AHRI'S RESEARCH EFFORTS ON HEAT PUMPS

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Abstract: This paper provides an overview of the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) research activities on heat pumps. During the past few years, AHRI has conducted research projects covering refrigerants testing, risk assessment of mildly flammable refrigerants, and Life Cycle Climate Performance (LCCP) of residential heat pumps. Several low-GWP alternative refrigerants were tested for heat pump applications in the AHRI Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP). The tested refrigerants aimed at replacing R-410A are classified as A2L, according to ASHRAE Standard 34. This paper also summarizes AHRI's study on the risk assessment of residential heat pump systems using A2L flammable refrigerants. The potential ignition risks of R-32, HFO-1234yf, or HFO-1234ze in a ducted residential split heat pump system during operation and servicing are presented. Finally, the development of an AHRI tool to evaluate heat pumps' LCCP is introduced. The tool can be used to evaluate residential heat pumps direct and indirect emissions over their life time when using different refrigerants in different geographical regions.

Key Words: heat pumps, refrigerants, LCCP

1 INTRODUCTION

The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) is a trade association representing manufacturers of HVACR and water heating equipment within the global industry. For more than 25 years, these manufacturers have provided leadership by sponsoring cooperative, pre-competitive research in the HVACR, water heating and building sectors. Over the past few years, AHRI has conducted many heat pump and refrigerant related research projects, including heat pump performance testing using low GWP refrigerants, risk assessment of residential heat pumps using mildly flammable refrigerants, and heat pump life cycle climate performance tool development. These projects were conducted by companies and contractors participating in AHRI's research activities either voluntarily or under AHRI research contracts. This paper is a high level summary of their work. More detailed information is contained in individual reports listed in the reference section of the paper.

2 HEAT PUMP PERFORMANCE FOR LOW-GWP REFRIGERANTS

AHRI is currently leading an industry-wide cooperative research program, the Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP). The program aims at identifying and evaluating promising low-GWP alternative refrigerants for major air conditioning and refrigeration products. The intent of the program is to help the industry select the most promising refrigerants, understand technical challenges and identify the research needed to use these refrigerants. The program does not prioritize these alternatives; rather, it identifies potential replacements for high GWP refrigerants, and presents the performance of these replacements in a consistent and standard manner. Phase I testing of the program was recently completed. Thirty-eight refrigerant candidates were tested by twenty one U.S. and international manufacturers and laboratories.

Eight heat pumps, including air-source and water-source types, were tested with different low-GWP refrigerants. Information on these tested refrigerants and their baseline is summarized in Table 1. The tested heat pumps and types of tests are summarized in Table 2. Two types of testing were conducted: drop-in and soft-optimized. The drop-in tests were conducted with the alternative refrigerants placed in heat pumps using baseline refrigerant R-410A with only minor modifications, if any, made to the equipment (e.g. adjusting charges or TXV settings). The soft-optimized tests were performed by modifying R-410A systems using standard production-line components.

Table 1: Low-GWP Refrigerants Tested for Air-Source Air-Conditioning Application

Development Code	Composition (Mass%)	GWP Value	ASHRAE Classification	Baseline
ARM-70a	R-32/R-134a/R-1234yf (50/10/40)	482	A2L	R-410A (GWP: 2100)
D2Y60	R-32/R-1234yf (40/60)	272	A2L	
DR-5	R-32/R-1234yf (72.5/27.5)	490	A2L	
L-41a	R-32/R-1234yf/R-1234ze(E) (73/15/12)	494	A2L	
L-41b	R-32/R-1234ze(E) (73/27)	494	A2L	
R-32	R-32(100)	675	A2L	
R-1234yf	R-1234yf (100)	4	A2L	
R-32/R-134a	R-32/R-134a (95/5)	713	A2L	
R-32/R-152a	R-32/R-152a(95/5)	647	A2L	

Table 2: Summary of Tested Equipment and Tests Conducted

Unit No.	Equipment Type	Refrigerants Tested	Test type	Test Standard
1	5-ton air source, split system [*Tio et al, 2012*]	R-32/R-152a (95/5)	drop-in	AHRI Standard 210/240
2	3.5-ton air source, split system [*Crawford et al, 2013, Uselton, 2013*]	R-32, R-1234yf	drop-in for R-32, soft-optimization for R-1234yf	
3	3-ton air source, split system [*Li et al, 2013*]	R-32	soft-optimization	
4	3-ton air source, split system [*Alabdulkarem et al, 2013 a, b, and c*]	R-32, D2Y-60, L-41a	drop-in and soft-optimization for D2Y-60 and L-41a	
5	3-ton air source, split system [*Burns et al, 2013*]	R-32, ARM-70a, DR-5, L-41a, L-41b	drop-in	
6	8-ton air-source, VRF [*Tsujii et al, 2013*]	R-32	drop-in	AHRI Standard 1230
7	3-ton water-to water [*Lim et al, 2013*]	R-32, R-32/R-134a (95/5), DR-5	drop-in and soft optimization for DR-5	ISO Standard 13256-2
8	air-to-water [*Besbes et al, 2013*]	ARM-70a, DR-5	drop-in	AHRI Standard 551/591

The tested systems' capacity and coefficient of performance (COP) for alternative refrigerants and baseline R-410A were measured and compared. Using Unit 7 as an example [*Lim et al, 2013*], the unit was a R410A water-to-water heat pump used in hydronic applications. It consists of a single-stage scroll compressor, co-axial heat exchangers, a thermal expansion valve, a reversing valve and a filter drier. The system was tested under the conditions listed in Table 3. R-410A was tested first to establish a baseline. The drop-in tests were conducted at the same test conditions using the same amount of refrigerant charge as for R-410A. No charge optimization was performed during the drop-in tests;

therefore, the unit was not optimized. For the DR-5 soft-optimization test, the original TXV was replaced with an adjustable expansion valve. The expansion valve settings and refrigerant charge were adjusted to obtain improved unit performance and a sufficient amount of superheat. The alternative refrigerants performance relative to R-410A is illustrated in Figure 1 below.

Table 3: Test Conditions per ISO 13256-2

	Water Loop Heat Pump (WLHP)		Ground Water Heat Pump (GWHP)		Ground Loop Heat Pump (GLHP)	
	Cooling	Heating	Cooling	Heating	Cooling	Heating
Liquid entering indoor side heat exchanger (load side[°F]	53.6	104	53.6	104	53.6	104
Liquid entering outdoor side heat exchanger (source side) [°F]	86	68	59	50	77	32
Air surrounding unit, Tdb (°F)	59-86	59-86	59-86	59-86	59-86	59-86

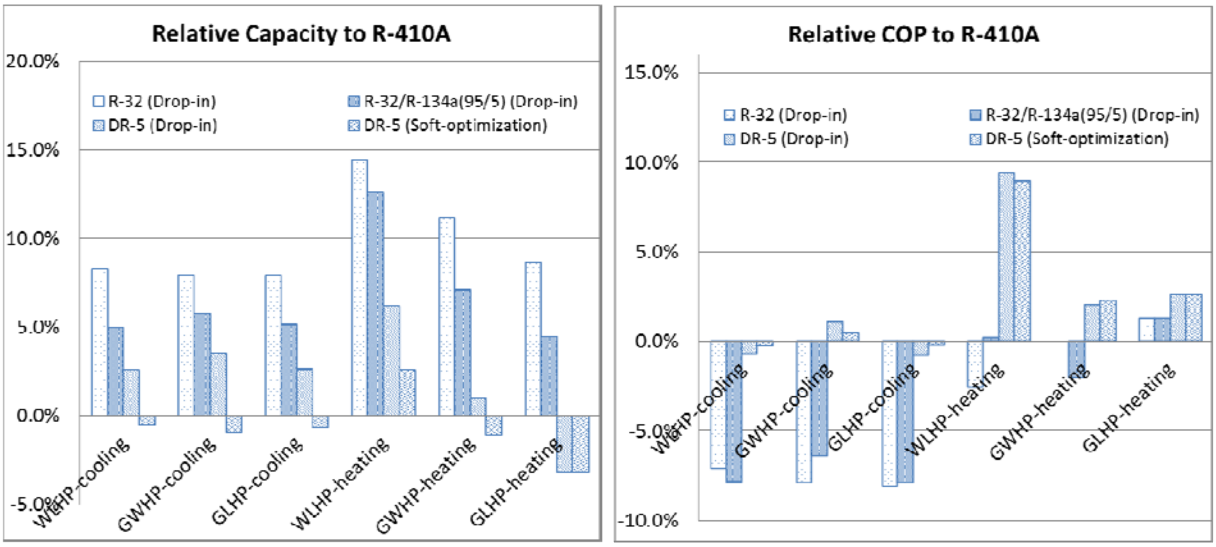

Figure 1: Relative Performance of the Tested Water-to-Water Heat Pump

Test results for all eight heat pumps can be found in the Low-GWP AREP Test Reports listed in the reference section. AHRI has recently launched a second phase of the Low-GWP AREP program, which will include newly developed refrigerant candidates that were not tested in Phase I, as well as refrigerant performance testing under high ambient conditions for various applications.

2 HEAT PUMP RISK ASSESSMENT FOR USING A2L REFRIGERANTS

In the Low-GWP AREP, all tested refrigerant candidates aimed at replacing R-410A in residential heat pump applications are classified or intended to be classified as A2L, according to ASHRAE Standard 34. These refrigerants have low burning velocity and are mildly flammable. AHRI completed a research project employing fault tree analysis (FTA) to assess the ignition risks of using A2L refrigerants in residential heat pump systems [*AHRI Report 8004, 2012, and Lewandowski et al, 2012*]. The scope of the risk assessment was to evaluate the refrigerant ignition risks during the operation and servicing of systems using R-32, R-1234yf or R-1234ze(E). The study consisted of CFD modeling of the refrigerants dispersion patterns for different leak scenarios, actual testing to validate the CFD results, and a fault tree analysis to evaluate the likelihood of refrigerant ignition.

A ducted residential split heat pump system was also studied. The system consisted of an outdoor unit and an air handler located inside one of four possible locations: basement, garage, attic, or utility closet. Seven leak scenarios were evaluated:

1. A leak occurs in the indoor portion (attic, basement, garage, or utility closet) while the system is idle.
2. A leak occurs in the outdoor portion of the unit.
3. A leak occurs while the system is operating (the indoor blower is on).
4. A leak occurs inside the indoor air handler when the system is not running (the blower is off) and prior to it being turned on.
5. A leak occurs while the system is not running, and the refrigerant diffuses back through the return air ductwork (i.e., the refrigerant would leak into the room supplying the return air).
6. A leak occurs due to rupture of refrigerant piping inside a wall.
7. A leak occurs during system repair due to improper practice.

A proprietary CFD tool was employed to simulate the refrigerants dispersion patterns at various locations inside a 200 m^2 two-story house. The virtual residential house had a basement and an attached garage. Figure 2 is an example of CFD results. It illustrates the refrigerant dispersion when the indoor unit is in the utility closet.

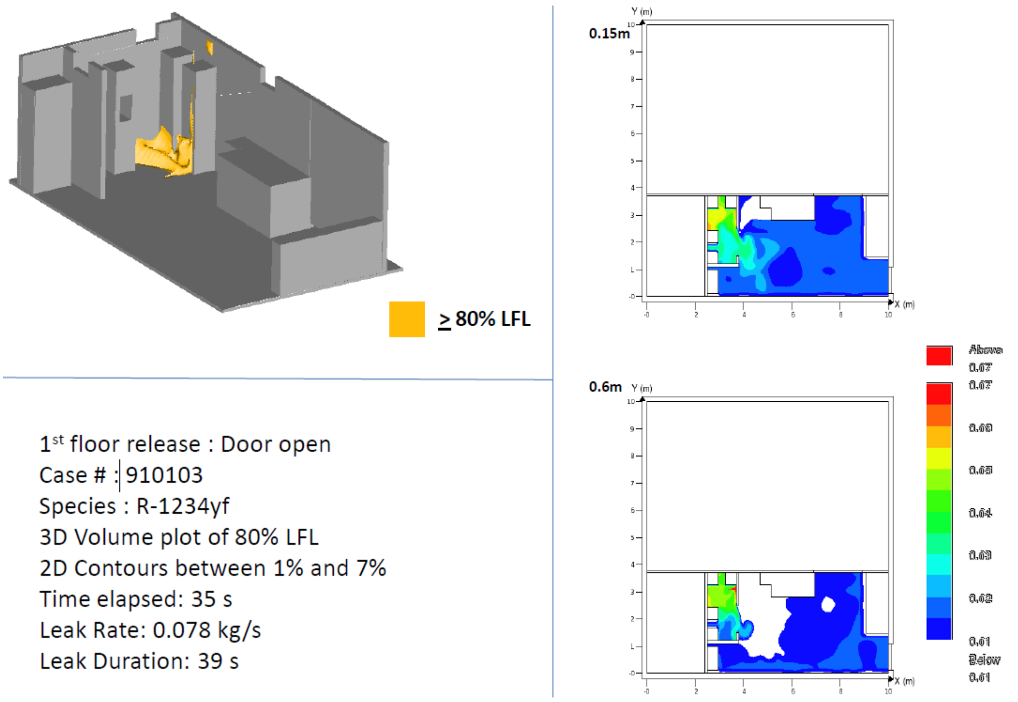

Figure 2: An example of CFD results (utility closet) [AHRI Report 8004, 2012]

Refrigerant R-32 and R-1234ze(E) were actually released to a mock-up residential building built to conduct validation tests. Refrigerant concentrations were measured at up to seven locations in each scenario using total hydrocarbon (THC) analyzers. These sampling locations were chosen with the consideration of possible ignition sources (e.g., water heater heat sources near the floor, wall sockets, counter top appliances, individuals lighting a cigarette). The measured concentrations were compared to the CFD modeling results and the two are in reasonably good agreement.

FTA was used to quantify the potential refrigerant ignition risks. It analyzes the potential combinations of events that might lead to refrigerant ignition, and provides an order of magnitude estimate of the likelihood that refrigerant ignition will occur. One should note that the FTA in this study only evaluated the likelihood of refrigerant ignition and did not determine whether the ignition would actually result in a fire due to the ignition of surrounding materials.

The FTA estimated that the risks of refrigerant ignition due to an accidental leak of R-32, R-1234yf and R-1234ze(E) were 9×10^{-5}, 2×10^{-5} and 2×10^{-5} ignition events per unit per year, respectively. For comparison, the risk of a significant home fire in the United States is 1×10^{-3} per home per year. A sensitivity analysis was also conducted in which certain inputs to the base fault trees were changed to other plausible values and the updated results were then compared to the value determined via the base fault trees. Nine different conditions were evaluated; none of the changes were substantial enough to alter the conclusions of the risk assessment (i.e., none changed the overall risk estimate by more than an order of magnitude and each produced ignition risks that were still far below risks of house fires from other causes).

The risks of refrigerant ignition from this study were compared to risks related to other events, which were derived from data reported in government or scientific publications. These comparison risks are shown in Table 4. The comparison illustrates the significance of individual refrigerant ignition risks in an appropriate context. As the table shows, the risks due to refrigerant release and ignition (almost entirely attributable to a leak in the outdoor condensing unit) are far below risks of other hazards that are commonly accepted by the public.

Table 4: Examples of risks of other hazards [AHRI Report 8004, 2012]

Hazard Description	Risk per Person or Home per Year
Slip/fall injury requiring medical treatment	3×10^{-2}
House fire significant enough to be reportable	3×10^{-3}
Injury in a house fire (reported or not) due to cooking activity	9×10^{-4}
Fatal injury at work (all occupations	4×10^{-5}
Bodily injury during use of fireworks	4×10^{-5}
Heat pump-related refrigerant ignition, R-32	9×10^{-5}
Heat pump-related refrigerant ignition, R-1234ze(E)	2×10^{-5}
Heat pump-related refrigerant ignition, R-1234yf	2×10^{-5}

3 LIFE CYCLE CLIMATE PERFORMANCE (LCCP) TOOL

AHRI's research arm the Air-Conditioning, Heating and Refrigeration Technology Institute (AHRTI) also completed a research project to develop a standardized methodology to calculate the LCCP of residential heat pumps [*AHRTI Report 9003, 2011*]. The project contractor implemented the methodology to a simulation tool, an excel program with VBA subroutines for evaluating the LCCP of residential heat pumps. The tool uses heat pump performance data and a linear relationship to derive annual energy consumption, as well as inputs for refrigerant charge and loss, mass of component materials, and others to calculate all direct and indirect emissions.

The tool considers both direct climate impact of refrigerant emissions and the indirect climate impact due to energy consumptions that are listed below:

- The direct emission due to refrigerant leakage includes the following:
    - Regular and irregular refrigerant leakage from heat pump equipment
    - Refrigerant loss at end of life (EOL)

  Other minor direct emission such as leakage during the manufacturing process is not listed here but it can be taken into account by adjusting the input to the above major refrigerant loss.

- The indirect emission due to energy consumption is an aggregate of:
    - System operating energy
    - Energy consumption for components manufacturing (including refrigerant manufacturing)
    - Energy consumption for components EOL (including refrigerant EOL)

The LCCP of a heat pump is calculated as follows [AHRTI Report 9003, 2011]:

LCCP = Direct emission + Indirect emission
= (Ref. GWP + Adp.GWP) x (annual leakage x years of lifetime + refrigerant loss at EOL) + years of lifetime x Σ (equivalent CO_2 kg/kWh x operating energy $kWh)_{annual}$ + Σ (equivalent CO_2 kg/kg material x mass of materials kg) + Σ (equivalent CO_2 kg/kg material x mass of recycled materials kg)

where:

Ref.GWP: the refrigerant GWP value
Adp.GWP: the GWP of atmospheric degradation product of the refrigerant.
Annual leakage: both regular leakage and irregular leakage (such as leakage due to service) and represents the average over a lifetime of being evaluated.

The heat pump operating energy is calculated based on AHRI Standard 210/240. It applies test data obtained at heat pump rating conditions and a linear relationship to derive energy for each temperature bin to obtain annual energy consumption. The standard outdoor temperature rating conditions are 95^{o}F and 82^{o}F for cooling, and 47^{o}F, 35^{o}F, and 17^{o}F for heating. The flowchart of the LCCP calculation is presented in Figure 3.

Information on many U.S. cities and refrigerants was built into the spreadsheet. Users also have the option to add additional locations and refrigerants as needed. The tool provides a list of cities and their heating region as well as the utility region needed to obtain the CO2 emission for each kWh of electricity produced by the power plant. The user can define the CO2 emission rate as a function of hour in a day and month in a year. The tool's default value of the average CO2 rate for each region is obtained from the NREL technical report NREL/TP-550-38617 [*Deru et al., 2007*]. According to Deru (*Deru et al., 2007*), North America can be divided into five interconnected utility regions: Eastern Interconnection, Western Interconnection, Ercot Interconnection, Alaska, and Hawaii. Within each of these utility regions, the power network is interconnected and one cannot tell which specific location or power plant the electricity comes from, and so the CO2 emission rate for power generation within each utility region is considered to be the same. The average CO2 emission rates within each region are 0.788, 0.594, 0.834, 0.774, and 0.865 kg CO2/kWh, respectively. This method is utilized in current work [*AHRTI Report 9003, 2011*].

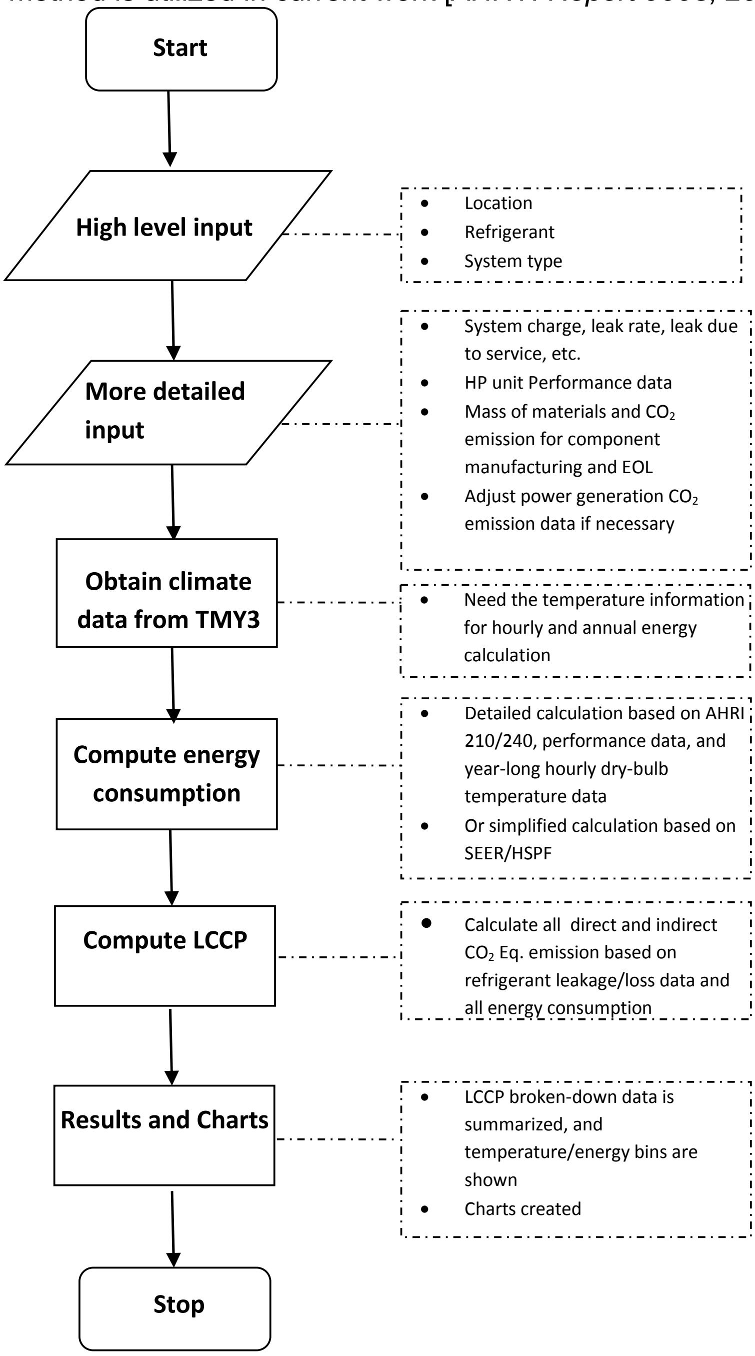

Figure 3: Flow chart for LCCP calculation [AHRTI Report 9003, 2011]

With the tool, one could conduct case studies such as:

1. Comparison of different units with the same refrigerant and location
2. Comparison of same unit at different locations
3. Comparison of units with different refrigerants

Using a heat pump located at different cities as an example, an actual residential heat pump from AHRI certification directory (http://www.ahridirectory.org) was modeled for different locations: Washington D.C., St. Louis, New Orleans, and San Francisco, The heat pump's specifications was listed in Table 5.

Table 5: sample heat pump specifications [AHRTI Report 9003, 2011]

Unit Code	F
Capacity95FHigh, btu/h	36170
EER95F	11.82
Capacity82FHigh, btu/h	38496
EER82F	14.17
Cooling Degrad. Coef.	0.13
SEER	13.26
IndoorCoilAirQty, cfm	1200.00
IndoorCoilAirQty2, cfm	n/a
HighHeat47F, btu/h	34015.00
HighCOP47F	3.56
LowHeat17F, btu/h	20337.00
LowCOP17F	2.40
Heating Degrad. Coef.	0.25
HSPF	8.24
Charge (R410A.):	~ 9 lbs. 12 oz.

The results are shown in Figure 4. St Louis has both higher cooling energy and higher heating energy than the DC area. New Orleans has a much higher cooling energy, but also a much lower heating energy, and the total energy and lifetime emission are lower than DC and St Louis. San Francisco has the lowest CO2 emission.

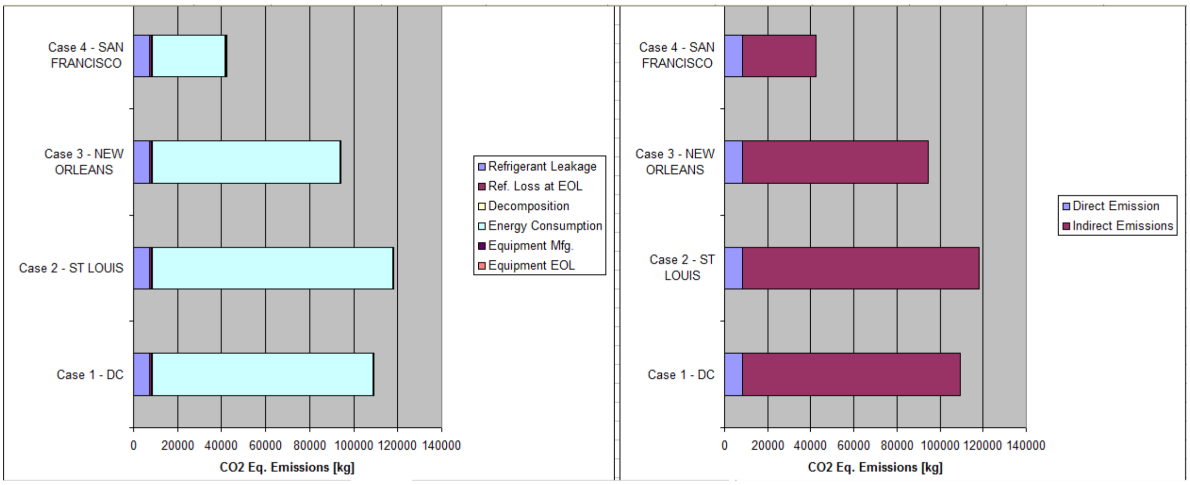

Figure 4: Results for different locations

4 SUMMARY

AHRI research activities on heat pumps evaluated several low-GWP alternative refrigerants, all mildly flammable. Additional research looked at the risk assessment of using mildly flammable refrigerants in residential heat pumps. The potential ignition risks of R-32, HFO-1234yf, or HFO-1234ze in a ducted residential split heat pump system during operation and servicing was investigated. Finally, an AHRI tool to evaluate the heat pumps' LCCP was introduced. The tool can be used to evaluate residential heat pumps' direct and indirect emissions over their life time when using different refrigerants in different regions.

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