Status of and Advances in Centrifugal Chillers

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ABSTRACT

This paper reviews typical applications for chillers using turbo, and specifically centrifugal, compressors. It outlines the driving factors for these uses and summarizes the levels of international usage. It identifies primary product distinctions with regard to performance, refrigerants, compressor options, stages, drives, and heat exchangers. It presents recommended minimum efficiency levels and reviews the historic progression in performance improvement in relation to environmental impacts. The paper discusses technology developments to reduce emissions of both refrigerants and the greenhouse gases associated with energy use. It briefly reviews conversion options for older chillers. It also comments on related use of heat recovery chillers and industrial heat pumps. The paper closes with mention of future opportunities for sustainable development and uncertainties for centrifugal chillers.

1. INTRODUCTION

Chillers offer several advantages particularly as system sizes increase. In addition to economic savings, they centralize the primary equipment to facilitate maintenance and repair. Similarly, they reduce the equipment space requirements, service traffic, noise, and heat rejection discharges (from condensers or cooling towers) in the occupied spaces served. They also simplify system modifications as uses of and loads in those areas change. While chillers require distribution piping, the cost is partially offset with reduced ducting and simplified electrical distribution. Chiller systems, and particularly central chillers, reduce openings for building intrusion, an advantage with current sensitivity to building security.

The smallest chillers use positive displacement compressors, notably scroll and reciprocating piston-compressors. The focus shifts first to screw compressors and then to turbo-compressors, specifically to centrifugal compressors, as capacities increase. While the ranges by compressor types overlap, centrifugal chillers (more precisely chillers employing centrifugal compressors) start from outputs of 300 kW and dominate for 1300 kW and higher. The largest machines run to approximately 34 MW, primarily limited by practical constraints (physical size and demand) rather than theoretical restrictions. The two largest centrifugal refrigeration machines known to the author actually are heat pumps, rather than chillers, with capacities of 45 and 46 MW. They are collocated with two “smaller” machines of 30 MW each. These four heat pumps serve a district heating system in Göteborg, Sweden. That country leads the world in application of large heat pumps for district heating, including a number of centrifugal machines of 25 MW output.

Axial compressors are conceivable and probably would take over in still larger sizes, again limited by practical constraints, or in compressors with more than three or four numbers of stages as might be desirable with use of ammonia or water as the refrigerant. The distinction between centrifugal and axial turbo-compressors is the direction of refrigerant flow in compression, parallel to the shaft — or along the axis — in axial and pushed outward from the shaft — along the radius — in centrifugal (sometimes also referred to as radial) machines.

1.1. Applications

Centrifugal chillers typically are the core of central systems serving large office, commercial, medical, entertainment, high-rise residential, and similar buildings or clusters of buildings. Both large central and interconnected plants, generally with multiple chillers in each, are common for shopping centers; university, medical, and office campuses; military installations; and district cooling systems. Centrifugal chillers also find application in industrial settings for both space conditioning and process or product cooling. They are essential both in electronics manufacturing and computing centers, where large amounts of heat often must be removed. Current use of axial machines is extremely limited, primarily for systems using water as both the refrigerant and distribution medium in specialty applications, such as for large mines, and in a number of demonstrations systems [1-4].

Not surprisingly, the highest use of centrifugal chillers occurs in countries with the greatest dependence on air conditioning, namely North America and Asia, which account for 40-45% and 25-30%, respectively, of the total. Use is increasing in Europe, in the Middle East, and especially in Asia. Locations such as Korea, Malaysia, and Taiwan with significant electronics manufacturing depend on such systems. Asian nations, and particularly those in hot or in hot and humid climates, are likely to see dramatic further growth attendant to rapid economic and industrial development and to expansion of the large cities leading the economic wave. Usage also is increasing in South America, though at a lower rate.

Eight manufacturers produce the majority of the roughly 4300 centrifugal chillers made each year. The quantity of manufacturers triples with counting of companies and joint ventures assembling them, using key components (notably compressors) supplied by those eight. The author knows of only one company manufacturing centrifugal chillers in Italy, and that with imported compressors.

1.2. Chiller Distinctions

The vast majority of centrifugal chillers are water-cooled. They typically use cooling towers to reject heat. Most air-cooled machines are smaller than the centrifugal range, but use of air-cooled centrifugal chillers is accepted in arid locations, notably in the Middle East.

While the refrigerant employed is often cited as the first distinction between offerings from different manufacturers, examination suggests that the primary distinction is more closely related to the technologies employed, which then dictate refrigerant preferences and for them specific optimization paths. The largest manufacturer of centrifugal chillers, with a market share approximately matching the total of its competitors, focuses on direct drive, hermetic approaches with refrigerant-cooled motors. The multistage design — two stages in large capacities and three stages in small sizes and older models — exploits the advantages of low-pressure refrigerants, formerly R-11 and (less commonly) R-113, but currently R-123. The next largest manufacturer deviates with open-drive (air-cooled motors), geared machines that use smaller, higher-speed impellers and the same low-pressure refrigerant choices in single-stage machines. A third manufacturer makes hermetic, gear-driven, single-stage R-123 chillers; four others made similar machines, but no longer do so.

The first two of the cited manufacturers also produce hermetic, gear driven machines formerly using R-12 and (less commonly) R-114 and R-500, but currently R-134a. Three of them also made machines using R-22, but the demand for R-22 centrifugal chillers is now reduced. The remaining manufacturers of centrifugal chillers also produce hermetic, gear driven machines using R-134a. Most of the R-134a chillers are single-stage except in very large (>7 MW) capacities, for which they employ multistage compressors.

Except for the condensers of air-cooled and remote-condenser chillers, these chillers generally use horizontal, shell-and-tube heat exchangers for both the condenser and evaporator, the latter commonly flooded. There are significant internal differences in the designs of the several manufacturers. While highly enhanced tubes are now typical, to reduce approach temperatures and thereby improve efficiencies, the specific enhanced surfaces and bundle configurations differ. At least one manufacturer employs a horizontal tube, falling-film, spray-evaporator in its R-134a design to reduce the amount of refrigerant needed. Falling-film evaporators with vertical tubes are common for the evaporators of very large centrifugal heat pumps, which often use sea, brackish, or dirty water (such as sewage effluent or even clarified but otherwise untreated raw sewage) as the heat source. Plate heat exchangers or compact brazed-plate exchangers are used for special purposes or when compact designs are needed, but such use is uncommon in the centrifugal class of chillers.

The control systems and control devices, notably the choice between fixed orifices, float valves, and even thermostatic expansion valves, also distinguish products. Nearly all centrifugal chillers today include sophisticated, electronic control modules that both optimize performance and provide on-board event logging and diagnostics. The more advanced systems interface with building control systems to enable anticipatory control schemes and even real-time operation optimization. Also, nearly all centrifugal chiller manufacturers now offer products with adjustable speed drives. Their use remains low, however, due to costs and limited gains when multiple chillers are operated to exploit the high part load performance inherent to centrifugal chiller designs. Similar performance gains often can be achieved for the same or a lower cost increment by selecting an initially higher-efficiency machine with a fixed-speed drive.

The initial equipment costs of the R-134a machines generally are more competitive in low efficiencies, while those of the R-123 machines tend to be more favorable at high efficiencies.

2. EFFICIENCY IMPROVEMENT

One of the primary reasons for selecting centrifugal chillers over alternative equipment types is to obtain higher efficiency — often double that of other, smaller systems. New centrifugal chillers typically use approximately half the energy of those installed just three decades ago. The average coefficient of performance (COP) today is approximately 6.1 at standard rating conditions [5]. Marketed R-134a machines reach COPs of 6.5, while those using R-123 reach 7.8. The 20% difference between those peaks compares to a difference of 4.5% between the theoretical performance limits of 10.89 and 11.38, respectively, for the same refrigerants and rating conditions. The higher practical efficiency advantage of 20% for R-123, despite the excellent heat transfer characteristics of R-134a, relates to the optimization options for it. The machines achieving the highest efficiencies use multistage compression with an economizer for cycle improvements and direct drives to avoid gear losses. The payback period for the cost premium depends on the chiller loads, local energy prices, and applicable power demand costs, but can be less than two years in some applications.

Table I: Minimum Efficiency Requirements for Centrifugal Chillers [a]

equipment type capacity (kW)	COP [b]	IPLV [b]
air-cooled, with condenser		
all capacities [c]	2.80	3.05
air-cooled, without condenser [d]		
all capacities	3.10	3.45
water-cooled		
<528	5.00	5.25
≥528 and <1055	5.55	5.90
≥1055	6.10	6.40

[a] from ANSI/ASHRAE/IESNA Standard 90.1-2001 [6] for electrically-operated centrifugal chillers: The older ASHRAE/IESNA Standard 90.1-1999 specified the same minimum COPs effective 2001.10.29.

[b] rated and certified in accordance with ARI 550/590-1998 [5]

[c] ASHRAE 90.1-2001 [6] actually shows minimum efficiencies for both <528 and ≥528 kW, but they are the same values.

[d] for use with remote condensers

Table I shows the minimum efficiencies stipulated for centrifugal chillers by the widely referenced ANSI/ASHRAE/IESNA Standard 90.1 [6]. This standard is only mandatory where adopted by laws or regulations, but the federal government in the United States is likely to require that states adopt requirements that are at least as stringent as those in the standard. The COP must be determined and certified at standard rating conditions representing full-load operation [5]. The Integrated Part Load Value (IPLV) is a weighted average calculated from prescribed rating conditions and weighting factors to approximate representative annual performance. The standard requires that chillers meet or exceed both the applicable COP and the applicable IPLV indicated.

ANSI/ASHRAE/IESNA Standard 90.1 also stipulates minimum required COP and Nonstandard Part-Load Value (NPLV) ratings for alternative design conditions. These minimum efficiency ratings cover a range of leaving chilled water temperatures, entering condenser water temperatures, and condenser flow rates for equipment designed to operate at nonstandard conditions. The alternative compliance ratings are important with the current shift to lower evaporator temperatures, higher condenser temperatures, and/or with reduced condensing water flows to conserve pumping and fan energy and to reduce piping, duct, and related space costs. Lowered chilled water temperatures also offer advantages for integration with thermal storage systems.

An approved change to the *International Energy Conservation Code* (IECC) [7,8], a model construction code gaining adoption in parts of the USA and in some additional countries, incorporates the same minimum COPs. Its IPLV minimums are numerically the same as the COPs. They were taken from an earlier version of ASHRAE/IESNA Standard 90.1, but effectively lowered further by unintentional adoption of a later edition of the applicable rating standard that reduced the weighting of full-load operation. Future changes probably will remove these inconsistencies.

The importance of Table I is that the efficiencies shown reflect available — and economically justified — minimum performance levels. Anticipated increases in energy prices and environmental concerns, discussed below, suggest specification of efficiency levels that exceed these minimums. As is evident in , and specifically for water-cooled chillers, the efficiency requirements increase with capacity. This forces the largest systems — typically those with the highest loads but sometimes with increased parasitic energy use for distribution pumping and losses — to achieve the highest performance.

3. REFRIGERANT EMISSION REDUCTIONS

Reference 9 and an expanded version in reference 10 tabulate compiled data on refrigerant releases from centrifugal chillers. Figure I summarizes the dramatic trend in release reduction, by as much as two orders of magnitude in several decades. This remarkable achievement was driven, for the most part, by growing environmental awareness, market economics including manufacturer competition to claim reduced emissions, and anticipation of refrigerant shortages and future regulations. Data from three independent studies for more than 4000 chillers confirm attainment of current levels below 0.5 %/yr [11].

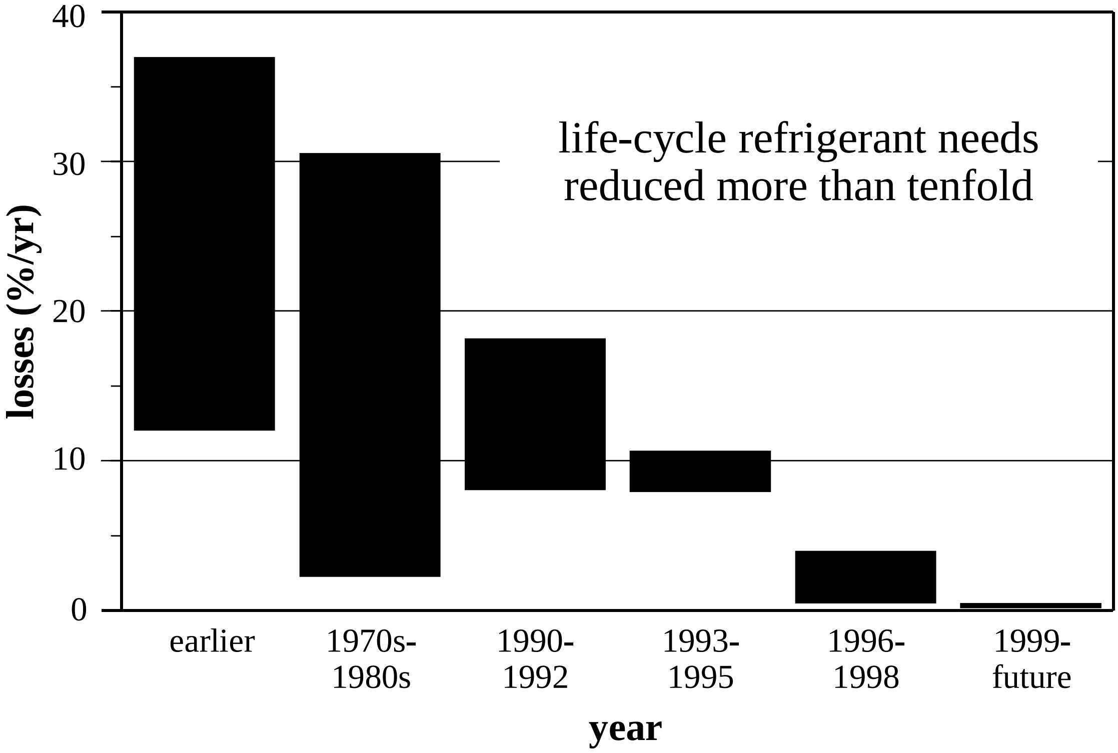

Figure I: Refrigerant Losses from Chillers

The dramatic reductions required changes in equipment design, manufacturing, service, and disposal as well as changes in refrigerant manufacturing and packaging. The following discussion highlights some of the key changes.

<u>Seals and Joints</u>

- <u>design changes to minimize the number of joints in refrigerant circuits</u>: Modifications and use of special assemblies reduced the number of joints and fittings to less than 10% of those previously used.
- <u>replacement of flared and other mechanical connections with brazed connections</u>: While brazed joints increase the cost of fabrication, they are not prone to loosening with vibration and service errors.
- <u>augmentation of threaded joints with o-rings</u>: For joints that cannot be eliminated, for service or other access needs, use of threaded joints with added o-ring seals lowers seepage.
- <u>use of new gasket materials</u>: A new class of flat gasket materials provides tighter seals, in some cases at lower sealing pressures. Similarly, systematic screening tests identified materials that are more durable and that absorb less refrigerant.
- <u>augmentation of flat face gaskets with silicone beads</u>: This change increases the local pressure in places where it is difficult to achieve high sealing pressure due to bolting patterns.
- <u>replacement or augmentation of gaskets and o-rings with adhesive sealants</u>: The new sealing materials, and especially anaerobic adhesive sealants, both reduce losses and lower the likelihood of manufacturing and field application errors.

Purge Systems

- use of condensing purges: Older purges used a variety of thermal, buoyancy, and pressure methods to separate air from refrigerants in low-pressure chillers and in subatmospheric operation of medium- and even high-pressure systems, at low or very low temperatures, for refrigeration. Modern purges cool the removed air below the boiling point of the refrigerant to separate them and return the condensed liquid refrigerant to the chiller or refrigeration machine. Condensing purges typically use a small, hermetic refrigeration circuit, but greatly reduce the refrigerant quantity released in venting the purged air. Other designs use lubricants or other fluids cooled by the chiller itself instead of separate refrigeration circuits; they are simpler, but cannot run when the chiller is off.
- use of vapor recovery systems in purge venting: Even though the amount of refrigerant released by condensing purges is very small, it can be reduced to virtually none by passing the removed air through a material that absorbs any residual refrigerant vapor. Typical systems employ activated charcoal pellets in tanks. Early systems required sending the tanks to a reprocessing facility. Current approaches process the tanks on site, during scheduled maintenance, and return the recovered refrigerant directly to the chiller.

Service

- incorporation of on-board refrigerant storage or means for charge recovery during service: Some designs include receivers or provisions to isolate the refrigerant in the evaporator or condenser, so some internal service procedures can be performed without having to remove the charge from the chiller. Others facilitate recovery into and recharge from permanently connected or portable storage systems. Both strategies are effective in containing the refrigerant charge during service.
- introduction of, and in some countries requirements for, refrigerant recovery equipment: Utilization of such equipment enables reuse of the refrigerant, often after passing it through filter-driers to clean it, and reduces the likelihood of intentional venting.
- shift from scheduled lubricant changes to when needed: By reducing the frequency of oil changes, both the dissolved refrigerant and lubricant quantities are conserved. Periodic oil analyses and chemical monitoring assure lubricant integrity with reduced chemical use, waste, and disposal burdens.
- increased diagnostic measures in preventative maintenance: Checking for conditions that suggest the likelihood of imminent failures, such as periodic eddy-current testing of heat exchanger tubes, enables corrective actions before failures and associated refrigerant releases occur.
- education and training of technicians: A number of associations, manufacturers, and labor unions have instituted training programs, often culminating in proficiency testing, to improve the qualifications of technicians who install and service air-conditioning and refrigeration equipment. Such programs improve the prospect that technicians learn the procedures necessary to minimize failures and to perform their tasks with lowered refrigerant losses.
- license requirements for technicians: Some countries, states, and local jurisdictions

require that technicians servicing specified equipment obtain licenses to do so. Candidates usually must demonstrate training through prescribed courses, testing, apprenticeship, or some combination of them. Such requirements provide a limited assurance of competency and frequently also verify awareness of environmental protection measures.

- increasing role of manufacturers in service operations: Whereas most chiller systems were installed and serviced by independent companies in the past, and sometimes by the staffs of building owners and/or managers, equipment manufacturers have increased their roles in and technical support for service operations. Similarly, both manufacturers and independent laboratories now offer chemical analyses of refrigerants and lubricants, to improve maintenance and to identify imminent failures. These shifts improved both the likelihood and the competence of preventative maintenance.

Other Changes

- use of cylinders instead of drums to transport and store low pressure refrigerants: Although they have a higher first cost, use of cylinders of the type commonly used for high-pressure refrigerants enables service technicians to draw vacuums on emptied containers to extract any residual refrigerant. The older drums would buckle when evacuated, so some refrigerant was lost each time one was disposed. Moreover, the bungs used to open and close those drums were more leak-prone than protected cylinder valves. The cylinders can be returned for reuse, which also reduces other waste.
- use of enhanced heat transfer surfaces: Although the primary incentive for this change was to improve efficiency, it also reduced internal volumes and thereby lowered the refrigerant charge size, the amount lost in catastrophic failures, and upstream (those in refrigerant manufacturing, packaging, transport, and storage before use). Related advances in heat exchanger design, such as in tube-bundle configuration and spray nozzle placement, and — in some chillers — shifts to compact plate heat exchangers provide similar benefits.
- design changes to extend service intervals: Some refrigerant, such as that trapped under gaskets or absorbed by motor insulation materials, is lost each time equipment is opened even with recommended pump-down procedures. By reducing service frequencies through design modifications and use of more durable materials, some refrigerant releases are avoided.
- design changes to reduce failures and extend equipment life: As an example, manufacturers changed the baffle designs and materials inside shell-and-tube heat exchangers, which are the type most widely used in water-cooled chiller condensers and in the majority of chiller evaporators, to reduce tube vibration and wear. Doing so minimizes one cause of potential leaks. Similarly, manufacturers also strengthened tube headers in heat exchangers and improved the fabrication methods to attach tubes; both of these changes improved initial tightness and reduced the likelihood of future leaks.
- manufacturing advances: Modern extrusion and other fabrication methods improve the integrity of refrigerant circuits. The seamless copper or other tubes used today, as an example, are less prone to failure than welded tubes of the past.
- factory tests: Most manufacturers now check all assemblies (not just random samples)

for leaks with helium mass spectrometers or other methods that are capable of detecting even miniscule leaks. These methods are more sensitive, reliable, and economical than older methods that used more primitive refrigerant detectors, air bubbles, or soap solutions. Manufacturers also check all completed chillers in the best cases.

- use of leak detectors: Although promoted to improve technician safety in refrigeration machinery rooms, use of detectors set at very low concentration levels provides an early warning of incipient leaks, before significant refrigerant losses occur. Both leak detectors and microcomputer controls, discussed below, can be connected to remote annunciators or phone dialers to notify technicians of leaks. New fire and mechanical regulations in some locations require remote annunciation, at constantly attended locations staffed with trained personnel, to assure that detector alarms are heeded.
- microcomputer control of operation: Computerized control systems to optimize operation for the highest efficiencies gained use in the last 15 years. They now are the norm chillers and other sophisticated air-conditioning and refrigeration equipment. Tracking of critical operating parameters enables detection of failures before their severity increases refrigerant losses and other damage. These microcomputers also monitor run time, purge operation, and refrigerant leak detectors to facilitate preventative maintenance and alert technicians of service needs and impending failures. As the technologies advance, some of these systems are incorporating anticipatory logic and schedules to project future loads and optimally control operation, for example with integrated thermal storage. Moreover, the computerized controls enable remote supervision and intervention by service technicians and trained supervisory staffs, technicians, and engineers.
- bearing advances to reduce or eliminate compressor lubricants: Reducing or eliminating lubricant needs also reduces or eliminates release of the refrigerant dissolved in the oil when changed. New approaches reduce service frequency and even eliminate the need for compressor oils and oil changes. One manufacturer already offers magnetic bearings in very large chillers. Other approaches, with announcements expected in the near future, include advanced hydrostatic, ceramic, permanently lubricated, and other bearing technologies.
- regulations to prohibit intentional venting: While deliberate release of refrigerants during service or upon equipment retirement historically was common in smaller systems, it was not a common practice in large chillers, for which the refrigerant amounts and costs already justified recovery measures. The regulations have some impact for chillers, for example to limit releases when the quantities taken from containers in charging do not fully empty them or when components are serviced (for example system cleaning after a hermetic motor burnout).
- regulations to require repairs when refrigerant make-up amounts exceed prescribed thresholds: Such regulations assure that chronic leaks are repaired or that the equipment involved is taken out of use or replaced. Again, chiller operating economics generally assured the same results, but the restrictions address the worst cases and increase the penalties for deferring prudent service and replacements.

This list of technology, service, and regulatory advances to reduce emissions suggests a revolution, rather than evolution, in measures to reduce refrigerant releases.

Moreover, this list highlights only the key changes; there were many others. Also, the technologies developed to reduce releasers for environmental reasons offer advantages for safety too.

4. ENVIRONMENTAL IMPACTS

Nearly all refrigerants used in centrifugal chillers just over a decade ago have been or are being phased out in new equipment [12]. R-11, R-12, R-113, and R-114 were eliminated in new equipment as chlorofluorocarbons (CFCs) to protect the stratospheric ozone layer. Their use will continue in existing equipment for decades to come using stocked and recovered refrigerants for service except in countries prohibiting such use. R-500, an azeotropic blend containing R-12, was similarly phased out. Of the old refrigerants for centrifugal chillers, only R-22, a hydrochlorofluorocarbon (HCFC) continues in use, though it too was displaced to some extent. The primary alternatives now are R-123 and R-134a. Like R-11, which it replaced, R-123 is used in nearly two thirds of centrifugal chillers based on its performance advantages and the benefits of low pressure operation.

R-22 and R-123 — both HCFCs — are scheduled for phaseout under the Montreal Protocol and implementing national regulations, though there is a strong environmental rationale to consider a reprieve for R-123 [13]. Rigorous analyses show that the impact of R-123 from refrigerant use on ozone depletion is negligible, with less than a 0.001% contribution to the peak [11]. Further studies indicate that its environmental benefits outweigh its ozone impact and justify reconsideration of its phaseout [9-11,13-16].

While the scientific justification for reprieve of R-123 is strong, the political aspects are harder to predict. Production is allowed for nearly three more decades (four in developing countries) even without reconsideration. For now, the Protocol calls for ceasing their production by 2030 in industrialized countries and by 2040 in developing countries. National regulations impose the same or earlier deadlines for use in new equipment, for production or import, and — in extreme cases — for all uses. These dates generally are earlier or much earlier for R-22, based on its higher ozone depletion potential (ODP).

The impact of chillers on global warming depends on the combined greenhouse gas influences of four components, namely:

- refrigerant releases, sometimes identified as the “refrigerant-related” or “direct” effect,
- emissions associated with system energy for normal operation, sometimes identified as the “energy-related” or “indirect” effect,
- emissions associated with increased energy use due to efficiency degradation with charge loss, and
- emissions associated with manufacturing and ultimate disposal of the refrigerant and equipment.

Of these four components, the second is by far the largest for centrifugal and other chillers. Its dominant magnitude points to the need to improve efficiency to lower global warming impacts. The refrigerant-related component — including initial, operating, intermittent, and retirement losses — amounts to less than 0.2% of the total for new R-123 and less than 3% of the total for new R-134a centrifugal chillers [9]. The third component may range from negligible to 10% or more of the total depending on the leak rate and service practices. It typically is comparable to the second component; reference 10 plots data for efficiency dependence on refrigerant charge. Recognition that leakage lowers efficiency underscores the importance both of minimizing refrigerant losses from leakage and service — even when using refrigerants with extremely low global warming potentials (GWPs) — and of proper equipment installation and maintenance. The fourth component is negligible for centrifugal chillers due to the larger impacts of the other terms over the long life of typical equipment.

Figure II shows the consequences of reduced emissions, both refrigerant- and energy-related, from centrifugal chillers on total greenhouse gas emissions. The data shown are for 1750 kW centrifugal chillers using R-11 and R-123, the most widely used refrigerants in such equipment. Similar conclusions can be drawn for replacement of R-12 with R-134a for the same time frame, although the absolute emissions both start and end at higher levels. The underlying analyses and data are detailed in references 14 and 17; the only change herein is recalculation with the refrigerant GWPs from the latest international scientific assessment [18]. The updated GWPs for 100-year integration are 4600 for R-11, 10 600 for R-12, 120 for R-123, and 1300 for R-134a.

The four components — or at least portions of the first (refrigerant-related) and the second (energy-related) — are commonly expressed as the *net warming impact* (NWI), *total equivalent warming impact* (TEWI), *life-cycle-warming impact* (LCWI), or *life-cycle climate performance* (LCCP).

R-11 dominated in centrifugal chillers almost since its introduction. Refrigerant losses were high; they often exceeded 15% of the total charge each year, as shown in Figure II for 1985. Small efficiency gains appeared by 1990, but more significant gains were introduced in system tightening and improved purge technologies. The figure

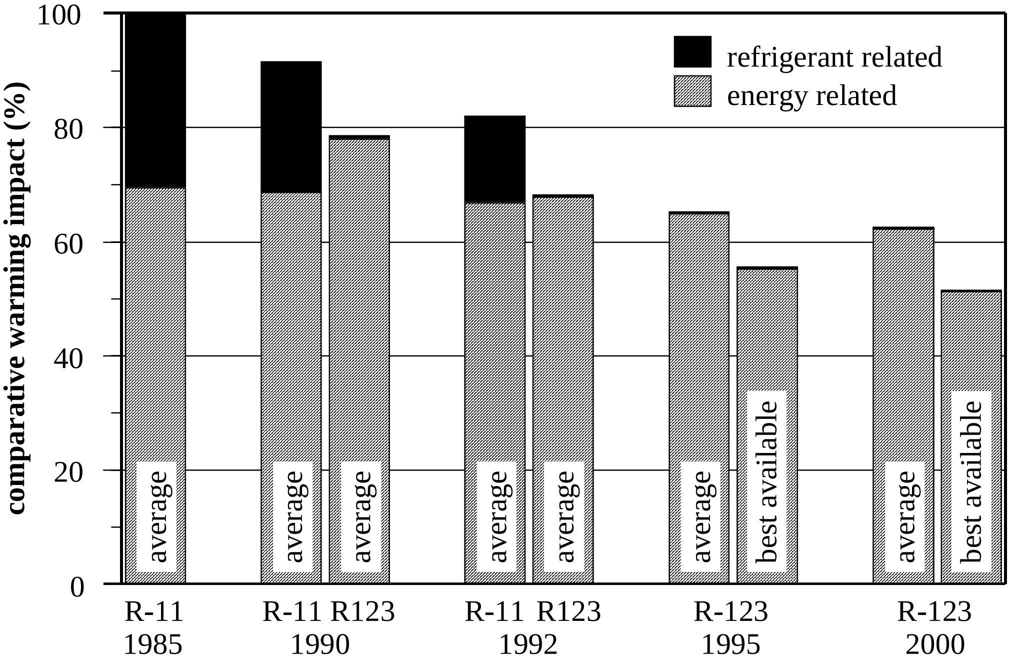

Figure II: Progression and projection for comparative warming impacts for centrifugal chillers for 1985-2000 with replacement of R-11 by R-123

shows the resultant drop in impacts from emissions. R-123 use also had begun, though the first machines — essentially R-11 designs with materials changes for compatibility — yielded 14-16% lower efficiency. The direct warming impact of R-123 emissions is barely visible, owing to the difference in GWPs, a decrease of more than 97%.

Release reductions continued both by equipment tightening and improved service practices, as discussed above. By 1992, the last year in which R-11 chillers were manufactured for domestic use in the United States, net refrigerant emissions for machines of comparable capacities were half of those in 1985 and before. These reductions offer several benefits beyond reduced global warming. They also lower the impact on ozone depletion. The ozone depletion potential (ODP) and GWP of a chemical are only relevant for the portion that is released. Refrigerant that does not escape, and is recovered for reuse or safe disposal, does not harm the environment. Reduced losses also eliminate the need for makeup, thereby saving other resources, lowering costs, improving safety, and avoiding performance losses from insufficient refrigerant charge.

Figure II also shows the dramatic improvements made by 1995 in R-123 chiller optimization, leading to higher practical efficiency than available with the retired R-11 designs. This achievement, and subsequent further gains, is all the more impressive since R-11 holds a small theoretical efficiency advantage over R-123 [14].

Further improvements in performance followed and will continue, but the pace will slow as gains approach theoretical limits. Coupled with emission reductions and the lower GWPs of R-22, R-123, and R-134a, the best chillers in 1995 reduced net global warming impacts by approximately 45% compared to typical machines a decade earlier. This fraction exceeded 48% by the year 2000 as shown Figure II.

R-245fa offers potential to approach R-123 efficiencies in large capacities, 3-15 MW, with use of multistage compressors [12,14]. Its commercialization as a refrigerant is still uncertain. Such use will depend on broad market acceptance as a foam-blowing agent, to reach affordable production levels. Even then, R-245fa is likely to cost more than other refrigerants, based on the manufacturing processes entailed. The decisive factor for equipment manufacturers is likely to be assurance of long-term availability [12,14].

5. CONVERSION OPTIONS FOR OLDER CHILLERS

Nearly a decade after the start of chiller conversions from CFCs to alternatives, owners have converted approximately 10% and replaced nearly 40% of the estimated inventory of 80 000 CFC chillers in the USA [19]. The conversions and most of the replacements were to machines using R-123 or R-134a. Analyses by the author show the cited estimate to have undercounted the initial inventory of 92 000-94 000 chillers, suggesting correction of those shares to 9% and 33% respectively. The conclusion is the same — there remains a long way to go and the process is moving slowly. Moreover, the conversion option is becoming less favorable than replacement as the original machines age, particularly since replacement often will result in lower life-cycle costs from energy savings with higher current efficiencies.

Owners have several options except as constrained by national regulations that may limit choices. The options include continued use with containment measures to reduce leaks, conversion to alternative refrigerants, and outright replacement. Several constraints on conversions worth noting are:

- Refrigerant conversions generally must be limited to fluids with similar pressure-temperature characteristics, namely R-123 for R-11 and R-134a for R-12 and R-500.
- No conversion should be attempted without contacting the equipment manufacturer to determine materials compatibility, safety, and control requirements.
- Conversions generally will require more than a simple changing of refrigerants. Other requirements could include replacement of impellers and/or drive gears, motors (for hermetic compressors), lubricants, seals, o-rings, and other components depending on the refrigerants. Conversion of R-12 to R-134a generally should be simpler than for R-11 to R-123.
- Introduction of new refrigerants often requires modifications to the machinery room.
- Equipment manufacturers offer several options for conversions, both on-site and in their factories. Two manufacturers offer replacement compressor and motor assemblies for conversion of chillers, including equipment manufactured by other companies, installed in locations that are difficult to access, such as building subbasements in cities.

Most manufacturers can reliably predict changes in capacity and efficiency for conversion of equipment that they produced. In some cases, gear changes or impeller modifications may allow trades between capacity and efficiency in conversions. Building or lighting upgrades may offset capacity losses. Addition of thermal energy storage may afford another opportunity to offset reduced capacity.

As a final note on conversions, related pumps and cooling towers also must be examined. A decrease in efficiency may require increased heat rejection.

Reference 20 offers more details on options for existing equipment.

6. HEAT RECOVERY CHILLERS AND INDUSTRIAL HEAT PUMPS

Centrifugal chillers can be fitted with auxiliary condensers for heat recovery. Likewise, centrifugal machines can be modified and controlled as heat pumps for a range of applications. The introduction above mentioned four large centrifugal heat pumps that serve a district heating system. These heat pumps extract heat from sewage to complement oil-fired boilers in the same system. The heat pumps actually pick up the majority of the load in the summer for service hot water. These machines were converted in 1994 from R-12 to R-134a.

Centrifugal heat pump use was more common in the past than today. A fair number of the R-114 machines produced were for high condensing temperatures for heat recovery and heat pump applications. One of the more innovative applications was a steam-producing machine for a pasta factory in Italy.

While interest in such applications is lower today, the technologies are well known. There is no suitable commercial substitute for R-114 for this purpose. Its primary replacement today for conversion of naval chillers is R-236fa, but equipment manufacturers are not promoting it for other uses due to its high GWP. Several studies have identified R-123, R-245ca, R-245fa, and hydrofluoroethers including R-E245cb1, among others as candidates for high-temperature applications. Facing uncertainties as to the future acceptability of such fluids, manufacturers are not pursuing them aggressively for heat pump uses despite potential environmental benefits.

7. OPPORTUNITIES FOR SUSTAINABLE DEVELOPMENT AND UNCERTAINTIES FOR CENTRIFUGAL CHILLERS

Manufacturers, design engineers, contractors, and service technicians deserve great credit for the advances made to phase out CFCs without compromise of safety or efficiency for centrifugal chillers. They likewise have made tremendous strides toward reducing global warming.

The next steps are precarious. We know how to switch to hydrocarbons, and analyses of n-butane, isobutane, and n-pentane show potential to approach the efficiencies of R-123 and R-134a. But use of hydrocarbons in centrifugal chillers is very different from their use in small systems such as domestic refrigerators. The charge amounts involved would exceed 100 kg in the smallest units and exceed 500 kg in typical and 7000 kg in the largest capacities. An explosion of that amount of hydrocarbon would easily demolish a building or even a neighborhood. Isopentane and n-pentane, in particular, despite their potential for high efficiency [9,14,21], would operate at subatmospheric conditions with the possibility of air entry though leakage. Compression of the resulting mixture would be extremely dangerous.

Ammonia and water both result in lower efficiencies [9,14] at higher costs in the centrifugal range and application conditions. Although they avoid fluids with high GWPs, use of absorption cycles would significantly increase net greenhouse gas emissions due to their low efficiency limits [17,22].

An integrated assessment shows that continued use of R-123 as a refrigerant in centrifugal chillers would have negligible impact on stratospheric ozone depletion and offers the lowest impact on global warming [11-13], but it is scheduled for phaseout under the Montreal Protocol — and already has been phased out in some European countries — as an HCFC. R-134a use is a good choice, but it is under attack as an HFC (a greenhouse gas) and would increase the net global warming impact for the best chillers by 14-20% compared to R-123 [12,14]. The “natural” refrigerant options would lower efficiencies further and thereby increase global warming impacts. If fluorochemical options are eliminated, ammonia offers the best overall replacement despite its marginal flammability and safety concerns with potential releases of large quantities. Significant development will be needed and probably result in an axial rather than a centrifugal compressor, particularly in large capacities, or reversion to many smaller screw compressors. Water also is an option, but still needs extensive development and will raise costs considerably.

8. CONCLUSIONS

Regardless of the refrigerant used, the reasons explained above necessitate greater attention to leak minimization and to proper initial installation and ongoing service. If the first goal of sustainable development is to reduce environmental impacts, responsible use of R-123 is the clear choice. However, its long-term future use will take an amendment to the Montreal Protocol. Failing that, R-134a and possibly R-245fa offer good options, but are less attractive environmentally than R-123. If the first goal is fluorochemical phaseout, then we need intensive effort to develop large ammonia and water machines and both recognition and acceptance that the result will do more harm to the environment than choices eliminated ostensibly to protect it.

9. REFERENCES

1 P. Albring, R. Apley, and B. Burandt, "Turbokaltwassersatz mit Wasser als Kältemittel" [Turbo Chiller with Water as a Refrigerant], Bericht über die Kälte-Klima-Tagung [Proceedings of the Refrigeration and Air-Conditioning Conference] (Hamburg, Germany, 19-21 November 1997), Deutscher Kälte- und Klimatechnischer Verein e.V. (DKV, German Association of Refrigeration and Air-Conditioning Engineers), Stuttgart, Germany, DKV-Tagungsberichte 24(II.2):119-130, 1997

2 J. Kuhnl-Kinel, *New Age Water Chillers with Water as Refrigerant*, Centre Européeane pour la Recherche Nucléaire (CERN) [European Center for Nuclear Research], Geneva, Switzerland, 1998

3 J. Paul, "Water as Refrigerant," *Proceedings of the 19th International Congress of Refrigeration* (The Hague, The Netherlands, 20-25 August 1995), International Institute of Refrigeration (IIR), Paris, France, IVb:955-960, 1995

4 S. E. Wright, T. Yoshinaka, B. A. LeDrew, and N. C. D'Orsi, *The Efficiency Limits of Water Vapor Compressors*, report ARTI-21CR/605-10010-01, Air-Conditioning and Refrigeration Technology Institute (ARTI), Arlington, VA, November 2000

5 *Water-Chilling Packages*, ARI Standard 550/590-1998, Air-Conditioning and Refrigeration Institute (ARI), Arlington, VA, USA, 1998

6 *Energy Standard for Buildings Except Low-Rise Residential Buildings*, ANSI/ASHRAE/IESNA Standard 90.1-2001, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, USA, and Illuminating Engineering Society of North America (IESNA), New York, NY, USA, 2001

7 *2000 International Energy Conservation Code*, International Code Council (ICC), Falls Church, VA, USA, December 1999

8 *2001 Supplement to the International Codes*, International Code Council (ICC), Falls Church, VA, USA, March 2001

9 J. M. Calm, "Emissions and Environmental Impacts from Air-Conditioning and Refrigeration Systems," *Proceedings of the Joint IPCC-TEAP Expert Meeting on Limiting the Emissions of HFCs and PFCs* (Petten, The Netherlands, 26-28 May 1999), Intergovernmental Panel on Climate Change (IPCC) of the World Meteorological Organization, Geneva, Switzerland, and Technical and Economic Assessment Panel (TEAP) of the United Nations Environment Programme, Nairobi, Kenya, 125-138, 1999

10 J. M. Calm, "Emissions and Environmental Impacts from Air-Conditioning and Refrigeration Systems," *International Journal of Refrigeration*, 24:, 2002 (in press)

11 J. M. Calm, D. J. Wuebbles, and A. K. Jain, "Impacts on Global Ozone and Climate from Use and Emission of 2,2-Dichloro-1,1,1-trifluoroethane (HCFC-123)," *Journal of Climatic Change*, 42:439-474, June 1999

12 J. M. Calm, “Options and Outlook for Chiller Refrigerants,” *Proceedings of the Earth Technologies Forum* (Washington, DC, USA, 30 October - 1 November 2000), Alliance for Responsible Atmospheric Policy, Arlington, VA, USA, 239-248, October 2000; in Chinese in *Journal of Refrigeration and Air Conditioning*, China, 1(2):59-67, April 2001; *Engineered Systems*, 18(5):88-99, May 2001; in traditional Chinese in *Heating, Ventilating, Air-Conditioning, Refrigeration, and Heat Exchange (Journal of HVACR & HX)*, Taiwan, 90.5(42):1-13, May 2001; in Japanese in *Reito* [Refrigeration], Japan, 76(889):993-1004 (63-74), November 2001; in Spanish in *ACR-Latinoamérica*, Columbia (distribution throughout Central and South America), 4(6):18-27, November-December 2001

13 D. J. Wuebbles and J. M. Calm, “An Environmental Rationale for Retention of Endangered Chemicals,” *Science*, 278(5340):1090-1091, 7 November 1997

14 J. M. Calm and D. A. Didion, “Trade-Offs in Refrigerant Selections: Past, Present, and Future,” *Refrigerants for the 21st Century* (proceedings of the ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD, USA, 6-7 October 1997), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, USA, 6-19, October 1997; in Japanese in *Reito* [Refrigeration], Japan, 73(847):433-444 (27-38), May 1998; *International Journal of Refrigeration*, 21(4):308-321, June 1998

15 C. Kroeze and L. Reijnders, “Halocarbons and Global Warming,” *Science of the Total Environment*, Part I - 111(1):1-24, Part II - 112(2-3):269-290, and Part III - 112(2-3):291-314, 1992

16 S. O. Anderson and E. T. Morehouse, “The Ozone Challenge,” *ASHRAE Journal*, 39(9):33-36, September 1997

17 J. M. Calm, *Comparative Global Warming Impacts of Electric Vapor-Compression and Direct-Fired Absorption Equipment*, report TR-103297, Electric Power Research Institute (EPRI), Palo Alto, CA, USA, August 1993

18 Intergovernmental Panel on Climate Change (IPCC, of the World Meteorological Organization, WMO, and the United Nations Environment Programme, UNEP), *Climate Change 2001: The Scientific Basis — Contribution of Working Group I to the IPCC Third Assessment Report*, Cambridge University Press, Cambridge, UK, 2001

19 Air-Conditioning and Refrigeration Institute (ARI), *Half-Way Marks in Sight for Replacement and Conversion of CFC Chillers Used for Air conditioning of Buildings*, press release, Arlington, VA, USA, 11 April 2001

20 J. M. Calm, “Alternative Refrigerants: Challenges and Opportunities,” *Heating/Piping/Air Conditioning Engineering*, 64(5):38-49, May 1992

21 I. Maclaine-cross, “Replacement Refrigerants for Water Chillers,” *Proceedings of the Joint IPCC-TEAP Expert Meeting on Limiting the Emissions of HFCs and PFCs* (Petten, The Netherlands, 26-28 May 1999), Intergovernmental Panel on Climate Change (IPCC) of the World Meteorological Organization, Geneva, Switzerland, and Technical and Economic Assessment Panel (TEAP) of the United Nations Environment Programme, Nairobi, Kenya, 241-251, 1999

22 J. M. Calm, “Global Warming Impacts of Chillers,” *Heating/Piping/Air Conditioning Engineering*, 65(2):28-39, February 1993