Understanding the CFC Challenge in a Changing World: The Commercial Building Response to the 1990 Clean Air Act Amendments

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The 1990 Clean Air Act requires a complete phaseout of CFC and HCFC refrigerant production, including commercial cooling refrigerants. Alternative refrigerants involve technical, environmental, and economic trade-offs. *Guidance is needed for owners, designers, and others to contain the CFCs and HCFCs currently in use and to make the transition to alternative refrigerants.* This paper attempts to briefly summarize relevant scientific research, provide guidance on containment, present available chiller equipment and refrigerant options, and make recommendations on how to convert and purchase chillers with alternative refrigerants.

It is an important shared responsibility of the owner and the designer to make informed decisions about what chiller/refrigerant course to follow. This paper investigates which criteria (first cost, energy efficiency, chiller type, etc.) are most important when making those decisions. To analyze the criteria, a systems engineering trade-off analysis model is applied to a cross section of chiller and refrigerant options.

The trade-off analysis model helps to show that selections of different chillers and alternative refrigerants are affected strongly by different perspectives that owners and designers bring to the decision process; *there is no single chiller/refrigerant combination right for all situations.* These owner/designer perspectives include the various degrees of emphasis on cost, environmental concern, etc. Owners/designers should recognize explicitly the criteria that affect equipment selection and then choose which criteria the owner/designer wants to emphasize.

Introduction

The 1990 Clean Air Act (CAA) Amendments require a production phase-out of CFC (chlorofluorocarbon) refrigerants by the year 2000 and a phaseout of HCFCs (hydrochlorofluorocarbons) by 2030. In February of 1992, President Bush issued a Presidential declaration[1]--anticipated to be implemented in regulations--that accelerates the phase-out of CFCs in the U.S. from the year 2000 to the end of 1995. Similarly, the phase-out of HCFCs may be accelerated to the year 2005 for new equipment and the year 2015 for existing equipment. Further acceleration for HCFCs is likely.

Since almost all types of commercial air conditioning equipment (with the exception of absorption chillers and desiccant dehumidification devices) rely on CFCs and HCFCs as refrigerants, the commercial air-conditioning industry has begun to make significant changes.

The challenge for building owners and designers is to determine how best to respond during this time of scientific discovery that necessitates changing regulations. Owners and designers need to plot a course for the future that minimizes risk while maximizing protection of the earth's environment. This paper attempts to:

- Briefly summarize much of the current **scientific research** on how refrigerants affect ozone depletion and global warming.
- Provide guidance on methods of practice for **containment** of refrigerants in current chillers.
- Present an overview of currently available **commercial chiller equipment and refrigerant** options.
- Make recommendations on how to **convert chillers** to alternative refrigerants and **purchase chillers** for new construction.

The emphasis on chillers in this paper is a practical one. Almost all types of unitary air-conditioning equipment used in commercial buildings run on HCFC-22, for which there is presently no alternative refrigerant available. This paper is intended to help owners and designers understand refrigerant phase-outs in order to make informed decisions. The paper is not intended to provide all the information necessary to convert or purchase a chiller for a specific building. That requires the guidance of a licensed engineering consultant who must weigh all local code requirements, safety issues, and individual site parameters.

Ozone Depletion and Global Warming

Ozone Depletion

The now-famous "ozone hole" seen over Antarctica in 1985 was only the tell-tale sign that focused scientists' attention on measuring and understanding how the ozone layer is undergoing a thinning process. The ozone thinning--thought at first to be significant only over the earth's poles and high latitudes--is now predicted over much of the earth's surface. Some of the most recent measurements, in February, 1992, with NASA satellite observations and a multi-agency airborne effort measured high levels of the ozone-depleting chemical chlorine monoxide (a product of CFC emissions) at lower latitudes than previously predicted.

In areas where the ozone layer thins and increased biologically damaging UV radiation reaches the Earth, a variety of effects are possible:

- Increased cases of skin cancer (and some deaths) may occur.
- The incidence of eye cataracts will probably increase.
- Crop yields could be reduced to an extent not yet known.
- Human immune systems may be weakened.
- Increased UV radiation will adversely affect aquatic and terrestrial eco-systems.

Confusion about ozone depletion sometimes exits because ozone acts very differently in the troposphere where we live and in the stratosphere from seven to 30 miles above the Earth's surface. In the troposphere ozone contributes to smog. Only very small amounts of this ozone migrate up high enough to enter the stratosphere, so it does very little is added to the ozone in the stratosphere where it is needed to trap UV radiation.

By contrast, the molecularly stable CFCs and HCFCs used as refrigerants (as well as for insulation blowing agents, industrial solvents, aerosols, and some other industrial chemicals containing chlorine) have atmospheric lifetimes long enough to allow for migration up to the stratosphere. Once there, the chlorine from CFCs and HCFCs acts as a catalyst, reacting many times with ozone molecules until significant numbers are depleted. Scientists quantify the degree to which a refrigerant can damage stratospheric ozone by its ozone depletion potential (ODP).

Global Warming

In addition to ozone depletion mechanisms, global warming mechanisms are affected by the emission of refrigerants as well. Though some of the mechanisms involved in increased global warming are less well understood than ozone depletion mechanisms, global warming is potentially an even greater threat to the world's ecological, economic, and social systems.

CFC refrigerants have global warming potentials (GWPs) thousands of times greater than carbon dioxide, the most common greenhouse gas. Because the quantities of refrigerants released to the atmosphere are very small compared to the large quantities of carbon dioxide emitted by the burning of fossil fuels worldwide, the *direct* contribution of refrigerants to global warming is relatively small overall. Because the global warming problems are potentially so great, however, refrigerants are being scrutinized for their GWPs as well as their ODPs.

Table 1 shows the ODPs and GWPs for the most common refrigerants used in commercial chillers.[2] GWPs, as presented here, are based on a 100 year time horizon. For both ODPs and GWPs, the larger the number the greater the potential environmental damage. ODPs are based on a comparison to CFC-11 with a value of 1.0. GWPs are based on a comparison to carbon dioxide with a value of 1.0.

In addition to the *direct affect* of the refrigerant on global warming (represented by the GWP), the carbon dioxide (and other emissions) released during the operation of a chiller produce an *indirect effect*. This includes the emissions of a power plant providing electricity for a chiller or the emissions from by the burning of natural gas on site in an absorption chiller. The direct and indirect

Table 1. Refrigerant ODPs and GWPs

Refrigerant	ODP	GWP
CFC-11	1.0	3,400
CFC-12	1.0	7,100
R-500	0.74	5,290
HCFC-22	0.055	1,600
HCFC-123	0.02	93
HFC-134a	0.0	1,200

effects combined can be referred to as the net equivalent warming impact.

The net equivalent warming impact is especially important when differences in chiller energy efficiencies are considered. For example, a two percent change in energy efficiency could change the net equivalent warming impact more than completely eliminating the direct (refrigerant-emission) effect.[3] Absorption chillers use water or ammonia as the refrigerant, and their GWP is zero, but because their efficiencies are low, their net equivalent warming impact is approximately twice that for comparable vapor compression chillers.[4]

Refrigerant Containment

Section 608 of the CAA Amendments makes it unlawful, as of July 1, 1992, to "knowingly vent or release any CFC or HCFC refrigerant." It also requires the industry to "maximize the recovery and recycling" of any CFC or HCFC. Federal sanctions for violations can be as high as $25,000 per day per violation and can include criminal penalties. In addition, standards issued by HVAC research groups, actions by model code bodies, the desire to protect worker safety, the need to protect the environment, and the economics of conserving ever-more-costly refrigerants during servicing have led to the need for the following practices.

Record Keeping

- Assemble the most complete data possible on use of refrigerants (past and present), relating use to specific machines. This is important for identifying "leakers" and for the economic analyses helpful in planning when to replace machines.
- Keep records of periodic leak checks done on each machine.
- Develop a plan for reducing refrigerant loss through the following service practices and equipment room modifications.

Service Practices

- Apply ASHRAE Guideline 3-1990[5] when servicing any chiller with a CFC, HCFC, or HFC refrigerant. The present Guideline is limited to CFCs, but a revision is under way to specifically address other refrigerants. Applying the Guideline will prevent refrigerant release through recovery, recycling, and reclamation as defined by ASHRAE below:
  - Recovery: to remove refrigerant in any condition from a system and store it in an external container without necessarily testing or processing it in any way.
  - Recycle: to clean refrigerant for reuse by oil separation and single or multiple passes through devices, such as replaceable core filter-driers, which reduce moisture, acidity and particulate matter. This term usually applies to procedures implemented at the field job site or at a local service shop.
  - Reclaim: to reprocess refrigerant to new product specifications by means which may include distillation. Will require chemical analysis of the refrigerant to determine that appropriate product specifications are met. This term usually implies the use of processes or procedures available only at a reprocessing or manufacturing facility.
- Regularly leak test each chiller with hand-held leak detectors, fluorescent dies, soap bubbles, etc., as needed.
- Use recovery equipment or pump down a chiller into an integral receiver before "opening" a chiller.
- For low-pressure centrifugals (e.g., CFC-11 or HCFC-123) and other "larger" chillers, recovery equipment often costs at least $5,000 for each piece of equipment. Check your maintenance and repair practices; it may be more cost-effective to contract repairs on these machines than to train personnel and purchase equipment to do it in-house. Also check--if considering contract services--that it would be

physically practical to bring in the large recovery equipment each time a chiller is opened for repairs.

- When refrigerant has been contaminated--such as when a hermetic motor burns--or if the refrigerant recovered from a chiller will be used in another machine, consider the risks of on-site recycling carefully. If the refrigerant is suspect, take the refrigerant to a certified reclamation service to be checked.

- The CAA Amendments also require licensing of service technicians and certification of recovery and recycling equipment. Most courses taught by established organizations are likely to be grand-fathered (often contingent upon passing a test) by the EPA when their final procedures are published. It is advisable, therefore, to get service technicians trained as soon as possible to help them start using recovery and recycling equipment. Similarly EPA will grandfather many models of recovery and recycling equipment if purchased before their final requirements are published. Current information on acceptable courses and products are available from EPA[1] or from refrigeration trade associations.

Equipment Room Modifications

- Follow all local code requirements and consider ASHRAE Standard 15R (public review draft 2) as a guideline. This public review draft is not yet a consensus document but can serve as an effective source in addition to others. Request the final published version when it is approved. Consider Standard 15 for guidance regarding:

  - Outside venting of rupture disks and purge systems.

  - Installation of oxygen or refrigerant monitoring systems.

  - Equipment room mechanical ventilation.

  - Provision for a self-contained breathing apparatus.

- The previous modifications are not yet required by law in most states but are important for safety, protection of the environment, and the economy of stopping potentially expensive refrigerant leaks.

- Consider installation of high-efficiency purge units on low-pressure centrifugals (such as CFC-11 and HCFC-123 units) if they currently have only low-efficiency purges. This can save money; it helps the environment; and it may be required in future regulations. Coordinate this decision with any plans you may be developing for potential replacement of a chiller. If a low-pressure unit is eventually replaced with a positive pressure unit, the new chiller will have not need for the purge.

Commercial Chillers--A Changing Industry

Forces of Change

The phase-out of CFCs and HCFCs is a considerable undertaking because it affects approximately $135 billion[6] of installed air-conditioning equipment. There are two main forces driving the industry to change to alternative refrigerants, and a third--perhaps even larger--is on the horizon.

The first force is increasing costs for CFC refrigerants. Federal taxes have been placed on all CFCs, based on their ODPs, and the taxes increase. The effect has been to add $1.67 per pound to the price of CFC refrigerants, thus far.

The second force is the accelerating timeline for phase-out of many commonly used refrigerants. There are obvious advantages in not waiting until the "last minute" before initiating system changes so that alternative refrigerants can be used. Less obvious and difficult to predict will be the availability and cost of reclaimed refrigerant that has been removed from chillers being retired. As phase-out targets set in the President's February directive have started to cause shortages of some refrigerants, their prices may increase in addition to the excise taxes on CFCs.

The third force affecting the industry, global warming regulations, is hardly being felt yet but could be even more significant. The global warming impact caused by commercial air conditioning is usually debated by focusing on the GWPs of emitted refrigerants. Many times these debates assume that all of the refrigerant in a chiller will be released into the environment relatively quickly, ignoring the improvements in high-efficiency purge units, new guidelines for containment and servicing, and increased use of refrigerant leak monitors. Historical debate has also often ignored the global warming contribution of the burning of fuel to power the chiller. Instead (as explained above), the net equivalent warming impact is becoming more frequently used to evaluate refrigerant alternatives.

This year's Earth Summit in Rio De Janeiro is focusing attention on global warming. Future federal or state regulations may include a "carbon tax." A carbon tax could be applied to each refrigerant, each piece of equipment, or perhaps to each unit of fuel or electricity consumed. One scenario is that future regulations will only regulate equipment efficiency, in an effort to reduce carbon dioxide emissions from the fuel used for cooling. The effect of these potential regulations on the decision-making process for owners and designers is to add to the degree of future uncertainty about what costs may be incurred because of choosing a type of refrigerant or a type of chiller today.

Chiller Options

Following is a list of most chiller and refrigerant options available today. For any given building, of course, only some of the options would apply. This list is included to help an owner or designer who is considering chiller decisions to think about a wide range of options before starting more detailed analyses.

Electric-Motor Driven Options. Reciprocating chillers. These machines usually use HCFC-22, sometimes CFC-12, with ammonia in industrial or retail applications, and will be available with HFC-134a in some models as markets develop. Reciprocating compressors are used in the majority of small chillers.

Scroll chillers. Currently use HCFC-22, and some models may soon be available with HFC-134a. Scrolls have only been sold in quantity since 1989. They are usually sold with groups of small hermetic compressors manifolded together.

Screw chillers. Currently use HCFC-22 and HFC-134a. An advantage for many screw chillers is their very good part-load efficiency. Some units with a full-load efficiency of 0.65 kW/ton, for example, will have an Integrated Part-Load Value (IPLV) of 0.55 kW/ton. This can translate into lower energy costs year-round in typical applications.

Low-pressure centrifugal chillers. In commercial buildings, these chillers have traditionally used CFC-11 and sometimes CFC-113. Most models can be operated with HCFC-123. Low-pressure centrifugals have been the most popular type of chiller used in the 300 to 600 ton range used for many commercial buildings. Consequently, since CFC-11 is on the list of refrigerants designated for early phase-out, low-pressure centrifugals with CFC-11 make up the majority of chillers being considered now for conversion to an alternative refrigerant. Because the evaporator side of the system operates below atmospheric pressure, it has the potential for air to leak into the system. Purge systems are provided with each system to remove air that leaks into the machine, and when it is necessary to purge the air, some refrigerant is released.

Positive-pressure centrifugal chillers. Traditionally have used CFC-12, HCFC-22, and sometimes R-500 (which contains 74% CFC-12). HFC-134a is now becoming available as a replacement for all of these, though its pressure levels and flow rates are most similar to R-500. Because these chillers operate above atmospheric pressure throughout the system, they do not require a purge unit. Because they run at higher pressures, they must meet pressure code requirements in the U.S.

Variable-speed drives. Various technologies have been used to successfully increase chiller efficiencies by varying the speed of the electric drive motor. Variable-speed drives can be used, however, with any electric motor-driven chiller and are not specific to any type of refrigerant.

Non-Electric Motor Driven Options. Direct gas-fired absorption chillers. Until the late 1980s most gas-fired absorption chillers in the U.S. were single-effect machines. Double-effect units with higher coefficients of performance (COPs), in combination with high electricity demand rates and utility rebates in some parts of the country, have made this technology much more attractive. The refrigerant currently used is usually water, with a working fluid of lithium bromide. Equipment costs for gas-fired absorption chillers are usually at least twice as expensive as electric motor-driven vapor-compression chillers. They are also usually considerably larger and require more cooling tower capacity than vapor-compression chillers. Maintenance costs are usually much higher as well.

Gas engine-driven chillers. This option matches an internal combustion engine--often run with natural gas and sometimes with more than one fuel--to one of the many different kinds of vapor compression chillers. The principle advantage over electric motor-driven chillers is that electricity peak-demand charges can be avoided by running the chiller with fuel on site. An advantage over the gas-fired absorption chillers is that gas engine-driven chillers can make use of the vapor compression chillers' high COPs. Coupled with the efficiencies of the internal combustion engine, overall efficiency can be significantly higher than gas-fired absorption chillers. All the trade-offs among refrigerant options remain, however, because the engine is coupled with a vapor-compression chiller. Disadvantages of gas engine-driven chillers include maintenance of an internal combustion engine and the emissions of that engine. Natural gas must also be available on site.

"Other" absorption chillers. These machines have typically been single-effect machines run off of steam or hot water produced by large boilers. Specific plant conditions--such as the availability of wasted heat--must be present to make this option attractive.

Co-generation options. Different combinations of gas engine-driven chillers or hot water-absorption chillers can be used while generating electricity in a co-generation system. For example, a gas engine can be used both for generation of electricity and for running an air conditioning compressor. Or waste heat from a traditional electric generator can be used to power an absorption chiller. The main advantage that justifies the higher cost of a co-generation system is higher total system efficiency.

Thermal Storage Options

Any of the options outlined above can be coupled in an integrated design with thermal storage. Different chiller systems will work best depending on storage type: chilled water, ice, brine, or eutectic. The total system must be analyzed carefully for technical and economic feasibility. The big advantage, however, is that when meeting any given building load, if thermal storage is used the size of the chiller and its charge of refrigerant can be reduced. During new construction if space is ample outside the building, chilled water tanks (which can be architecturally "enhanced" to reduce the "eyesore problem") can sometimes be constructed more cheaply than the equivalent cost for chiller capacity.

Refrigerant Options

CFC-11: CFC-11 has been one of the most commonly used refrigerants--after many years of chiller development--because it is safe, efficient, and inexpensive. Because it is a CFC it will probably be phased out of production no later than the end of 1995. The ability to use CFC-11 after that time depends on the ways in which the refrigerant reclamation market develops. Some supplies will certainly be available, although at significantly increased cost. Concerns about the environment make it desirable to phase-out all CFCs as soon as possible because they have the highest ODPs and GWPs (see Table 1).

CFC-12: Like CFC-11, CFC-12 is commonly used because it is safe, efficient, and inexpensive. Future availability and effect on the environment are almost identical to CFC-11.

R-500: R-500 has been used in specialized applications such as in large positive-pressure centrifugals and for low-temperature refrigeration. Because R-500 is 74% CFC-12, it will be phased out quickly along with the CFCs. R-500 also has a very high ODP and GWP.

HCFC-22: HCFC-22 is the most common refrigerant used today. Like the CFCs it is common because after many years of air-conditioning development, HCFC-22 has been safe, efficient, and inexpensive in many types of equipment. The phase-out date for HCFC-22 is frequently debated and predicted. With an ODP approximately five and a half percent of that for CFC-11 and CFC-12, HCFC-22 could be phased out immediately with relatively little effect on the peak ozone depletion level in the stratosphere, predicted to occur sometime near 2005 to 2010. Continued emissions of HCFC-22 now, however, could prolong lower ozone levels for decades after that peak occurs. HCFC-22 has a GWP almost half that of CFC-11.

No alternative refrigerant currently exists for HCFC-22, and it is seen as an important transition refrigerant to make the shift away from CFCs practical. If HCFC-22 is put on an accelerated phase-out schedule, some suggest, equipment owners will be hesitant to invest in conversions or in new equipment to replace CFC equipment. Some environmental groups counter that practical alternatives already exist. Refrigerant manufacturers are testing various alternatives that look promising. Because the installed base of many kinds of air-conditioning equipment using HCFC-22 is so large, one can predict with reasonable certainty that HCFC-22 cannot be phased out until good alternatives are available. Converting to those alternatives, however, may be complicated and costly.

HCFC-123: HCFC-123 has only been used commercially in chillers for a few years, serving as an alternative to CFC-11. HCFC-123 has been much more expensive than CFC-11. HCFC-123 prices have been coming down quickly while CFC-11 has been taxed increasingly. Prices for the two are predicted to be the same near the beginning of 1993.

With an ODP only two percent of CFC-11 and CFC-12, HCFC-123 does far less damage to stratospheric ozone than CFCs. Refrigerants 22 and 123 are both HCFCs, but the latter has a much shorter atmospheric lifetime, so more HCFC-123 will have decayed before reaching the stratosphere. HCFC-123, therefore, yields a low global warming impact and has a lower ODP.

HCFC-123 is also considered an important transition refrigerant to make it practical for owners to switch from CFCs. Some environmentalists and politicians have suggested that the dangers associated with ozone depletion are severe enough that all HCFCs should be phased out quickly. Future regulations on phase-out schedules, however, may make distinctions between HCFC-22 and HCFC-123.

HCFC-123 is more toxic than most refrigerants, with a recommended chronic exposure limit one tenth of that for all major refrigerants except for ammonia. Toxicological testing is not yet complete. Even so, if safety precautions that should be applied in the handling of all refrigerants (local codes and ASHRAE Standard 15R, public review draft 2) are followed, HCFC-123 can be safely used.[2]

HFC-134a: HFC-134a has also been used only recently in commercial chillers, serving as an alternative for CFC-12 and R-500. HFC-134a has been many times more expensive than CFC-12 or R-500. HFC-134a prices are dropping quickly, CFC-12 is being taxed, but the costs are not predicted to be the same nearly as quickly as for HCFC-123 and CFC-11. HFC-134a is produced with a more complicated process that will always make HFC-134a more expensive than refrigerants such as HCFC-22 or HCFC-123.

HFC-134a has no chlorine and therefore no ozone depletion potential. It does, however, have a GWP approximately a third of that for R-11.

Ammonia: Use of ammonia as a refrigerant in commercial buildings has been almost nonexistent because of ammonia's flammability and toxicity. Model and local codes have usually restricted ammonia's use to applications where equipment rooms are separate from the main building structure, for example, in central plants for a group of buildings. Future code changes or exemptions may allow for greater use of ammonia, but special emphasis must be placed during design to provide for adequate refrigerant monitoring, mechanical ventilation, physical protection and/or separation of refrigerant from occupants, and provision for either flaring the ammonia outside, absorbing the ammonia in a tank of water, or chemical absorption in the event of a major leak.

Water: Water has been used for years in absorption chillers. It is safe and cheap, but its efficiency is tied to the relatively low COPs of the absorption cycle. No regulatory phase-out is considered!

Chiller Conversions and Replacements

Introduction

Some of the most difficult decisions prompted by the CAA Amendments involve converting chillers to alternative refrigerants and choosing chiller/refrigerant combinations for new construction. These are the decisions that involve a considerable degree of the owner's financial risk in combination with many technical, safety, political, and environmental considerations.

Without exception, an owner or designer considering a chiller conversion to an alternative refrigerant should contact the original equipment manufacturer (OEM) for input. The OEM can provide necessary data regarding seals, gaskets, lubricants, heat exchangers, impeller aerodynamics, and other information for the original chiller and for available conversion options. Remember, however, that the advice of the OEM will usually represent only one marketing point of view when it comes to making the right decision on whether or not to convert, buy another chiller, or just "limp along" with the current chiller/refrigerant combination until the unit is retired.

It is an important shared responsibility of the owner and the designer to make informed decisions about what chiller/refrigerant course to follow in either conversions or in new construction. This section investigates which criteria (first cost, energy efficiency, chiller type, refrigerant monitoring equipment, etc.) are most important when making those decisions. A systems engineering trade-off analysis model is used here for a cross section of chiller and refrigerant options. There are a number of advantages in using a trade-off analysis model for such an analysis. One advantage is to overcome the difficulty in objectively weighing more than a couple different criteria mentally at one time. The trade-off analysis model allows a person to prioritize and analyze different criteria separately before the model combines them mathematically. Another advantage of using the model is the ability to quickly "play what if" with different criteria and to run scenario analyses on the problem.

Criteria Used to Evaluate Chiller Options

Five criteria are used here to evaluate chiller options for both installed chillers and new construction. The sixth criterion, "Loss in Capacity," applies to installed chillers only.

1. **Life Cycle Cost:** based on annual energy cost, any additional annual maintenance costs, the installed cost for the chiller, and any additional first cost for safety considerations. The analysis period used is 20 years, with an effective interest rate of five percent used for the baseline model.

2. **First Cost:** including the installed cost for the chiller, refrigerant and starter costs, demolition costs if the analysis is for a replacement, and any additional costs for larger condenser piping and cooling tower capacity for absorption chillers.

3. **Environmental Impact:** considering the ODP and GWP of each refrigerant as well as the net equivalent warming impact of the system. An HCFC-22 screw chiller, for example, is scored slightly better than an HCFC-22 centrifugal because the screw option often has a higher part-load energy efficiency and lower total energy consumption. This usually results in lower emissions at the power plant for the screw option.

4. **Safety:** based on the toxicity and flammability of each refrigerant, as well as additional costs necessary to ensure safe operation.

5. **Future Uncertainty:** based on the future uncertainty of refrigerant availability and possible future regulations and taxes (such as accelerated phase-out schedules or a carbon tax).

6. **Loss In Capacity:** Because some chillers (including almost all CFC-11 chillers) suffer a loss in capacity when converted, they may require compromises in building operations to make up for the loss in capacity. In some cases, conversion is not even an option because of lost capacity. In this model's baseline, an option is scored low if 100 percent capacity is not available.

Life-Cycle-Cost (LCC) Analysis

Table 2 is the baseline model used in the LCC analysis for nine chiller conversion and purchase options. A 325 ton CFC-11 centrifugal was used as the original chiller for the conversion scenarios, a commonly encountered example. The baseline model includes 1,200 full-load hours per year. Energy efficiencies (kW/ton) and installed chiller capital costs are estimated from equipment bids provided for an actual building. Added annual maintenance costs are based on discussions with contractors, consultants, and manufacturers. The higher cost to maintain the installed CFC-11 chiller is because of its age. The utility rates for natural gas and electricity are taken from *Energy User News* (December 1991 edition) for the month of August, 1991. The baseline rates of $0.49/therm and $0.08/kWh for electricity are typical for an area such as Washington, D.C. The added safety cost of $25,000 for the ammonia chiller is an estimate to allow for mechanical room modifications. A private sector discount rate of nine percent with an inflation rate of four percent (effective interest rate of five percent) is used for

Table 2. Baseline Life-Cycle-Cost Analysis Model

	Amounts in $1000s								
Type of Chiller	IPLV KW Per Ton (Or COP)	Annual Energy Cost	Added Annual Maint. Cost	Total Annual Operating Cost	NPV Total Annual Operating	Installed Chiller Capital Cost	Added Safety Capital Cost	Total Capital Cost	20 Year Present Worth
CFC-11 Original	0.75	$23.4	$1.0	$24.4	$304.0	$0.0	$0.0	$0	$304.0
Modify for HCFC-123	0.7875	$24.6	$0.0	$24.6	$306.1	$66.0	$0.0	$66	$372.1
New 123 centrif.	0.65	$20.3	$0.0	$20.3	$252.7	$128.0	$0.0	$128	$380.7
New 134a centrif.	0.65	$20.3	$0.0	$20.3	$252.7	$141.5	$0.0	$142	$394.2
New 22 Centrif.	0.65	$20.3	$0.0	$20.3	$252.7	$133.0	$0.0	$133	$385.7
New 22 Screw	0.6	$18.7	$0.0	$18.7	$233.3	$134.0	$0.0	$134	$367.3
New Ammonia Screw	0.6	$18.7	$0.0	$18.7	$233.3	$165.0	$25.0	$190	$423.3
New 134a Screw	0.6	$18.7	$0.0	$18.7	$233.3	$154.0	$0.0	$154	$387.3
New Gas Absorption	0.95	$24.1	$3.0	$27.1	$338.2	$320.0	$0.0	$320	$658.2

the baseline. All of these rates are varied later to examine their impact on the model.

As one might expect, the original CFC-11 chiller has the lowest LCC because no capital costs are incurred. LCC does not address the key problems with CFC-11, its environmental impact and its phase-out schedule. The six next best options are within seven percent of one another, probably within the range of error for this kind of analysis. Only the ammonia chiller and the gas-fired absorption chiller have a considerably higher LCC than the group of six options, with absorption the worst.

A series of scenario runs revealed the following from the LCC model:

- Twenty Year Present Worth values are two to three times as large as the Total Capital Cost. This is not surprising, but it is useful to note for the following reason. If one is concerned about which refrigerant to use because of added first costs for small equipment such as monitoring devices or additional mechanical ventilation, these types of issues are far less important than the yearly operating costs, which are driven primarily by chiller energy efficiency and utility rates.

- For scenarios where annual electric energy costs are very low--such as combinations of fewer hours of operation and/or lower electricity rates--conversion to HCFC-123 has the most favorable LCC except for the original CFC-11 option.

- Conversely, with high annual electric energy costs, either conversion to HCFC-123 or keeping the CFC-11 option has an unfavorable LCC. Under this scenario the three screw-chiller options are the best, a result of their commonly higher part-load energy efficiencies.

- Even with high electricity rates of $0.11/kWh and with low gas rates of $0.43/therm (such as in parts of Rhode Island), the absorption chiller option still has the highest LCC. Only with these electricity and gas rates, and with a utility rebate available for two-thirds of the first cost, does the absorption chiller have the most favorable LCC.

- With the baseline rate of $0.08/kWh for electricity, with an interruptable gas rate of $0.40/therm, and with a utility rebate for half the first cost, the absorption chiller's LCC is still the highest.

- Variations in effective interest rates or variations in the analysis period to fewer than 20 years do not significantly affect the results in most cases. When a 10-year period is used, however, conversions to HCFC-123 become more favorable.

Trade-off Analysis

The results of the LCC analyses above and the five other criteria previously described were applied to each chiller option in a trade-off analysis model. The baseline model is shown in Table 3. As each criterion is applied to each chiller option, the merits of each option are expressed as a scaled figure of merit. For example, the chiller option with the lowest first cost is scored a 1.0 and the option with the highest first cost is scored a 0.0. As seen in Table 3, a weighting factor is applied to each criterion, with the sum of all weighting factors equaling 100 percent. These weighting factors, and other factors from the LCC model, can easily be changed to perform scenario analyses on the trade-off model. The results of a series of scenario analyses are summarized in Table 4.

Recommendations and Conclusions

For installed chillers only:

- If an installed CFC chiller is operating well, it will often be better to maintain the current chiller as long as CFC refrigerant supplies are adequate rather than convert or replace immediately. It is prudent, however, to convert or replace the chiller before CFC refrigerant supplies (even reclaimed) become too low. The lead time necessary to plan and perform a conversion or replacement makes it important to start the planning now and to make the changes to the CFC chiller before conditions are critical.

  The recommendation above to continue using an installed CFC chiller is based on a common perspective that first cost and LCC are the most important criteria for many owners. If an owner is equally concerned about the environmental damage of CFC refrigerant emissions, then a conversion or replacement sooner is advised.

  The age of the chiller is also a factor, of course. If the chiller is near the end of its useful life, the decision may be simple to wait a short time and then replace it.

- Converting a CFC-11 chiller to HCFC-123 is usually not the best option. If first cost is very important, however, then it will probably be as good an option as some of the others (see Table 4).

Table 3. Baseline Trade-off Analysis Model

		CFC-11		Convert 123		123 Centrif.		134a Centrif.		22 Centrif.		22 Screw		Ammonia		134a Screw		Gas Absorp.	
Criteria	WF	SFM	WSFM	SFM	WSFM	SFM	WSFM	SFM	WSFM	SFM	WSFM	SFM	WSFM	SFM	WSFM	SFM	WSFM	SFM	WSFM
LCC	0.3	1.00	0.30	0.81	0.24	0.78	0.24	0.75	0.22	0.77	0.23	0.82	0.25	0.66	0.20	0.76	0.23	0.00	0.00
Final Cost	0.3	1.00	0.30	0.79	0.24	0.60	0.18	0.56	0.17	0.58	0.18	0.58	0.17	0.41	0.12	0.52	0.16	0.00	0.00
Env. Impact	0.1	0.00	0.00	0.50	0.05	0.80	0.08	0.90	0.09	0.40	0.04	0.50	0.05	1.00	0.10	0.90	0.09	0.60	0.06
Safety	0.1	1.00	0.10	0.70	0.07	0.70	0.07	1.00	0.10	1.00	0.10	1.00	0.10	0.00	0.00	1.00	0.10	1.00	0.10
Uncertainty	0.1	0.00	0.00	0.60	0.06	0.70	0.07	0.90	0.09	0.50	0.05	0.50	0.05	1.00	0.10	0.90	0.09	0.90	0.09
Capacity	0.1	1.00	0.10	0.00	0.00	1.00	0.10	1.00	0.10	1.00	0.10	1.00	0.10	1.00	0.10	1.00	0.10	1.00	0.10
Total Score			0.80 (high)		0.66		0.74		0.77 (high)		0.70		0.72		0.62		0.77 (high)		0.35 (low)

Note: WF is Weighting Factor, SFM is Scaled Figure of Merit, WSFM is Weighted and Scaled Figure of Merit

Also, if capacity loss is not a problem, conversion is often one of the best options. If the installed CFC-11 chiller is somewhat oversized or if a lighting project can be performed, the loss in capacity may not be a problem.

Conversions will also often be the best option if mechanical rooms are poorly accessible. In those situations, the additional costs for taking out the old chiller and getting the new unit inside may make the costs for new chiller options prohibitive.

For installed chillers or for new construction:

- This author does not recommend purchasing a new CFC-11 or CFC-12 chiller with the intent of converting it later. By the time a chiller selected now is installed, the relative benefits of starting the chiller with a CFC refrigerant will be less than the disadvantages.

- HFC-134a chillers--in either a centrifugal or screw configuration--often scored the highest in trade-off analysis scenarios (or next highest, behind keeping CFC-11 chillers) and deserve careful consideration for many individual building applications. For owners and designers looking for a balance of moderate first cost, low environmental impact, low toxicity and flammability, and good chances for future availability, HFC-134a options are often the best compromise.

- New HCFC-123 and 22 chillers may also be good options if first cost and LCC are perceived to be most important.

- Ammonia screw chillers do not usually represent an attractive option at this time for commercial applications where the chiller plant is near occupied areas. If the chiller is located in a central plant or another remote area, the ammonia chiller option will be much more competitive.

- Gas-fired absorption chillers are probably best only in areas where utility rates favor gas and where utility rebates are available for more than half the installed cost of the absorption chiller. If prices for absorption chillers come down while their COPs go up, this conclusion may change.

- If the kW-per-ton efficiency of the original CFC-11 chiller is different from that used in the baseline scenario, it does not significantly affect the results of the analyses.

- If one believes that potential regulations related to global warming are too unclear at this time to warrant any judgement of the global warming impacts of various refrigerant options, one can judge the environmental impact of each option based on ODP only. Under these scenarios, the HCFC-123 options are more competitive, but the overall advantages of each option are basically unchanged.

Table 4. Summary of Scores from Trade-off Model Scenario Analyses

Model Changes	Keep CFC-11	Convert To 123	123 Centrif.	134a Centrif.	22 Centrif.	22 Screw	Ammonia Screw	134a Screw	Gas Absorp.
Baseline	0.80 high	0.66	0.72	0.77 high	0.70	0.72	0.62	0.77 high	0.35 low
Baseline (ODP only)	0.80 high	0.70	0.75	0.78 high	0.72	0.73	0.62	0.78 high	0.39 low
First Cost=60% LCC-20%, Env.=0% Uncertainty=0%	1.00 high	0.71 next	0.69 next	0.68 next	0.70 next	0.71 next	0.48	0.66	0.20 low
First Cost=0% Environ.=40%	0.50 low	0.57	0.72	0.87 high	0.64	0.70	0.80	0.88 high	0.53 low
First Cost=0% Environ.=40% (ODP only)	0.50 low	0.73	0.84	0.91 high	0.72	0.74	0.80	0.92 high	0.69
First Cost=0% LCC=60%	0.80	0.66	0.77	0.83 high	0.75	0.79	0.70	0.84 high	0.35 low
First Cost=40% Capacity=0%	0.80 high	0.74 next	0.68	0.73 next	0.65	0.68	0.56	0.72 next	0.25 low
High Electricity & Low Gas Rates	0.80 high	0.61	0.69	0.74 next	0.67	0.71	0.58	0.75 next	0.35 low
High Electricity, Low Gas, & 2/3 Absorption Rebate	0.78 high	0.44	0.50	0.52	0.47	0.55	0.30 low	0.54	0.78 high
Interruptable Gas Rate and 2/3 Absorption Rebate	0.80 high	0.50	0.50	0.53	0.47	0.53	0.30 low	0.53	0.57 next
10 Year Analysis Period for LCC	0.80 high	0.66	0.70	0.75 next	0.68	0.70	0.59	0.74 next	0.35 low
Low Energy Cost	0.80 high	0.67	0.70	0.75 next	0.68	0.69	0.59	0.74 next	0.35 low
High Energy Cost	0.64	0.49	0.71	0.78	0.70	0.77	0.70	0.83 high	0.35 low
Old CFC-11 at 0.70 kW/ton	0.80 high	0.68	0.69	0.75 next	0.67	0.70	0.60	0.74 next	0.35 low
Old CFC-11 at 0.85 kW/ton	0.80 high	0.65	0.74	0.80 high	0.72	0.75	0.65	0.79 high	0.35 low

The trade-off analysis model helps to show that selections of different chillers and alternative refrigerants are affected strongly by different perspectives that owners and designers bring to the decision process; *there is no single chiller/refrigerant combination right for all situations.* These owner/designer perspectives include the various degrees of emphasis on cost, environmental concern, etc. The key, as mentioned earlier, is for the owner/designer to make **informed** decisions, recognizing explicitly the criteria that affect equipment selection and choosing which criteria the owner/designer wants to emphasize.

An owner or designer can examine the scenarios presented here to derive insights into what options would be best to study in more detail. Also, a copy of the spreadsheets used for this model can be obtained from this author[3]. Data specific to an individual building--based on contractor quotes--can then be used with the model for more accurate analysis.

Endnotes

1. U.S. EPA Global Change Division
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   Washington, DC 20046

2. As stated earlier, this public review draft is not yet a consensus document but can serve as an effective source in addition to others. Request the final published version when it is approved.

3. Dale R. Stanton-Hoyle
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   Rockville, MD 20850

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