Energy and Global Warming Impacts of Next Generation Refrigeration and Air Conditioning Technologies

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ABSTRACT

Significant developments have occurred in hydrofluorocarbon (HFC) and the application of ammonia and hydrocarbons as refrigerant working fluids since the original TEWI (Total Equivalent Warming Impact) report in 1991. System operating and performance data on alternative refrigerants and refrigeration technologies justify and updated evaluation of these new alternative refrigerants and competing technologies in well-characterized applications. Analytical and experimental results are used to show quantitative comparisons between HFCs, HFC blends, hydrocarbons, and ammonia, used as refrigerants.

An objective evaluation is presented for commercial and near commercial non-CFC refrigerants/blowing agents and alternative refrigeration technologies. This information is needed for objective and quantitative decisions on policies addressing greenhouse gas emissions from refrigeration and air conditioning equipment. The evaluation assesses the energy use and global warming impacts of refrigeration and air conditioning technologies that could be commercialized during the phase out of HCFCs. Quantitative comparison TEWI for two application areas are presented. Opportunities for significant reductions in TEWI are seen with currently known refrigerants through improved maintenance and servicing practices and improved product designs.

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Abstract: Significant developments have occurred in hydrofluorocarbon (HFC) and the application of ammonia and hydrocarbons as refrigerant working fluids since the original TEWI (Total Equivalent Warming Impact) report in 1991. System operating and performance data on alternative refrigerants and refrigeration technologies justify an updated evaluation of these new alternative refrigerants and competing technologies in well-characterized applications. Analytical and experimental results are used to show quantitative comparisons between HFCs, HFC blends, hydrocarbons, and ammonia, used as refrigerants.

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Introduction: Alternative refrigerants and blowing agents developed to replace CFCs are now being affected by regulations proposing a phase-out of all chlorine-containing replacements and investigations into how these alternatives affect greenhouse or global warming. A concept which evaluates the Total Equivalent Warming Impact (TEWI) is being used to assess alternative refrigerants and air conditioning technologies because it accounts for the global warming effects of refrigerants and insulating foam blowing agents released to the atmosphere (direct effects) and the CO_2 released as a result of energy used to provide the refrigeration or comfort cooling effect required for the application (indirect effect). TEWI is a more balanced measure of the environmental impact because it is not based solely on the global warming potential (GWP) of the working fluid, and it shows the environmental benefit of efficient technologies which result in less CO_2 emissions to the earth's atmosphere. The goal of TEWI is to minimize total global warming impact of all the gases released to the atmosphere, including the lifetime CO_2 emissions from energy use.

As with any other composite index of performance, calculated values of TEWI are sensitive to an underlying set of key values and assumptions. Most of the criticisms of results presented in the two previous AFEAS TEWI reports focused on the justifications and fairness of these assumptions in the resulting technology comparisons.[1,2] Some assumptions used for TEWI calculations and TEWI calculation results for two of the five refrigeration and air conditioning application areas are summarized on the following pages.

<u>Direct TEWI Contributions:</u> *Direct* global warming results from the atmospheric accumulation of chemicals used a refrigerants and blowing agents. Like CO_2, these absorb and redirect infrared energy normally radiated back out to space from the earth's surface. The Intergovernmental Panel on Climate Change (IPCC) has chosen an index and definition of global warming potential (GWP) which uses the environmental warming effects of one kilogram of CO_2 as a reference gas. This definition is a convenient index to use for TEWI evaluations because it provides a normalizing unit for combining the net environmental effects of a wide variety of chemical compounds with the CO_2 emissions resulting from energy use.

Table 1 is a listing of CFC/HCFC alternative refrigerants and blowing agents with their GWPs, using CO_2 as the reference gas and integration time horizons (ITHs) of 100 and 500 years. Shorter ITHs accentuate the direct TEWI contributions of refrigerants and blowing agents with atmospheric lifetimes shorter than CO_2. Policy makers typically use the 100 year IPCC ITHs because these values balance the long term effect of CO_2 emissions which has a long atmospheric lifetime against the more immediate effects of high release rates of other greenhouse gases.

<u>Indirect TEWI Contributions:</u> In the five application areas covered by the study -- automotive air conditioning, domestic refrigerators, building chillers, unitary heating/air conditioning, and supermarket refrigeration -- indirect TEWI contributions result from gasoline burned to power the automobile, fossil fuels used to generate electricity, and natural gas or petroleum products used as a direct source of heat. Carbon dioxide emission rates have been calculated for these fuels.

- Natural Gas 51.1 g. CO_2/MJ
- #2 Fuel Oil 69.5 g. CO_2/MJ
- Automobile Gasoline 2.32 kg CO_2/liter

Assuming a 90% distribution efficiency for natural gas, which accounts for the energy consumed in pumping losses, increases the CO_2 emission to 56.9 g CO_2/MJ.

Carbon dioxide emission rates from electric power generation are dependent primarily on whether coal, oil, gas, hydro, or nuclear power is used for the power plant. Plant firing efficiency and electric power transportation and distribution losses must also be considered. Published values for CO_2 emission rates for *delivered* electric power are used for TEWI calculations. Wide regional variations are possible depending on the primary source of energy. As shown in Figure 1, variations in the kg $CO_2/kWh_{electricity}$ within the United States range from about 0.49 kg CO_2/kWh for the west and northwest regions where nuclear and hydro power are used, to 0.94 kg CO_2/kWh in the east central U.S. were coal is used for 88 – 90% of the total electrical power generation.

Domestic Refrigerator/Freezers

Direct TEWIs for domestic refrigerators result from the losses of the refrigerant used in the mechanical refrigeration circuit and the blowing agent used to produce insulating foams for the refrigerator cabinet. All of the indirect TEWI for refrigerators is from CO_2 emissions associated with electric power used to operate the refrigerator over its 15 – 20 year lifetime.

Assuming a 550 liter (20 – 22 cu. ft.) top-mount refrigerator which is the most popular model and size in the United States, about 1.1 kg. (2.4 lbs.) of HCFC-141b with a GWP of 630 is used to "blow" the polyurethane insulating foam for the cabinet, all of which is eventually lost to the earth's atmosphere. Roughly 0.15 kg, (5.5 oz.) of HFC-134a refrigerant with a GWP of 1300 kg CO_2/kg HFC-134a is needed for a refrigerant charge, which may or may not be recovered when the refrigerator is scraped at the end of its useful life.

Direct TEWI Calculation:

([kg of refrigerant charge] x [annual loss/service rate] x [years of life] + [% loss at disposal]) x $GWP_{refrigerant}$ + (kg blowing agent) x $GWP_{blowing\ agent}$ = **DIRECT TEWI**

([0.15 kg x 0% x 19 years] + [0.15 kg.]) x 1300 + (1.1 kg) x 630) = **888 kg. CO_2**

The indirect TEWI for refrigerators is calculated on the basis of an annual energy consumption, which for a1996, 550 l, top-mount model is about 647 kWh/year, the number of years of useful life (19), and the CO_2 emission rate for electric power generation.

Indirect TEWI Calculation:

$$\text{(kWh/year energy use)} \times \text{(years of life)} \times \text{(kg. } CO_2/kWh_{elect} = \text{INDIRECT TEWI}$$

$$647 \text{ kWh/year} \times 19 \text{ years} \times 0.65 \text{ kg } CO_2/kWh_{elect} = 7{,}990 \text{ kg } CO_2$$

TEWI Results: TEWI values calculated for representative North American refrigerators and several HCFC and HFC alternatives for the currently marketed product are shown in Figure 2. Most of the research effort for domestic refrigerators at present is directed at finding a non-chlorine containing blowing agent to replace HCFC-141b, which is scheduled for phase-out in 2003. The direct TEWI obtained by assuming a 100% loss of the HFC-134a refrigerant charge after 19 years of service has a relatively small effect (1 – 2%) on the total TEWI. Current and proposed recapture and recycling laws will diminish this contribution.

Using cyclo-pentane or pentane hydrocarbon isomers as blowing agents for the refrigerator insulating foam virtually eliminate any direct TEWI from this source, but result in an insulation with higher thermal conductivity and larger annual energy use which increases overall TEWI due to indirect effects.

Household refrigeration is an application in which indirect TEWI from CO_2 emissions dominate the global warming impact with a lesser contribution from the blowing agent and very little contribution from the refrigerant because little, if any, refrigerant loss or make-up occurs over the life of the product. The most significant opportunity to improve the TEWI of this product is via improved insulating foams and increased energy efficiency.

Retail Refrigeration

An application area where TEWI analysis has shown an opportunity to improve the global warming impact by reducing the direct contribution of refrigerants is in retail refrigeration. Traditional approaches to supermarket refrigeration systems are characterized by a centralized rack of compressors connected by long refrigerant lines to remotely located condensers and refrigeration cases located throughout the supermarket. The large internal volumes of these systems necessitate large refrigerant charges while the multitude of field-assembled joints and connections provide ample opportunities for leakage. Annual charge leakage or make-up rates of 15 – 30% of the total refrigerant charge are commonly reported.

Typically, two different refrigerants will be used in a store, one for low temperature cases which hold products like ice cream and frozen meats and another refrigerant for medium and high temperature cases used for products like fresh meats, dairy products, or produce. Refrigerant selections have been made on the basis of overall efficiency with compromises to reduce the total number of refrigerants used. The original provisions of the Montreal protocol led the manufacturers of compressors and refrigeration cases to use HCFC-22 for medium and low temperature applications and HFC-134a in high temperature cases. Revisions to the Montreal Protocol which outline a schedule for the phase-out of HCFCs has prompted the development of chlorine-free mixtures of refrigerants for medium and low temperature refrigeration. Alternative chlorine-free refrigerants suggested for low-temperature retail refrigeration applications are R-402A, R-404A, R-407A, R-407B, R-407C, R-507, and ammonia. Zeotropic mixtures R-407C, R-410A, R-401A, and ammonia have been offered as medium temperature refrigeration alternatives.

Additionally, two fundamental design changes have been proposed for supermarket refrigeration systems which could significantly reduce the amount of annual refrigerant leakage and the total refrigerant charge size. One approach utilizes a secondary fluid loop rather than refrigerant lines to distribute cooling from a smaller, leak-tight refrigeration circuit to the cases.[3] The other design, being developed by Hussman, moves the compressor with its associated high pressure liquid and suction lines as close as practical to the case evaporator loads and employs a closed-loop, water circuit to reject the heat of condensation.[4] Both of these alternative approaches drastically reduce the refrigerant charge size by as much as 75 – 90% and make it practical to minimize refrigerant leaks.

The secondary loop (SL) approach must operate over a larger temperature lift to accommodate the intermediate level of heat exchange and has an additional parasitic load associated with a fluid circulating pump. Retail refrigeration systems utilizing ammonia as a refrigerant would also have to function with a secondary heat exchange loop. The distributed (dist.) system with compressors located near or in the refrigeration cases requires a larger number of smaller compressors located throughout the store.

TEWI Results: TEWI results from the various combinations of alternative refrigerants with these three fundamental refrigeration circuit designs are shown in Figure 3 for a medium and low temperature supermarket application in Europe. From these results it is possible to see the remarkable improvement (decrease) in direct TEWI that is possible when the conventionally used direct expansion (DX) refrigeration circuit is replaced with a secondary loop (SL) or distributed system (dist.) approach.

The relative energy use of each system is indicated by the length of the indirect TEWI bars. Small differences are seen between the alternative refrigerant choices. Utilizing ammonia as a refrigerant in a SL system shows a small TEWI advantage due to an improved cycle efficiency.

Conclusions

Through results presented in this paper and those obtained in looking at all five of the CFC/HCFC alternative application areas, it is possible to form the following conclusions:

- Reductions in TEWI through the use of ammonia and hydrocarbons as refrigerants are insignificant for refrigeration systems with low emissions and may lead to increases in energy use and higher TEWI if forced to comply with the same design criteria applied with fluorocarbon refrigerants.
- Although ammonia and hydrocarbon refrigerants may have theoretical cycle efficiencies comparable to other refrigerants, product modifications necessary for safe consumer products (e.g. secondary loops) reduce overall efficiency.
- Significant reductions in TEWI are possible using currently-known chlorine-free refrigerants with evolving maintenance practices and improved product designs such as curtailing the venting of refrigerant during servicing and the use of distributed refrigeration systems in supermarkets.
- No clear conclusions are possible using currently-known foam blowing agents to replace HCFC-141b where it is commonly used. Hydrocarbon blown foam continues to have higher thermal conductivity than HFC blown foam and consequently higher application energy use.
- TEWI remains a valuable tool in assessing the environmental impact of different refrigeration and air conditioning technologies.

References

/1/ S.K. Fischer, et al. 1991. *Energy and Global Warming Impacts of CFC Alternative Technologies*, AFEAS Program Office, Washington, D.C.

/2/ S.K. Fischer, et al. 1994. *Energy and Global Warming Impacts of Not-In-Kind and Next Generation CFC and HCFC Alternatives*, AFEAS Program Office, Washington, D.C.

/3/ U. Hesse, 1995. *Secondary Refrigerant System Options*, Proceedings of 1995 CFC and Halon Alternatives Conference and Exhibition, p. 322.

/4/ T. Broccard, 1995. *A Revolutionary New Approach to Supermarket Refrigeration*, Proceedings of 1995 CFC and Halon Alternatives Conference and Exhibition, p. 313.

Table 1: Environmental Properties of Refrigerants and Blowing Agents

	Lifetime (yr.)	ODP	100 year ITH	500 year ITH
CFCs				
CFC-11	50	1.0	4000	1400
CFC-12	102	1.0	8500	4200
CFC-113	85	0.8	5000	2300
CFC-114	300	1.0	9300	8300
CFC-115	1700	0.6	9300	13000
HCFCs				
HCFC-22	13.3	0.055	1700	520
HCFC123	1.4	0.02	93	29
HCFC124	5.9	0.022	480	150
HCFC-141b	9.4	0.11	630	200
HCFC-142b	19.5	0.065	2000	630
HCFC-225ca	2.5	0.025	170	52
HFCs				
HFC-23	264	0	11700	9800
HFC-32	5.6	0	650	200
HFC-125	32.6	0	2800	920
HFC-134a	14.6	0	1300	420
HFC-143a	48.3	0	3800	1400
HFC-152a	1.5	0	140	42
HFC-227ea	36.5	0	2900	950
HFC-236ea	8	0	110	510
HFC-236fa	209	0	6940	4700
HFC-245ca	6.6	0	560	170
HFC-245ea	5	0	420	140
HFC-245eb	5.5	0	490	170
HFC-245fa	7.3	0	820	290
HFC-356mcf	1.3	0	125	38
HFC-356mffm	11.6	0	1160	390
HFC-365mfc	12	0	750	200-300
HFC-43-10	17.1	0	1300	400

	Lifetime (yr.)	ODP	100 year ITH	500 year ITH
HCs				
HC-50 (methane)	12.2	0	21	6.5
HC-170 (ethane)	–	0	3	–
HC-290 (propane)	–	0	3	–
HC-3(11)0 (butane)	–	0	3	–
Cyclo-Penane	–	0	11	8
Zeotropes and Azeotropes				
401A	–	0.037	970	300
401B	–	0.04	1060	320
401C	–	0.03	760	230
402A	–	0.021	2250	720
402B	–	0.033	1960	620
403B	–	0.031	3570	4190
404A	–	0	3260	1150
405A	–	0.028	4480	5630
406A	–	57	1560	480
407A	–	0	1770	580
407B	–	0	2290	750
407C	–	0	1530	490
408A	–	0.026	2650	920
409A	–	0.048	1290	390
410A	–	0	1730	560
411A	–	0.048	1330	400
411B	–	0.052	1410	420
500	–	0.74	6010	2990
501	–	0.29	3150	1350
502	–	0.33	5230	6610
503	–	0.6	11350	11750
504	–	0.31	4890	6560
507	–	0	3300	1160

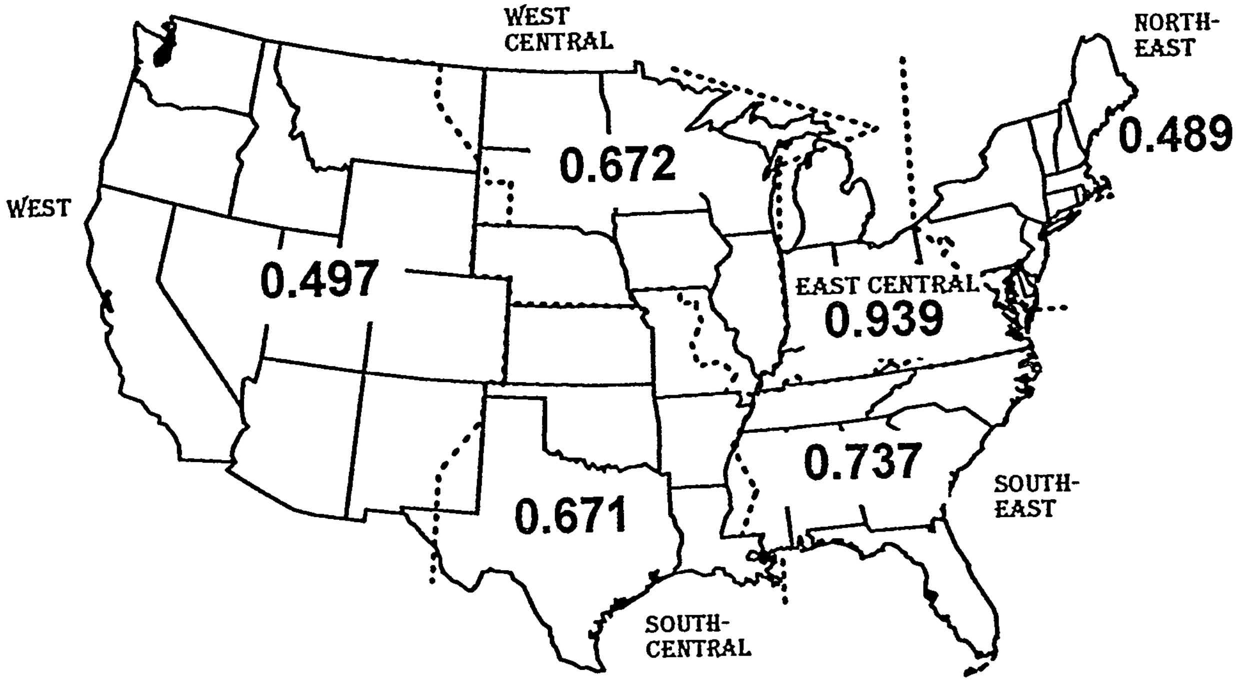
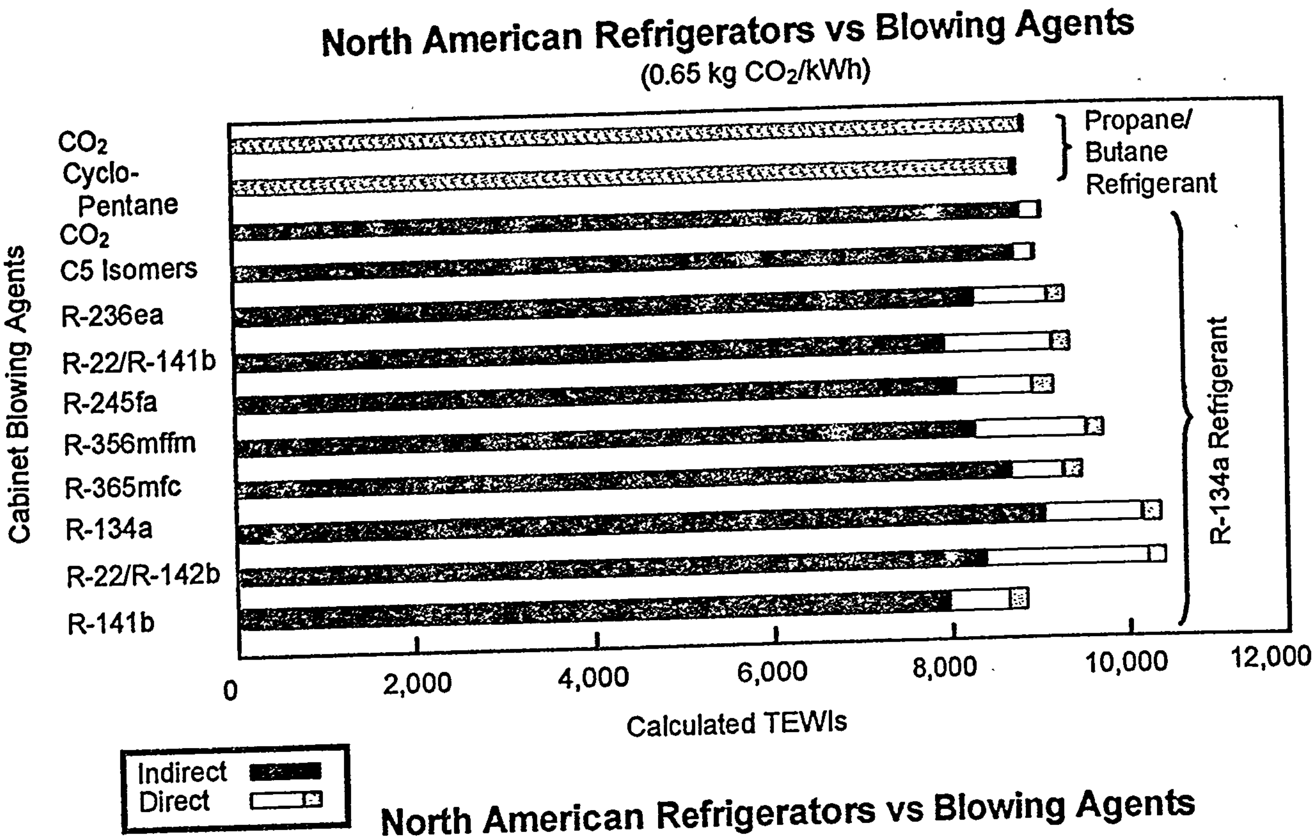


Figure 1. United States kg CO_2/kWh electricity Emission Rate (0.650 kg CO_2/kWh average)



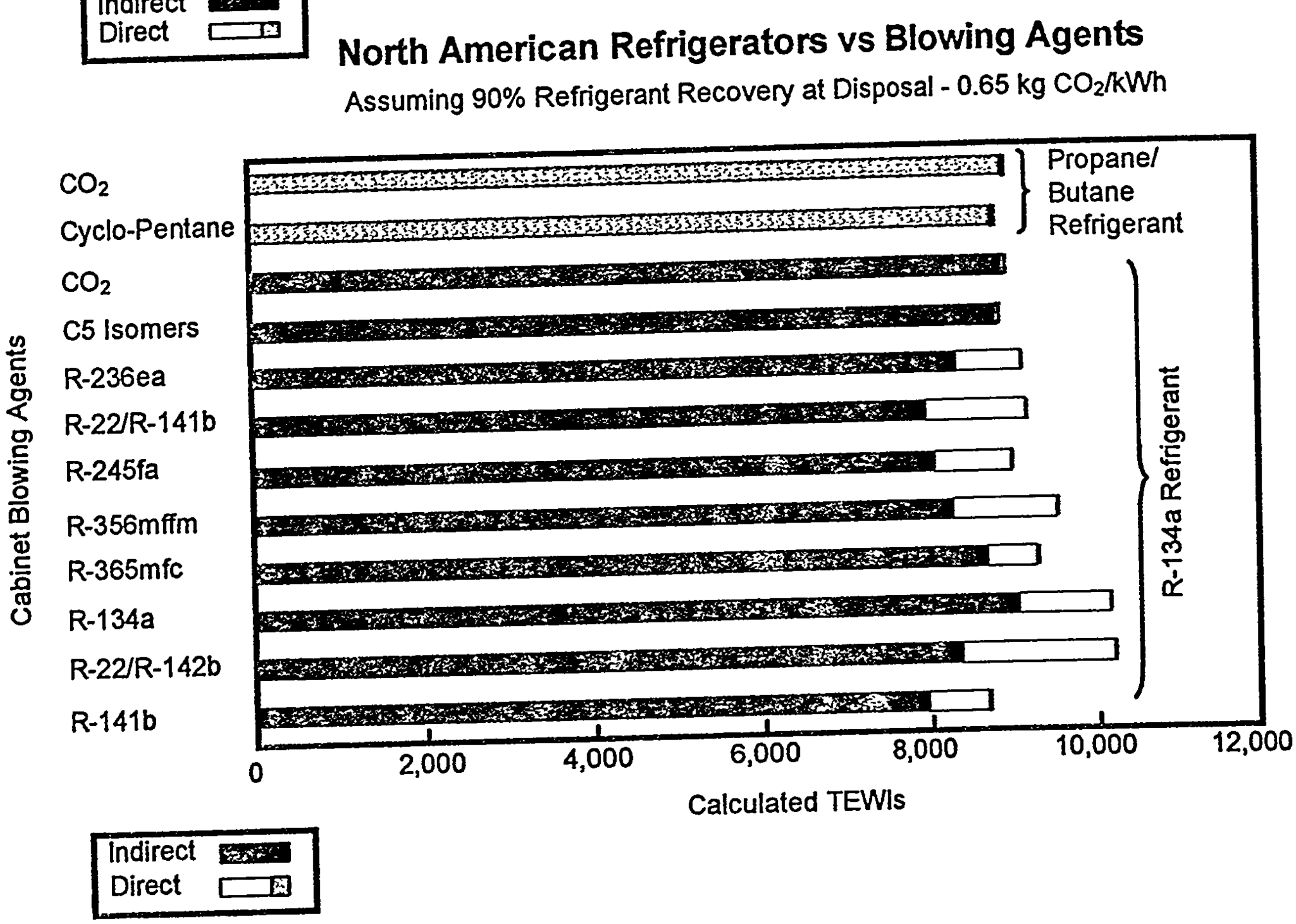


Figure 2. TEWI Values for U.S. refrigerators

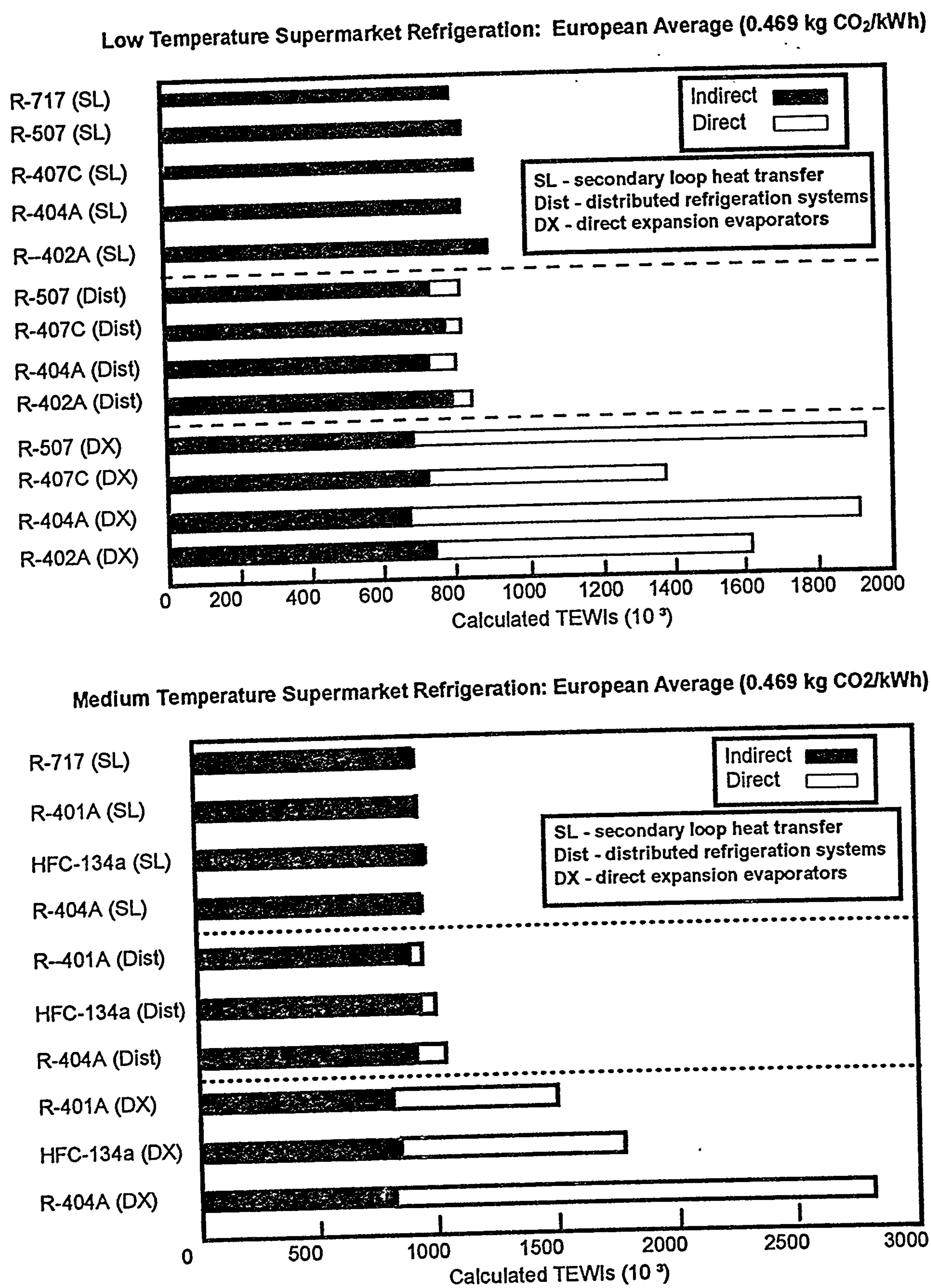


Figure 3. TEWI for low and medium Retail Refrigeration Application