Analysis of Overall Environmental Impact from CFC Alternatives in Commercial Building Cooling Applications

William L. Kopko, U.S. Environmental Protection Agency

This paper provides an analysis of overall costs associated with different refrigerants and cooling systems. This analysis combines installation and operating costs with capital costs for power generation and external costs associated with refrigerant and fuel emissions to estimate total societal cost of different cooling alternatives. Conclusions of this analysis include:

Emissions of R123 appear to have a substantially lower overall environmental impact than equal emissions of R22 or R134a.

Efficiency differences between different refrigerants used in similar equipment are usually small, not more than five to ten percent. Efficiency differences associated with different technologies are frequently much larger, as much as 30 to 50 percent.

Water-cooled or evaporatively cooled equipment can offer significantly better efficiency than air-cooled equipment. Energy savings of 30% or more are possible depending on the application.

Using gas to generate electricity appears to be a much better option than using it to power absorption chillers. Efficient, water-cooled electric chillers run with power from gas advanced combined cycle generators produce less than half of the carbon dioxide emissions of gas absorption chillers.

Introduction

Both industry and government have been working to identify ways to reduce or eliminate chlorofluorocarbon (CFC) refrigerants, which face a 1995 production ban. A variety of chemical substitutes and alternative cooling technologies have been identified to replace CFCs in commercial air conditioning applications.

Substitutes need to be evaluated for a variety of factors including ozone depletion, flammability, energy efficiency, toxicity, global warming potential, and other human health risks. In evaluating CFC substitutes it is essential to balance the risks and benefits of all options to determine optimal choices.

This paper illustrates this evaluation process by considering the various chiller alternatives for a 600-ton design cooling capacity. Options were evaluated for their contributions to chlorine reductions, energy efficiency and associated pollution generation, safety, and installation and operating costs.

Method of Evaluation

In addition to the normal considerations of installation and operating costs, there are important factors from a societal or environmental perspective that are important in determining the overall costs associated with different cooling alternatives. These factors include:

Refrigerant Emissions

Ozone depletion and global warming potential are two important considerations in evaluating refrigerants. One difficulty in evaluating different refrigerants is determining the relative importance of these two environmental considerations.

One approach is to assign dollar values to the external costs for ozone depletion and global warming. Table 1 summarizes estimated values for these costs. The costs associated with ozone depletion are based on deaths and injuries associated with increased incidence of skin cancer and other health effects.

Table 1. Estimate of External Costs of Emissions of Refrigerants

	Cost
CO_2	\$.01 to .02/lb CO_2 for planting trees in U.S.
Using earlier data on ozone depletion:	
CFCs	\$10/lb of R11 equivalent for U.S. damages ~\$50/lb for worldwide damages
Using new ozone depletion data:	
CFCs	\$30/lb for U.S. ~\$150/lb for worldwide damages

Assumptions: Global warming potentials are relative to carbon dioxide equivalent based on a 100-year time horizon. The value of carbon dioxide emission is assumed to be \$.01/lb based on cost of planting trees in the U.S. The first case assumes a value of \$50/lb of R11 equivalent for ozone depletion. This figure is based on an estimate of damage of \$10/lb for the U.S. with an assumption that world damages are roughly five times that of the U.S. (ICF 1992 and John Wassen, ICF, personal communication.) The second case uses a value of \$150/lb of R11. It also assumes that cooling from ozone depletion is equal to the warming from infrared absorption for R11.

The cost for global warming emissions is based on the cost of planting trees to remove an equivalent amount of carbon dioxide from the air. An implicit assumption is that the cost of planting trees is lower than the damages that would result from global warming.

Two important results have come from recent studies (UNEP 1991). The first finding is that measured ozone depletion is much worse than expected based on earlier work. The second result is that ozone depletion cools the earth and counteracts at least a portion of the global warming associated with CFCs and hydrochlorofluorocarbons (HCFCs).

Table 2 shows how several refrigerants compare in terms of environmental costs. The new scientific data mean that damage from ultraviolet radiation should be raised to reflect the greater ozone depletion. On the other hand, this ozone depletion provides a benefit by reducing the greenhouse warming. Unfortunately the cooling benefit appears to be on the order of \$35/lb while ultraviolet damage is on the order of \$150/lb of R11. The conclusion is that CFCs are still a major problem even including the effect of lower global warming potential.

Table 2 indicates that R123 is a good choice from an environmental standpoint although it has a non-zero ozone depletion potential. Even with a value of ozone depletion of \$150/lb of R11, the total external cost from an emission of R123 is only one fourth of that for R134a.

Another important conclusion from this table is the importance of recycling and conservation of all refrigerants, especially CFCs. If R11 and R12 were priced to include the true cost of emissions, handling procedures would certainly be different than those used today. Indeed the cost of these materials would be so high that it is unlikely that they would be used in new equipment.

Energy Efficiency

Table 3 compares the ideal efficiency of the different refrigerants at typical water-cooled chiller conditions. These theoretical numbers give a reasonable comparison between refrigerants with similar operating pressures since the compressors and heat exchangers are very similar. Unfortunately theoretical efficiency provides only a starting point in comparing refrigerants that have substantially different operating pressures. For example, comparing an R123 centrifugal chiller to an R22 screw chiller requires consideration in differences in cost and performance of different types of compressors and different heat exchanger designs.

Fluoroether E134 is an attractive alternative in this analysis. It has the best cycle efficiency of the chlorine-free alternatives and has a low direct global warming potential. It is also nonflammable and has a low acute toxicity. Unfortunately it has proved to be difficult to

Table 2. Societal Cost for Refrigerant Emissions

	Refrigerant									
	R11	R12	R22	R123	R134a	R152a	R125	R32	E245	E134
GWP (CO2=1)	3500	7300	1500	85	1200	140	2500	600	~500	~250
ODP (R11=1)	1.00	1.00	.05	.02	0	0	0	0	0	0
Likely Production Price ($/lb)	1	1	1	3	6	3	5	5	8	?
Based on UNEP 1989 values for ODP and GWP:										
chlorine ($/lb)	50	50	2.5	1	0	0	0	0	0	0
Greenhouse ($/lb)	35	73	15	.85	12	1.40	25	6	5	2.5
Total External Costs	85	123	17.5	1.85	12	1.40	25	6	5	2.5
Revised values based on new scientific evidence:										
Chlorine ($/lb)	150	150	7.5	3	0	0	0	0	0	0
Cooling effect from ozone depletion ($/lb)	-35	-35	-1.75	-.7	0	0	0	0	0	0
Greenhouse ($/lb)	35	73	15	.85	12	1.40	25	6	5	2.5
Total External Cost Using New Data	150	188	20.75	3.15	12	1.40	25	6	5	2.5

Table 3. Ideal Cycle Efficiency of Selected Alternative Refrigerants for Centrifugal Chillers

Designation	CFC11	HCFC123	E245	E134	HFC134a	HCFC22
Formula	$CFCl_3$	$CHCl_2\ CF_3$	$CF_2\ HOCH_2\ CF_3$	$CHF_2\ OCH_2F$	$CF_2H\ CF_3$	$CHCl_2F$
Evaporator Pressure (psia)	7.03	5.80	5.24	13.6	49.7	83.6
Condenser Pressure (psia)	23.5	20.8	20.1	47.1	139	212
Discharge Temperature (F) or Quality (%)	112°F	99%	89%	102°F	106°F	112°F
CFM/ton	15.5	18.2	21.0	8.14	2.82	1.81
Speed of Sound at Suction (ft/sec)	443	414	409	468	485	536
Capacity in a Centrifugal Compressor (R11=1)	1.00	.80	.68	2.01	6.0	10.3
Coefficient of Performance (COP)	7.83	7.73	7.36	7.54	7.37	7.35
Efficiency (R11=1)	1.00	.99	.94	.96	.94	.94

Assumptions: Ideal cycle with evaporating temperature = 40°F
condensing temperature = 100°F
liquid subcooling = 10°F
suction superheat = 0°F.

Calculations were made using refrigerant properties form the NIST REFPROP computer program.

make and may be very expensive to produce in commercial quantities.

Power Plant Emissions

Table 4 summarizes external costs for power plant emissions. The costs represent the value of scrubbers or other control measures that are required by government regulations. In general, utility commissions are using control costs as a means for evaluating external costs of pollution. These costs are probably the best measure of the value that society places on controlling pollution.

Table 4. Approximate External Costs for Power Plant Emissions

	Cost Control
CO_2	\$.01/lb
SO_2	\$.75/lb
NOx	\$3.25/lb

Sources:
R.J. Moulton and K.R. Richards 1990.
Massachusetts Department of Public Utilities 1989.

Safety

There are several safety issues associated with cooling systems. Among them are acute toxicity, long-term toxicity, and flammability of the refrigerant. In addition, potential for fires and other hazards from electrical or gas systems used to run the equipment should be considered. Finally, growth of potentially lethal bacterial, such as legionella, is an important factor when comparing risks of air-cooled and water-cooled equipment.

As far as exposure to refrigerants from chiller equipment, recent field test show that exposure levels for equipment-room operators and service personnel are usually less than 1 ppm when good practices are followed (Meridian Research 1991). These low exposure levels make the risks associated with long-term exposure to refrigerants very small. The real safety concerns from refrigerant comes from suffocation or cardiac sensitization caused by accidental releases of large amounts of material. These risks are probably highest in older chiller installations that do not have good ventilation and lack sensors to warn of dangerous levels of refrigerant. Risks associated with sudden, large releases of material are common to all refrigerants.

A significant safety concern that is frequently overlooked is legionnaire's disease. The legionella bacteria that are responsible for this pneumonia-like disease are found widely in soil and natural bodies of water. They can flourish in poorly maintained cooling towers and evaporative condensers. Cooling towers and evaporative condensers require regular water treatment and maintenance to ensure that these risks are eliminated (Broadbent 1991).

One problem with evaluating relative safety risks is that they can vary depending on the details of design and application of the equipment. Another problem is the difference between perceived and actual risks. In general, existing risks are considered to be more acceptable than new risks. For example, many building codes ban the use of even small amounts of hydrocarbons as refrigerants but allow unlimited use of the same materials as fuels. It is important to fairly evaluate all the risks, including those to the global environment to ensure overall risk is reduced.

Sample Analysis

Table 5 summarizes installed costs for six different chiller alternatives with a total design cooling capacity of 600 tons. This table shows that the air-cooled reciprocating chiller has the lowest installed cost to the builder. However, when the cost of power generating capacity is included the water-cooled chillers have a clear advantage. The gas absorption chiller has the largest capital cost, even considering the reduced power generation needs.

There does not appear to be a large difference in cost between the water-cooled electric chillers. The R11 centrifugal chiller is the least expensive and the R134a screw chiller is the most expensive. The R123 centrifugal and the R22 screw have costs in between.

Table 6 gives the energy use estimates for the chillers. The electric water cooled chillers were selected to have similar energy efficiency, and they all show significantly better efficiency than the air-cooled reciprocating chiller and the absorption chiller.

Table 7 summarizes the total societal costs associated with each alternative. The variable-speed R123 chiller appears to be a good choice on this basis. Absorption and air-cooled reciprocating chillers appear to have much higher cost than the water-cooled electric chillers.

Table 5. Chiller Installed Cost (600-Ton Total Capacity)

	Centrifugal		Variable Speed	Screw		R22	LiBr/Water Gas
	R11	R123	R123	R22	R134a	Recip	Absorption
Chillers	$148,000	164,000	198,000	154,000	177,000	192,000	426,000
Installation	$90,000	95,000	95,000	90,000	90,000	100,000	130,000
Cooling Tower	$37,000	37,000	37,000	37,000	37,000	0	67,000
Condenser Piping	$36,000	36,000	36,000	36,000	36,000	0	58,000
Total Installed Cost	**$311,000**	**332,000**	**366,000**	**317,000**	**340,000**	**292,000**	**681,000**
Peak kw	444	444	452	444	444	780	105
Electric Power Generation Capacity (at $400/kw)	$266,000	266,000	271,000	266,000	266,000	468,000	63,000
Total Capital Costs	**$577,000**	**593,000**	**637,000**	**583,000**	**606,000**	**796,000**	**744,000**

Notes: Costs for equipment and installation are from Means 1991 and communication with chiller manufacturers. All systems assume two 300-ton chillers, except for the air-cooled reciprocating which uses three 200-ton chillers. The variable-speed R123 chiller system assumes that a variable-speed drive is included on the lead chiller only.

Conclusions

Emissions of R123 appear to have a substantially lower overall environmental impact than equal emissions of R22 or R134a. R123 also has the best cycle efficiency of any alternate refrigerant considered.

Efficiency differences between different refrigerants used in similar equipment are usually small, not more than five to ten percent. Efficiency differences associated with different technologies are frequently much larger, as much as 30 to 50 percent.

For a given chiller, efficiency improvements are possible at increased cost. The comparison between different refrigerants is difficult when they use different compressor or heat exchanger technology since these can have great effect on costs.

Water-cooled or evaporatively cooled equipment can offer significantly better efficiency than air-cooled equipment. Energy savings of 30% or more are possible depending on the application.

Using gas to generate electricity appears to be a much better option than using it to power absorption chillers. Efficient, water-cooled electric chillers run with power from gas advanced combined cycle generators produce less than half of the carbon dioxide emissions of gas absorption chillers. Total capital costs for installing electric chillers and necessary generating capacity appear to be lower than those for absorption chillers. The main application of absorption chillers should be with cogeneration and other applications that have large amounts of waste heat.

References

Broadbent, C.R. 1991. "Developments in Australia to Control *Legionella*," *ASHRAE Transactions*, volume 97, part 1, page 258.

ICF Inc. 1992. *Regulatory Impact Analysis: Compliance with Section 604 of the Clean Air Act for the Phaseout of Ozone Depleting Chemicals*. Prepared for the U.S. Environmental Protection Agency, Washington DC.

Table 6. Chiller Energy Use and Emissions

	Centrifugal		Variable Speed	Screw		R22	LiBr/Water Gas
	R11	R123	R123	R22	R134a	Recip	Absorption
Average Annual Chiller Efficiency (kw/ton)	.64	.64	.48	.64	.64	1.1	n.a.
Condenser Fan and Pump Energy (kw/ton)	.1	.1	.1	.1	.1	n.a.	.175
Chiller Power (MWH/year)	384	384	288	384	384	660	20
Condenser Fan and Pump (MWH/year)	60	60	60	60	60	0	105
Total Electric MWH/Year	464	464	348	464	464	660	125
Gas (Million BTU)	0	0	0	0	0	0	6,550
Emissions Assuming Electric Power Generation Using Current U.S. Fuel Mix:							
CO2 (lb/year)	742,000	742,000	557,000	742,000	742,000	1,056,000	979.000
SO2 (lb/year)	5,430	5,430	4,080	5,430	5,430	7,730	1,460
NOx (lb/year)	2,870	2,870	2,150	2,870	2,870	4,080	1,430
Emissions Assuming Electric Power Generation from Gas Advanced Combined Cycle:							
CO2	418,000	418,000	313,000	418,000	418,000	594,000	879,000
SO2	0	0	0	0	0	0	0
NOx	371	371	278	371	371	528	754

Notes: Energy use figures assume 600000 ton-hours per year cooling load. Air-cooled reciprocating chiller efficiency includes condenser fans. Absorption chiller c.o.p. is assumed to be 1.10. Emission figures were provided by Adam Klinger, EPA.

Massachusetts Department of Public Utilities. 1989. Report 89-239, page 85.

Moulton, R.J. and Richards, K.R. 1990. *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States*. General Technical Report WO-58. Forest Service, U.S. Department of Agriculture.

Means Company, Inc. 1990. *Means Mechanical Cost Data 1991*.

Meridian Research Inc. 1991. *Results of Employee Exposure Monitoring for HCFC-123 at Centrifugal Chiller Installations*. Prepared for the U.S. Environmental Protection Agency.

UNEP, August 1989. *Scientific Assessment of Stratospheric Ozone: 1989.*

UNEP, November 1991. *Synthesis of the Reports of the Ozone Scientific Assessment Panel, Environmental Effects Assessment Panel, Technology and Economic Assessment Panel.*

Table 7. Total Cost of Chiller Alternatives Including External Costs

	Centrifugal		Variable Speed	Screw		R22	LiBr/Water Gas
	R11	R123	R123	R22	R134a	Recip	Absorption
Cost to Chiller Owner:							
Total Installation Cost	$311,000	332,000	366,000	317,000	340,000	292,000	681,000
Annual Energy Cost	33,000	33,000	26,300	33,000	33,000	52,000	41,500
Annual Water Cost	2,160	2,160	2,160	2,160	2,160	0	3,780
Total cost to Building Owner in Present Dollars (20-year life, 10% real discount rate)	610,000	631,000	608,000	616,000	639,000	734,000	1,066,000
External Costs:							
Refrigerant Emissions in $/Year (50 lb/year emission rate)	7,500	158	158	1,040	600	1,040	0
Cost of Emissions Assuming Current U.S. Generating Mix:							
CO2 ($/year)	7,420	7,420	6,300	7,420	7,420	10,560	2,000
SO2 ($/year)	4,070	4,070	3,060	4,070	4,070	5,800	1,095
NOx ($/year)	9,330	9,330	6,990	9,330	9,330	13,260	4,650
Total External Costs of Fuel and Refrigerant Emissions in Present Dollars	241,000	178,000	141,000	186,000	182,000	261,000	66,000
Total Societal Cost in Present Dollars Using Current U.S. Generating Mix	851,000	809,000	749,000	802,000	821,000	995,000	1,136,000
Cost of Emissions Assuming Advanced Combined Cycle (ACC) Electric Generation:							
CO2 ($/year)	4,180	4,180	3,130	4,180	4,180	5,940	8,790
SO2 ($/year)	0	0	0	0	0	0	0
NOx ($/year)	1,200	1,200	900	1,200	1,200	1,720	2,450
Total External Cost of Fuel and Refrigerant Emissions in Present Dollars with ACC	110,000	47,000	36,000	55,000	51,000	74,000	96,000
Total Societal Cost in Present Dollars Using ACC Generation	720,000	678,000	644,000	671,000	690,000	808,000	1,162,000