigerant for use in a specific application.

Figure 1: Challenge: Balancing Environmental, Safety, Sustainability with Design Requirements

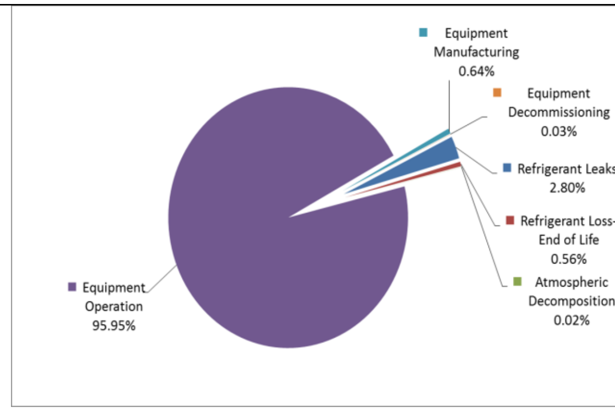

Figure 2: Example of LCCP analysis output from AHRI LCCP heat pump tool. SEER 13 heat pump, cooling only operation utilizing DR5 in Houston

LCCP is a methodology that is used to assess the total GWP impacts (both direct and indirect emissions), expressed as carbon dioxide equivalent mass (kg-CO_{2eq}), over the lifetime of a particular refrigerant, piece of equipment or system. LCCP can be expressed as a summation of all sources of direct and indirect source emissions. Figure 2 is an example of a LCCP breakdown that was obtained from the AHRI heat pump LCCP tool (Zhang, et al., 2011). DR5 was used as the refrigerant to demonstrate the contribution of atmospheric decomposition products of the refrigerant. These calculations can be very simple, looking at only one or a few contributing factors, or they can be very complete, even detailing the type of connection hoses and the leak rates associated with each type of hose technology as in the GREEN-MAC-LCCP assessment tool. In general, there are three major contributing sources of LCCP emissions in HVACR systems, the energy consumption of a system, the GWP of the refrigerant, and the refrigerant leakage potential. A certain level of granularity is sometimes necessary in the energy consumption contributions since the refrigerant efficiency, in combination with the refrigeration or air-conditioning cycle chosen, can act together as major indirect contributors.

LCCP representations are increasingly being used to demonstrate or compare the environmental impact of various refrigerants and cycle technologies for HVACR systems. However, to date the LCCP analyses conducted have been few, limited in scope, and fragmented investigations that are refrigerant specific or application/system specific (Riva, et al., 2006; Minor and Spatz, 2008; Pham and Rajendran, 2012; Kontomaris, et al., 2012). There are few LCCP studies that do a complete job of covering a whole product area in detail comparing various refrigerants and technologies to achieve the lowest environmental impact. Fricke et al. (2013) reported an analysis for supermarket refrigeration systems. They found that refrigerant employed in combination with various refrigeration cycles and leak rates needed to be balanced to capture the lowest LCCP. The paper did not investigate general GWP limits for R404A replacements. One point of interest from the study is that once the GWP of the refrigerant was less than 675 to 1400, depending on the cycle employed, direct emissions from the refrigerant fell below 10% of the total emissions.

At present, most LCCP methodologies and calculations have not been standardized and so can lead to differing results and conclusions. The UNEP RTOC recognized this need and made an attempt to create a chapter dedicated to LCCP and its methodologies in 2012 and IIR has a Working Party to formalize LCCP calculations.

2. DISCUSSION OF LCCP INVESTIGATIONS

Discussions of LCCP investigations conducted by the authors and by others are summarized here for stationary and transport refrigeration products and for stationary unitary air conditioners and chillers. Table 1 provides a summary of the GWPs and composition of refrigerants mentioned in this paper. GWP[1] is the currently accepted GWP for the refrigerants while GWP[2] is the likely future GWP refrigerant values based on a recent study by Hodneberg, et al., 2013. A number of GWP values for refrigerants have dropped significantly, especially R125 (3500 to 3170) and R134a (1430 to 1300). Also note that a number of the unsaturated hydrofluorocarbons may have GWPs of 1 or less, which are comparable to the GWP of CO_2. The cities and climate zones used for the transport refrigeration, unitary and chiller LCCP studies are Houston (2A, Hot Humid), Phoenix (2B, Hot Dry), Chicago (5A, Cool Humid), Denver (5B, cool dry) which covered a wide spectrum of climate performance impacts (ASHRAE Standard 169 2010). Fricke, et al. (2013) conducted LCCP studies across seven climate zones that included a number of the above climate zones.

Table 1: Refrigerant descriptions

Refrigerant	GWP[4]	GWP[5]	ASHRAE Safety Class[3]	Composition	% by Weight
R404A	3900	3943	A1	125/143a/134a	44/52/5
R407A	2100	1920	A1	R32/R125/R134a	20/40/40
R407F	1820	1670	A1	R32/R125/R134a	30/30/40
DR34	2140	1940	Likely A1	R32/R125/R1234yf	11/59/30
DR33	1410	1280	Likely A1	R32/R125/R134a/R1234yf	24/25/26/25
DR7	244	244	Likely A2L	R32/R1234yf	64/36
R134a	1430	1300	A1	n/a	n/a
XP10	630	572	Likely A1	R1234yf/R134a	56/44
R1234yf	4	<1	A2L	n/a	n/a
R1234ze(E)	6	<1	A2L	n/a	n/a
R410A	2080	1920	A1	R32/R125	50/50
R32	675	677	A2L	n/a	n/a
DR5	490	491	Likely A2L	R32/R1234yf	72.5/27.5
L20	331	333	Likely A2L	R32/R152a/R1234ze(E)	45/20/35
R123	77	79	B1	n/a	n/a
R1233zd(E)	5	1	A1	n/a	n/a

[4](IPCC, 2007), [5](Hodneberg, 2013) and (ASHRAE Standard 34,2013)

2.1 Stationary Supermarket Refrigeration

One of the complicating factors in understanding the LCCP impacts of a product is whether the particular application area has minimum efficiency standards in place. Minimum efficiency standards allow for the largest portion of the LCCP impacts to be fixed and which enables an easier comparison of various other tradeoffs. At this time, large stationary refrigeration systems do not have minimum efficiency standards and test methods in place to allow for this simplification of the LCCP analyses. From a product application standpoint, the lack of efficiency standards also leads to a large variation in the type of products available to a consumer even though those products may not be comparable in energy efficiency. Fricke, et al. (2013) demonstrated this wide variability of technology options and their various contributions to LCCP emissions as summarized in Figure 3 and Figure 4.

Depending on how the data is portrayed, a regulator could get many different impressions from the Fricke study. Looking at it from average LCCP emissions across all climate regions standpoint, Fricke pointed out there were four systems with similarly low LCCP emissions in the Miami, Florida climate zone. These were the transcritical CO_2 booster, R32/CO_2 cascade, R1234yf/CO_2 cascade and R717/CO_2 system (Figure 3). However, if energy efficiency is the focus, the transcritical CO_2 booster system has the poorest energy efficiencies, as much as 15% higher than the best configuration.

It has been the contention of Kujak and Thompson (2013) that some refrigerants and technologies being considered and adopted today, like R744, can meet the lower efficiency standards of certain products or compete within product sectors that have no minimum efficiency standards. However, these refrigerants or technologies will be phased out because of implementation of minimum energy efficiency standards or due to ever increasing product efficiency requirements. Some technologies perform better in colder climatic regions than in warmer climatic regions, but this type of fragmented market approach only drives up prices and complexity to consumers and, in the end, is the least sustainable. Some technologies being offered or considered are at or near their thermodynamic limit while others are still just simple cycles and still have room for incremental efficiency improvements. This paper will extend Fricke's observations to a number of new refrigerant candidates that have been developed for refrigeration products.

A number of new refrigerant blends have been developed that offer other alternatives in addition to the options Fricke investigated. A number of the refrigerants chosen for this study have competing alternatives from other suppliers that are similar. The authors tried to pick a representative number of alternatives for comparison in this study. These refrigerants, in GWP order, were DR34, DR33, XP10 and DR7 in Table 1. DR34 is a near R404A drop-in with comparable capacity, efficiency and compressor discharge temperature. DR33 is an engineered drop-in for R404A with capacity, efficiency and compressor discharge temperatures that require slight system modifications. XP10 has been shown to be a near drop-in for R134a (Schultz and Kujak, 2013a). All three of these candidates are non-flammable and of lower toxicity, ASHRAE Class A1. DR7 is an ASHRAE class A2L engineered drop-in for R404A, which will require some system modifications to accommodate. For this analysis, each candidate was considered a near equivalent from an efficiency and capacity perspective, compared to the refrigerant being replaced.

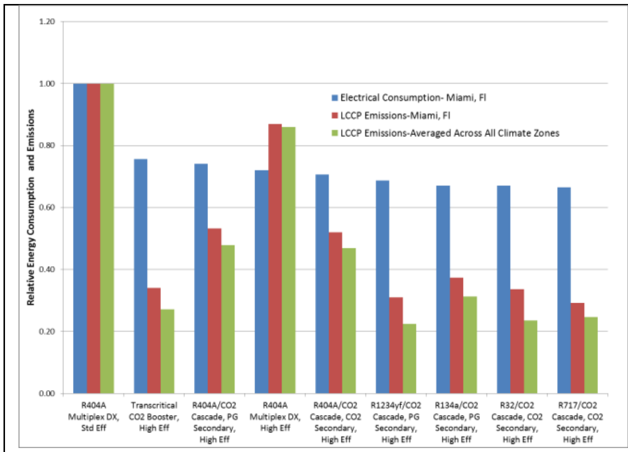

Figure 3: Summary of relative electrical consumption and total LCCP emissions in Miami, Florida and LCCP emissions averaged across all climate zones for various refrigeration products (Fricke et al, 2013)

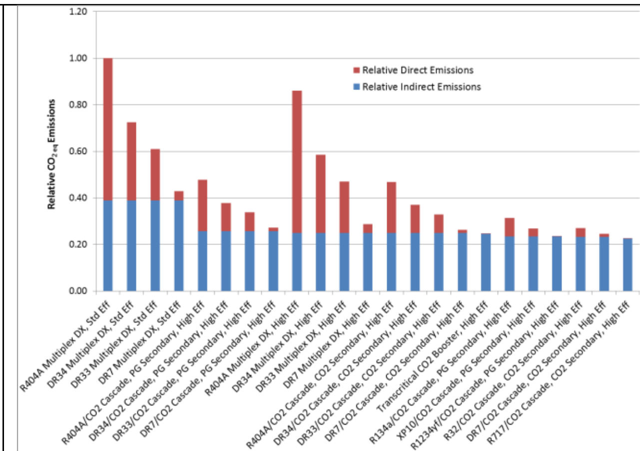

Figure 4: Summary of extending relative indirect and direct emissions for various refrigeration products by (Fricke et al, 2013) to more potential refrigerant options

Including these refrigerants into the Fricke study was accomplished by simply reducing the accumulated direct emissions by the ratio of the refrigerant GWPs. Figure 4 is a summary of the results with the addition of these new candidates. The baseline case (1.0) was a R404A standard efficiency multiplex DX system. The systems are sorted by indirect emissions. The highest energy efficiency allows for the greatest sustainability from the perspective of reduced energy use and operating cost. For the number of systems that have similar energy efficiencies, the direct emissions make the difference.

If the goal was to reduce R404A's direct refrigerant emission impact by 80% and maintain safety, this leaves a number of non-flammable and technologically easy "near drop-in" or "engineered drop-in" solutions. DR34, DR33, R134a and XP10/CO_2 cascade systems meet this requirement. These systems can meet the demands of ever increasing product efficiency while balancing direct refrigerant emissions. In a multiplex direct expansion system, DR7 can deliver a 94% reduction in direct emissions while a DR7/CO_2 cascade can achieve a 98% reduction, although handling a slightly flammable refrigerant in an occupied space needs vetting by the industry.

2.2 Transport Refrigeration

A transport refrigeration LCCP tool was utilized to study the effect of alternative refrigerants on the overall LCCP of a transport application (Nasuta et al., 2014). For this study, five different refrigerants from Table 1 were analyzed using the four locations described earlier for a typical daily distribution scenario. The daily distribution used for the study represented a mix of fresh and frozen products. The transport refrigeration system used represents a typical system for this application which utilized R404A as the baseline refrigerant. The vehicle was a single compartment diesel-driven tractor trailer with swing type doors and exterior dimensions of 16.2 m length, 2.6 m width, and 2.9 m height with a box loss of 95 W/°K new with 5% degradation each year and a life expectancy of 15 years. Refrigerants evaluated were R404A, DR34, DR33, R407A and R407F at a constant 5.9 kg refrigerant charge. Application conditions were short haul daily distribution runs of 5 days/week for 50 weeks with 3 days/week at fresh set point of 1.1°C and 2 days/week at frozen set point of -23.3°C. The haul load was 18,140 kg for both cases. Operation of fresh conditions were a 1-hour pull-down, followed by 14 hours of operation starting at 5 a.m. Operation included six door openings of 30 minutes each. Frozen operational conditions were a 2-hour pull-down with the same hours and door openings as the fresh operational conditions. Start-stop (cycle sentry) with cool restart at 2.8°C and heat restart at 1.9°C.

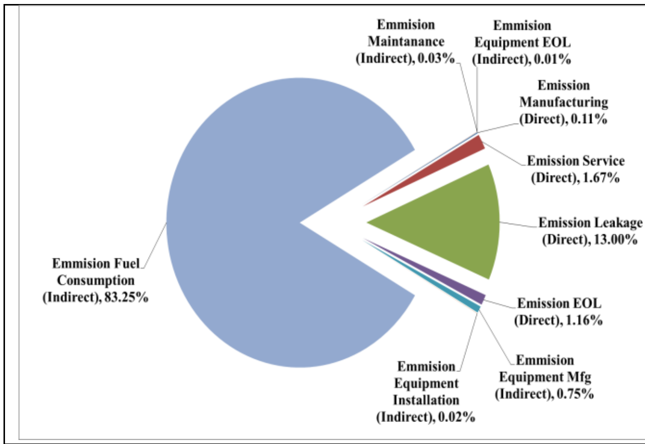

Figure 5: Sample of LCCP breakdown analysis output from transport LCCP tool for Phoenix – R404A

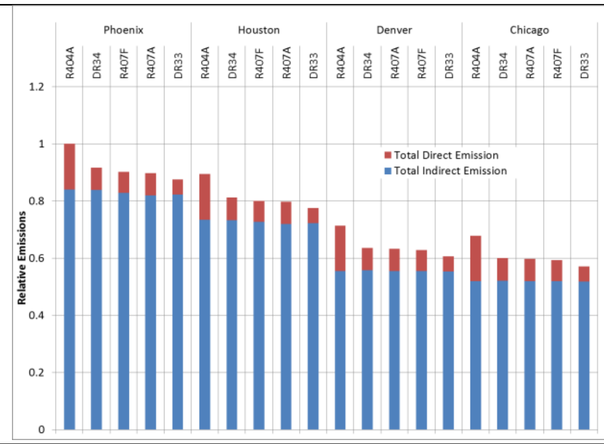

Figure 6: Transport LCCP Analysis

In evaluating the alternative refrigerants, the refrigerant charge to the system was fixed with the baseline charge even though it is known that utilizing an alternative refrigerant might result in a small change in the refrigerant charge level for the system. Accurate testing of the system is performed to determine optimal charge level and it is not expected that the alternative refrigerants would significantly change the overall charge for the system from the baseline R404A charge. Performance and efficiency of the system were calculated assuming use of the alternative refrigerant as a "drop-in"; however, the addition of liquid injection to the suction line was added to the system model for the alternative refrigerants DR33, R407F, and R407A as these refrigerants produced an unacceptable discharge temperature at high ambient temperatures.

In the transport LCCP model, manufacturing and service information are inputs based on known information about the system. However, as concluded before, the major contributing indirect emission source of LCCP emissions is the energy consumption of the system and the refrigerant leakage potential for the system is the largest source of direct emissions (Figure 5). Leakage rates for transport refrigeration application are a topic which needs further study within the industry. Publications from the IPCC (2006) have transport refrigeration application at leakage rates of 15% to 50%. Many in the industry feel this number is too high. The proprietary data that is available has shown that the leakage rate can be even below the minimum 15% stated by IPCC if the transport refrigeration unit is maintained and serviced as specified by the manufacturer. Nevertheless, the leakage rate was fixed at the minimum IPCC leakage rate of 15% for this analysis. Figure 5 shows the sample emission breakdown for the Phoenix location utilizing the baseline R404A refrigerant. The analysis indicated that the energy consumption of the system, which is achieved by burning diesel fuel, represents the most dominant percentage (>80%) of the overall CO_2 emission.

Figure 6 shows the overall comparison of the direct and indirect LCCP relative contribution to the baseline of

Phoenix with R404A for the other refrigerants and locations. While the alternative refrigerants show a reduction in the direct emission due to the lower GWP, the overall indirect emission has remained relatively unchanged as the efficiency of the system is roughly the same.

The LCCP accounts for the time dependent dynamics of the trailer and its load driven by changes in ambient temperature. Figure 7 shows the bin analysis of the return air temperature profile representing the air temperature around the product and not the product temperature itself. The transport distribution application is demanding in that the refrigerated box is subjected to a pull-down temperature from ambient every day and the relatively long (30 minutes) door opening events mean that the system spends a majority of its time recovering from those events. The return air temperature profile shows that the alternative refrigerants can supply essentially equivalent capacity as the baseline R404A system at fresh operating conditions (1.1°C). At the frozen operating conditions, a slight capacity reduction of the system can be seen with the alternative refrigerants showing a lower percentage of time in the -25°C to -20°C bin and a higher percentage of time in the -20°C to -15°C bin when compared to R404A for the temperature set point of -23.3°C.

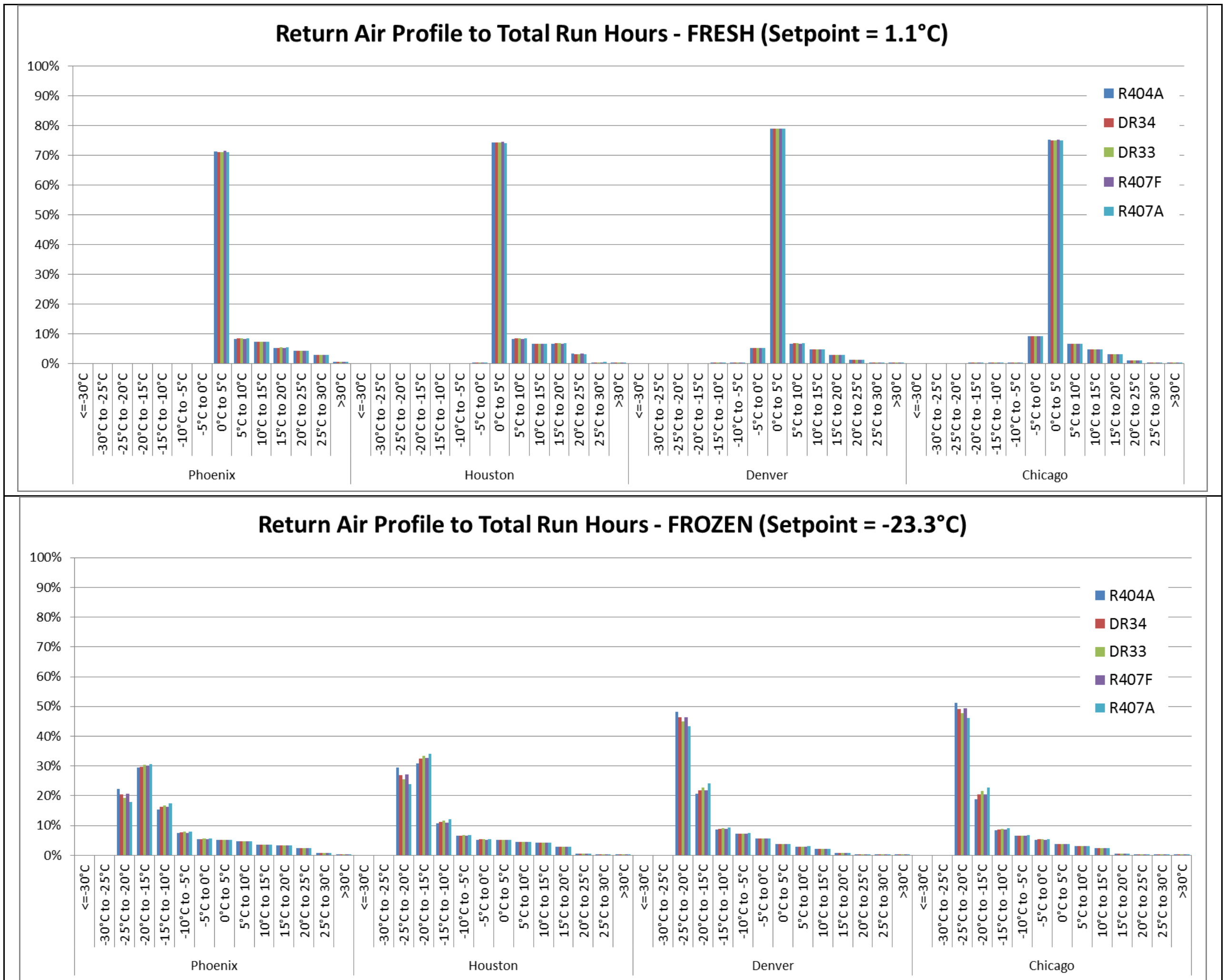

Figure 7: Transport LCCP Return Air Profile

2.3 Stationary Unitary Air Conditioning

AHRI has developed an LCCP tool for residential heat pumps that evaluates direct and indirect GWP contributions throughout the life of a heat pump based on defining both heating and cooling loads for various cities in the United

States (Zhang, et al., 2011). This study investigated four efficiency levels in cooling-only operation for four climate regions of the country with three refrigerants, compared against R410A. It was assumed that all three refrigerant candidates could meet each efficiency level through changes in the product design. This assumption is corroborated by testing conducted by Schultz and Kujak (2013b, 2013c) in which all three candidates achieved similar or better efficiencies than R410A. The amount of each refrigerant used to charge the unit was based on the optimum charges found by Schultz and Kujak. Higher efficiency units generally have larger heat exchangers and therefore require more refrigerant. The relative refrigerant weights used here were 1.00, 1.28, 1.71 and 1.55 for SEER (Seasonal Energy Efficiency Ratio) 13, 15, 18, and 19 units, respectively. The SEER 19 unit achieves its high efficiency through variable speed compression, using smaller heat exchangers. To account for heat exchanger size, relative equipment weights of 1.00, 1.15, 1.30, and 1.23, respectively, were used here. The refrigerant weights used at SEER 13 for R410A, R32, DR5 and L20 were 0.21, 0.17, 0.20 and 0.17 kg of refrigerant per unit of SEER, respectively.

The LCCP simulation results are shown in Figure 8 where the SEER 13 unit in Houston was taken as the reference. Indirect contributions, mostly related to CO_2 produced as the result of electric power consumption, account for a majority of the LCCP emissions for R410A systems. It is not surprising that the reduction in LCCP from increasing SEER level is greater than the increase in LCCP due to the corresponding increase in charge level for all climate zones investigated. Only in Denver did the trade-off between indirect and direct emissions balance. In the end, air conditioning demand varies around the United States and a general reduction in indirect emissions should be considered the true measure of sustainability.

R32 and DR5 are near R410A "drop-in" candidates with GWPs of 675 and 490 GWP respectively. R32 is currently being considered by developing countries as a future replacement for R22. However, DR5 will additionally reduce the direct contribution by roughly another 15%. In addition, L20 is an R22-like candidate being offered at 331 GWP which could further reduce the direct contribution by 50% compared to R32; see Figure 9. A concern with R32 is that it offers only short term GWP reduction and fewer GWP technology options are under development that have better safety and LCCP performance. If governments want to realize the full potential of reducing the GWP of R410A and R22, they would have to force manufacturers to transition to R32 first, and then transition again in the next 5–10 years to another refrigerant with an even lower GWP."

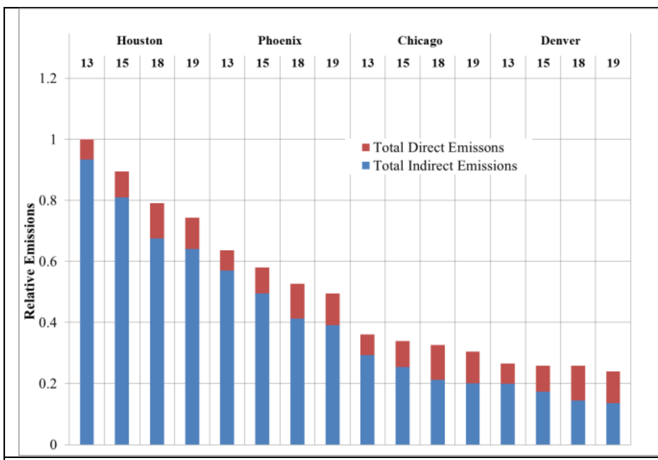

Figure 8: LCCP Analysis–R410A Heat Pump varying location and SEER

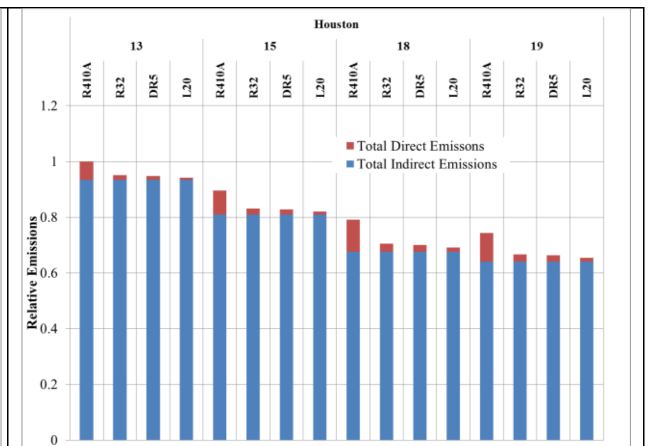

Figure 9: LCCP Analysis–Houston Heat Pump varying SEER and refrigerant

2.4 Chiller Air Conditioning

The energy efficiency of chillers used for air conditioning has been regulated for over 20 years in the United States. Chillers must now meet minimum efficiency standards per ASHRAE 90.1. In the case of large water-cooled centrifugal chillers, both R134a and R123 are used successfully to meet the ever increasing energy efficiency requirements of 90.1. In this study, two 550-ton chillers with 0.59 kW/ton efficiency were used to obtain the amount of electrical energy consumed by an office building in the four climatic zones over 20 years of life expectancy. The amounts of indirect CO_2 emissions were then calculated from the average utility emission rates used in the AHRI LCCP heat pump tool. The energy consumption tool employed was a Trane proprietary model that included chiller, control, cooling tower and water pump models. The tower model assumes variable speed fans. The building loads with this model were generated from the public domain EnergyPlus profiles developed at the Pacific Northwest National Labs (PNNL) for energy analysis work in conjunction-with and with oversight from-ASHRAE, for the development of ASHRAE/IES 90.1-2010. The refrigerant charge was assumed to be 0.9 kg/ton for both refrigerants. Indirect emissions from the energy consumption in Houston, Phoenix, Chicago and Denver were determined to be 18856, 10511, 6463, 4365 kg of CO_2 per ton of cooling. Leak rates of 0.5%, 1%, 5% and 10% were used in this study since these are typical for R134a (2–10%) and R123 (0.5–1%) chillers.

The energy use profiles follow the same pattern obtained in the unitary air conditioning study with Houston being the highest and Denver being the lowest. Using Houston as the baseline, Figure 10 shows the portion of LCCP due to direct refrigerant emissions as a function of refrigerant GWP and leak rate. If all chillers would leak at <1%/year, a refrigerant with a GWP <1500 would be acceptable for the long term. With leaks rates of 5% to 10%, R134a will have a direct contribution of ~6% to 11%, while a R123 would have direct contribution values of <1%. In addition, if you apply the typical leak rates for low pressure chillers which have been documented to be <1%/year, the direct refrigerant emission contributions are <0.1% or basically de minimis.

Today, there are a number of new refrigerant candidates for R134a and R123: R1234yf, R1234ze(E) and R1233zd(E) are potential replacements for R134a and R123 with GWPs of 4,6 and <5 respectively with potential future GWP of 1 or less. GWPs this low have a near zero contribution to the total LCCP given any leak rate. XP10 (non-flammable) has been shown to be a near drop-in for R134a (Schultz and Kujak, 2013a) and would allow for a large reduction in direct effects while maintaining safety for R134a type products. A unique characteristic of these chillers is that they contain large refrigerant charges because they are typically used in large capacity air conditioning applications. A GWP limit for chillers of <600 would allow manufacturers to provide consumers with safe non-flammable solutions while reducing refrigerant direct emissions by greater than 50%.

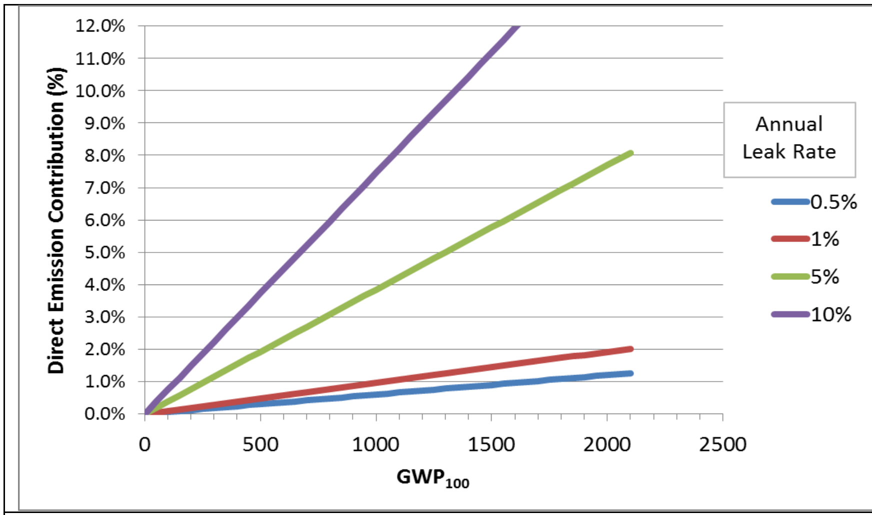

Figure 10: LCCP Analysis – Contribution of direct refrigerant emissions as the result of refrigerant leak rate and refrigerant GWP for a Houston

3. CONCLUSIONS

Stationary Refrigeration

- The lack of minimum energy efficiency standards in large supermarket systems results in a complex LCCP discussion about the impacts of energy efficiency (indirect emissions) versus a refrigerant's direct GWP. Fricke, et al., showed that even among the high efficiency technologies, energy efficiency can vary as much as 15% in a Miami-type climate zone. Minimum efficiency standards would allow this industry to consolidate on the most efficient technology while balancing the direct refrigerant GWP effects.

- Extending Fricke, et al. investigations to more refrigerant options allows for significant reductions in refrigerant direct impacts while maintaining safety and energy efficiency. If the goal was to reduce R404A's direct refrigerant emission impact by 80% and maintain application safety (remaining non-flammable), a number of technologically easy "near drop-in" or "engineered drop-in" solutions are available. DR34, DR33, R134a and XP10/CO_2 cascade systems meet this requirement. If slightly flammable refrigerants were allowed, DR7 can deliver a 94% reduction in direct refrigerant emissions in a multiplex direct expansion system while a DR7/CO_2 cascade can achieve a 98% reduction.

Transport Refrigeration

- For the transport industry, the vast majority of CO_2 emissions from the LCCP study are from the burning of diesel fuel for power which accounts for 80% or more of the total emissions. Similar to the stationary refrigeration findings, standardized efficiency regulations similar to the SEER rating for air conditioning systems would have a far greater impact on lowering overall CO_2 emissions in the transport industry than regulations on refrigerant GWP choice.
- Reducing the direct refrigerant emissions from leak rates for transport refrigeration systems by using electrically driven hermetic compressors should be balanced against the increase in indirect emissions due to the power generation losses, which will increase fuel consumption as well.
- A number of candidates exist that can reduce the direct refrigerant LCCP impacts by >45% in transport refrigeration without compromising safety (flammability). DR34 looks to be a near drop-in and requires minimal redesign of the product and limited losses in efficiency. DR33, R407A and R407F would require significant redesign of the product to accommodate matching capacity, efficiency and compressor discharge temperatures in current R404A based designs.

Unitary Air Conditioning

- The indirect emissions reduction achieved through increasing the SEER of unitary products in increments of 13, 15, 17 and 19 outweighs the impacts of using larger R410A refrigerant charges to achieve those SEER levels in all evaluated climate zones.
- Direct refrigerant emission contributions in unitary products are a small portion of the LCCP emissions for unitary products.
- Reductions in direct refrigerant emissions at the expense of safety should be weighed very carefully, especially in large tonnage, i.e. large refrigerant charge, unitary products or chiller products that use R410A.
- This study indicates that there are lower GWP refrigerant options that have better LCCP potential than R32.

Chillers Air Conditioning

- The direct emissions from the use of energy for chillers follows the same relationship as with unitary air conditioning products with Houston being the highest and Denver being lowest.
- The contribution of refrigerant emissions to the LCCP for chillers can range from <0.1% to <15% depending on the refrigerant used and the chiller technology using Houston, Texas as the baseline.
- A GWP limit for large tonnage chillers of <600 would allow manufacturers to provide consumers with a safe, non-flammable option while reducing refrigerant direct emissions by greater than 50%.
- Reducing leak rates in chillers through either making systems more hermetic or using lower pressure refrigerants can drastically reduce the refrigerant direct emission impacts.

Overall

- LCCP tools are an effective way to evaluate the various tradeoffs of refrigerants and HVACR technologies in various applications types. There is a need to standardize the LCCP methodology to ensure fair and equal comparisons.
- The most sustainable technology is not necessarily the technology with the lowest LCCP emissions. The most sustainable technology should be able to be applied in all climate zones without increasing the use of energy, while balancing the direct impacts of the refrigerant. Energy efficiency is the largest contributor to LCCP emissions in all applications studied. A direct refrigerant emission, as the result of refrigerant's GWP in combination with leaks, is the next biggest LCCP contributor. Further improvements in reducing the GWP of the refrigerant in combination with lower refrigerant leak technologies are possible to reduce the refrigerant direct emissions by >50% in all applications without compromising energy efficiency of various technologies.
- Maintaining safety (flammability and toxicity) are important factors in maintaining the sustainability of all HVACR products. It is possible to reduce the direct refrigerant LCCP impacts by >50% in stationary refrigeration, transport refrigeration and chillers without compromising safety. Some flammability will have to be accepted in reducing the refrigerant impacts in unitary air conditioning products, but the overall impact of using R410A should be reviewed since it is a small portion of all direct refrigerant emissions.

- Caution should be used when averaging LCCP impacts across all climate zones, since the energy efficiency of the refrigerant/equipment combination varies greatly with climate temperatures. For example, the high efficiency energy efficiency variation was 15% presented by Fricke et al for the climate zone containing Miami while the gap closed to <5% in cooler climate zones. This result indicates that the most sustainable technology is not necessarily the technology with the lowest LCCP emissions. The most sustainable technology should be able to be applied in all climate zones without increasing the use of energy while balancing the direct emission impacts of the refrigerant.

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