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RESOURCE, OZONE, AND GLOBAL WARMING IMPLICATIONS OF REFRIGERANT SELECTION FOR LARGE CHILLERS

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ABSTRACT

This paper examines current refrigerant options for centrifugal chillers, the type most widely applied in capacities of 1-9 MW (300-2500 RT) though available in capacities as small as 300 kW and as large as 35 MW (90-10,000 RT). The examination addresses global environmental impacts and specifically those for stratospheric ozone depletion, climate change, and similar but still uncertain future issues. It also addresses efficiency and resulting implications for energy use, both at full (peak) load and on a seasonal basis, as well as other resources. The focus includes chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), and hydrofluorocarbon (HFC) refrigerants as well as alternatives such as ammonia, hydrocarbons (HCs), carbon dioxide, and water, for which selection influences the environment directly and through the resulting efficiency indirectly. Analyses summarized in this paper indicate significant reductions in energy-related greenhouse gas emissions and atmospheric pollutants with upgrading efficiency levels to the best available. The analyses also indicate opportunity to reduce peak electricity demand, potentially avoiding the need for 13 additional gas, 2 coal, or 1 nuclear generating unit(s) per year on a worldwide basis. Additionally, the upgrades identified reduce water usage, chemical treatment for cooling towers, and required fuel imports.

1. CENTRIFUGAL CHILLERS

Chillers are refrigeration machines that cool water, other heat transfer fluids, or process liquids by a vapor-compression (modified reverse-Rankine), absorption, or other thermodynamic cycle. Such machines typically are the core of central systems to air condition large office, commercial, medical, entertainment, residential high-rise, and similar buildings or clusters of buildings. Both large central and interconnected plants, generally with multiple chillers in each, are common. The chilled water or heat transfer fluid (such as a brine or glycol solution) is piped through the building or buildings to other devices, such as zoned air handlers, that use the cooled water or brine to air condition (cool and dehumidify) occupied or controlled spaces. By their nature, efficiency and reliability are essential attributes of chillers.

Both mechanical vapor-compression and absorption systems employ refrigerants. Absorption cycles differ from mechanical compression systems by use of heat-driven, chemical absorption processes to raise the refrigerant pressure. Fuel prices or peak-electric demand avoidance justify absorption chillers in some applications, and they are common in countries with unique energy

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circumstances, such as Japan, and in countries with inadequate electric power infrastructures. However, mechanical vapor-compression dominates in most locations based on significant advantages in efficiency, size, and equipment cost. The compressor types used in mechanical vapor-compression chillers vary with capacity. Positive-displacement compressors dominate in small sizes, starting with piston and scroll compressors and shifting, with overlapping ranges, to screw compressors as capacities increase. Turbo-compressors are the most common type in the largest capacities. Nearly all are centrifugal (radial) rather than axial designs. The remainder of this paper focuses on chillers using centrifugal compressors, or *centrifugal chillers*.

Their capacities range from 300 kW to 35 MW (90 to 10,000 RT). In addition to offering cost advantages in these ranges, centrifugal chillers achieve significantly higher efficiencies than other types. For comparison, the minimum efficiencies recommended (and required in locations adopting the consensus standard) for electrically-powered, water-cooled chillers with capacities of 1055 kW (300 RT) and larger are 4.20 with reciprocating compressors, 5.50 with screw and scroll compressors, and 6.10 with centrifugal compressors (ASHRAE, 2007). The minimums on an integrated-part-load value (IPLV) basis are 5.05, 6.15, and 6.40, respectively (ASHRAE, 2007). The corresponding minimum COPs for single- and double-effect absorption chillers are 0.70 and 1.00, respectively, though these COPs are relative to gas or heat (from hot water or steam) rather than electricity, hence different on a primary energy basis by a factor of approximately three.

2. REFRIGERANT CONSIDERATIONS

Nearly all centrifugal chillers employ fluorochemical refrigerants. Ammonia (R-717) requires an impractical number of centrifugal compressor stages. Furthermore, ammonia leaks pose concerns with flammability and, at high concentrations, also with corrosive affects to skin, the eyes, and mucous membranes. Low cost and high performance offsets these disadvantages in some uses. Ammonia is more commonly limited to use with positive-displacement — notably screw — compressors and primarily in industrial applications. Flammability hazards (notably the potential for massive explosions) generally preclude use of hydrocarbons in centrifugal chillers. Unlike domestic refrigerators, for which hydrocarbon use now dominates in many parts of the world, the larger charge sizes needed for chillers presents too great a risk in urban areas. Also, the hydrocarbons offering the highest efficiency potentials, such as isopentane (R-601a), isopentane/pentane (R-601a/601) blends, or isopentane/hexane (R-601a/602) blends, would operate at subatmospheric pressures, leading to potential formation of explosive mixtures as air leaked in or with high-side leaks as refrigerant escapes. Water is an option especially when designed to produce ice slurries, but the high mass-flow rates required generally dictate use of axial compressors. There are several such chillers in use, but they have not gained broad acceptance primarily due to costs.

Figure 1 contrasts the ozone depletion potentials (ODPs) and global warming potentials (GWPs) for key refrigerants (based on IPCC, 2005; WMO, 2007; and Calm and Hourahan, 2007). A unit of ODP on the left is not equivalent in impact to a unit of GWP on the right; the two metrics gauge dissimilar effects that cannot be equated numerically. However, the figure is useful to show which chemicals are offensive based on ODP, GWP, or both. The Montreal Protocol only addresses protection of the stratospheric ozone layer. The left (ODP) side of Figure 1 reveals the logic of phasing out high-ODP CFCs quickly, moving to zero ODP solutions such as ammonia (or similarly hydrocarbons, carbon dioxide, or water) or to HFCs with practically zero ODP, and allowing

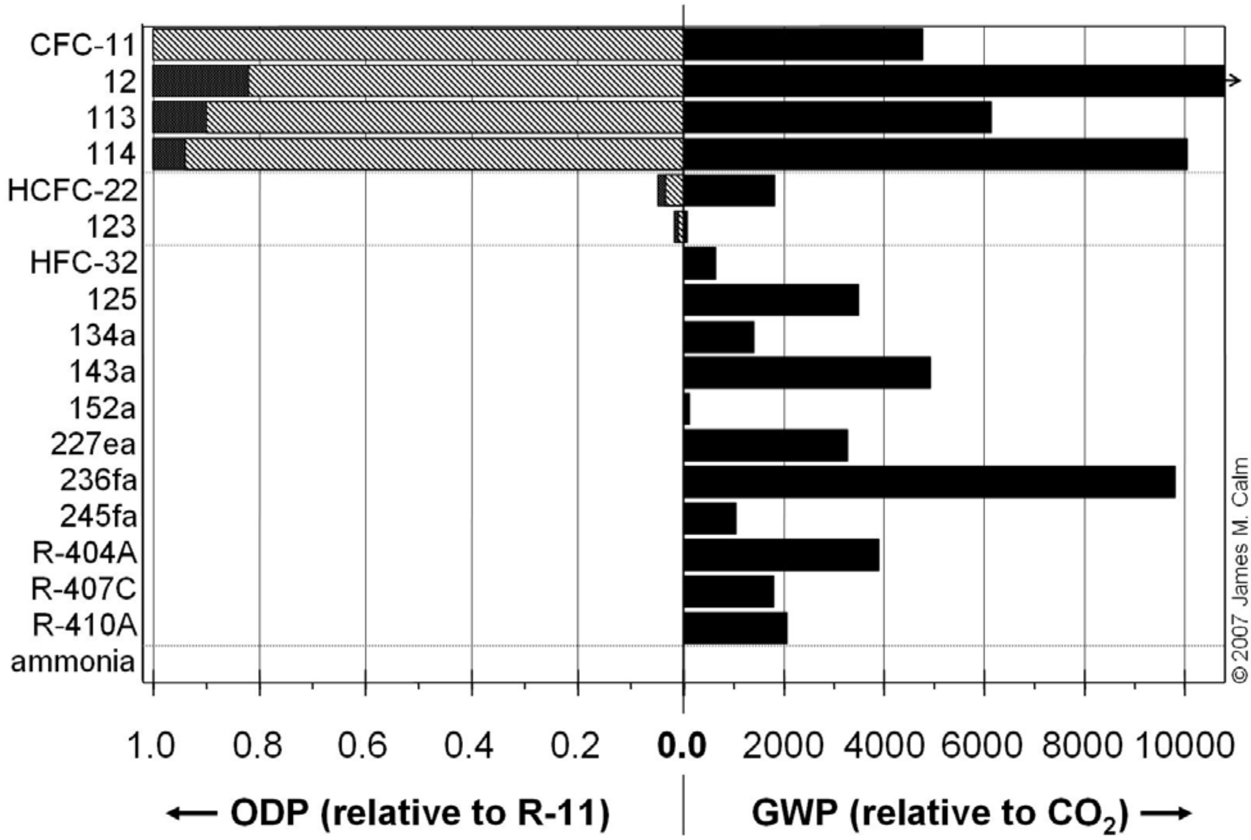

Figure 1: Ozone depletion potential (ODP) contrasted to global warming potential (GWP) for key refrigerants (darker-speckled and lighter-slashed shading indicate semi-empirical and modeled ODPs, respectively). CFCs generally have high ODP and GWP. HCFCs generally have much lower ODP and GWP. HFCs offer near-zero ODP, but some have very high GWPs.

interim use of low or very low ODP HCFCs. The right (GWP) side of Figure 1 — momentarily covering the ODP side on the left — suggests a very different outcome had global warming been addressed first. The GWPs of some HFCs (and perfluorocarbons, PFCs) are comparable or even higher than those of CFCs. The terminology CFCs, HCFCs, and HFCs might not have come into popular usage if climate change had been addressed before ozone depletion, since the right side of the figure shows high GWP variability within these composition families. That variation would have forced selection based on the specific attributes of individual candidates rather than by groups.

Now return to both sides of Figure 1 together. It is clear that ammonia (or similarly hydrocarbons, carbon dioxide, or water) offers zero ODP and near-zero GWP. Likewise, R-32 and R-152a are attractive based on near-zero ODP and low GWP. All three are flammable, though R-32 and ammonia burn less readily. The figure reveals clear advantages for R-123, with both very low ODP and very low GWP. Its GWP of 77 is one of the lowest among fluorochemicals (WMO 2007), and its net-GWP, with adjustment for its impact on ozone (a potent greenhouse gas), of -61 to +49 (midpoint of -6) is lower than for hydrocarbons (Daniel, Solomon, and Albritton, 1995; Calm 2005; WMO 2007). Additional awareness of its very high thermodynamic efficiency, low pressure (hence reduced leakage) of operation, and short atmospheric lifetime increase its environmental appeal. Its fire suppression ability further enhances its attraction as a refrigerant.

Refrigerant selections influence global warming two ways, directly by releases acting as greenhouse gases (GHGs) and indirectly by emissions associated with energy use. The refrigerant-related component can be determined by summing initial, operating, intermittent, and ultimate retirement losses weighted by the appropriate GWP. The majority of refrigerant releases occur on site — at the point of use — from leakage, servicing, and discharges from accidents, some of them catastrophic, and failures. Upstream emissions associated with manufacturing, packaging and repackaging, transport, storage, and equipment charging as well as downstream losses associated with ultimate recovery and disposal occur only once in the life of the refrigerant use. They constitute a small fraction, compared to the operating and intermittent service and failure losses, when annualized for an application with a typical life of 20-30 years.

The energy-related impact results from operation and is strongly influenced by the chiller efficiency and thus by the refrigerant choice. The energy-related GHGs usually are released at the power plants that provide the electricity, or less commonly the steam or hot water, used to power air-conditioning and refrigeration systems. The releases can be largely on-site in the case of engine- or turbine-driven systems, but they too typically use some remotely generated electricity for controls, pumps, fans, and similar auxiliary devices.

Summed over many hours of operation, the energy-related carbon dioxide, nitrous oxides, and other GHGs from fuel use far overshadow the refrigerant-related GHG impact. The ratio of the two effects varies by refrigerant due to differing GWPs, refrigerant emission rates, efficiency, and operating profile. The energy-related component typically exceeds 95% of the total for centrifugal chillers and can exceed 99% for chillers with the lowest refrigerant leak rates (Calm 2005 and 2007). Accordingly, the chiller's efficiency is the key indicator of its global warming impact.

3. CHILLER EFFICIENCIES

R-123 is the most efficient refrigerant for water chillers other than R-11 and R-141b (UNEP, 2007b), with differences of 1.2 and 1.1%, respectively, based on theoretical efficiencies (Calm, 2005). R-11 (a CFC) and R-141b (an HCFC) both have much longer atmospheric lifetimes, higher modeled and semi-empirical ODPs, and higher GWPs than R-123 (an HCFC), by factors of 35, 83, 50, and 62, respectively, for R-11 and 7, 6, 7, and 9, respectively, for R-141b (based on data from WMO, 2007, and Calm and Hourahan, 2007). Additionally R-141b is flammable and both R-11 and R-141b have higher acute inhalation toxicity, but lower chronic inhalation toxicity than R-123. Developed countries have phased out commercial production of both R-11 and R-141b, the latter from primary use as a foam-blowing agent rather than as a refrigerant.

Figure 2 depicts the ranges of rated efficiencies for the five refrigerants most-widely used in current centrifugal chillers. While R-11 and R-12 (both CFCs) theoretically exceed the efficiencies of R-123 and R-134a, respectively, manufacturers ceased improvement for the CFCs in developed (and in most developing) countries in the late 1980s in anticipation of their phaseout. R-123 and R-134a are the most common choices today, with lesser use of R-22. All three can achieve the minimum efficiencies allowed in the most widely adopted energy standards (ASHRAE, 2007, and derivative codes and regulations). The minimum COP labeled in the figure as the "90.1 minimum" is for water-cooled chillers of 1055 kW (300 RT) capacity or larger. The figure shows that R-123 is critical to achieve a 20% improvement, in fact for any improvement exceeding 12%, to address greenhouse gas emissions from associated energy use. For perspective, air conditioning

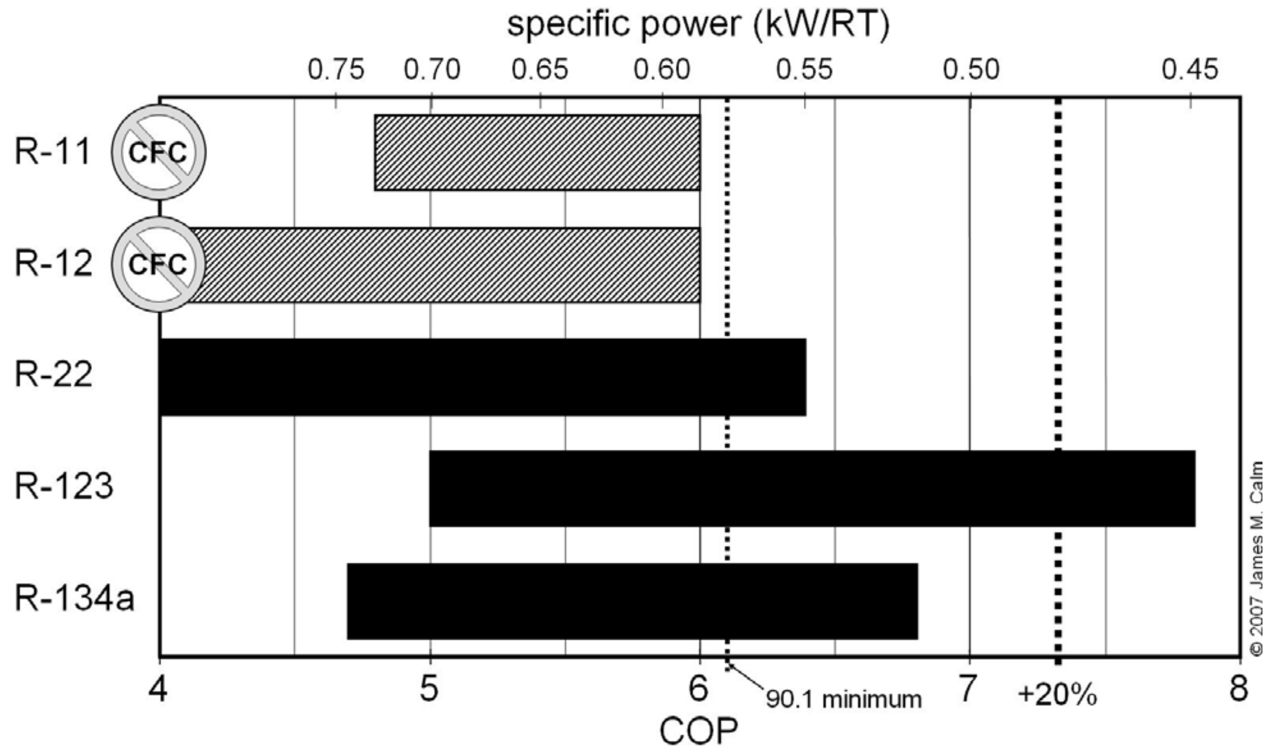

Figure 2: Efficiency ranges by refrigerant in centrifugal chillers

accounts for 26% – the largest single component — of commercial building electricity use in the USA; the sum of all thermal services including cooling, refrigeration, ventilation, and space and water heating amounts to 48% of the total, overshadowing even the sum of lighting, office equipment, and cooking (EIA, 2006; Calm, 2007). These statistics highlight the large opportunities for resource conservation and for emission reductions by increasing efficiency.

Vendors of centrifugal chillers using R-134a (the primary alternative to R-123) insist for marketing reasons that R-123 is not needed. They argue that R-134a chillers driven by adjustable-speed drives (ASDs, primarily inverters) can achieve high annual performance. This argument overlooks the opportunity to apply ASDs with R-123 to realize even higher corresponding efficiencies. Moreover, near-universal use of drive gears for the higher-speed R-134a impellers reduces actual efficiency by 3-4% beyond the 3-5% thermodynamic advantage of R-123. Inverters characteristically degrade full-load efficiency by an additional 3% or more, taxing peak-loaded power transmission and distribution systems and, similarly, requiring more power plants to meet peak air-conditioning demands. Despite aggressive marketing, only one manufacturer — in Japan — has opted to use R-245fa (developed chiefly for foam-blowing use) as a chiller refrigerant, and that as a complement to its primary R-123 line for higher capacities with similar equipment. Although R-245fa offers higher efficiency than R-134a, but still lower than R-123, manufacturers remain concerned with R-245fa's (1) long-term availability based on potential regulation due to its GWP of 1030, (2) significantly higher cost, and (3) potential flammability, despite classification as nonflammable, since it closely approaches the flammability envelope and is marginally flammable at some test conditions.

Prior studies show the impact on stratospheric ozone from R-123 use in chillers — even with exemption from phaseout — to be less than 0.001% of total chlorine-bromine loading (Wuebbles and Calm, 1997; Calm, Wuebbles, and Jain, 1999); that impact is indiscernible and potentially eliminated with any resulting acceleration of CFC retirements. An international technical assessment notes that R-123 has a very low overall impact on the environment because of its low ODP, very low GWP, very short atmospheric lifetime, very low emissions in current chiller designs, and efficiency (UNEP, 2007b). Still, R-123 currently is lumped with all other HCFCs despite its unique environmental and other qualities. It already was phased out in Europe as an ODS and is scheduled, barring reconsideration, for similar phaseout in new chillers by 2020 in non-Article 5 countries and by 2040 in Article 5 countries. The Montreal Protocol allows limited production for service needs until 2030 in non-Article 5 countries. The Protocol imposes no limits anywhere for continued use and service of existing equipment or stockpiled or recovered refrigerant. At least one recent assessment suggests possible reconsideration of earlier proposals regarding phasing out all ODSs. It indicates that “production and consumption of specific chemicals proved to be harmless to the ozone layer could be permitted after the assessment through an adjustment of the Protocol” (UNEP, 2007a).

A typical centrifugal chiller with capacity of approximately 2000 kW (570 RT) and COP of 6.2 (0.57 kW/RT) imposes a peak electrical demand of approximately 370 kW with allowance for condensing pumps and cooling tower fans, also influenced by chiller efficiency. Gas turbine, coal (steam electric), and nuclear generating units average approximately 35, 280, 930 MW, respectively, for summer operation, without adjustment for the number of units per representative plant. Annual production of centrifugal chillers for new construction, expansion, and replacement is approximately 9100 chillers per year on a worldwide basis. Allowing for representative transmission and distribution losses, annual installations require approximately 110 gas, 15 coal, or 4 nuclear units per year. These estimates exclude increases for replaced chillers, generally with significantly lower efficiency than current products, to enable subsequent calculation of incremental generating units (at the margin) with differences in attainable chiller efficiencies.

The best commercially available R-123 and R-134a chillers offer full-load COPs of 7.83 and 6.78 (0.449 and 0.519 kW/RT), respectively, based on certified product ratings. These levels correspond to 69% and 62% of the theoretical efficiency limits for the two refrigerants, again respectively, at standard rating conditions. The best R-123 chillers marketed more closely approach its theoretical limit by use of a two-stage, economizer cycle, whereas the best R-134a machines marketed still use single-stage compressors and suffer gear-drive losses. Both optimize the extent of subcooling, superheating, and similar parameters for the individual refrigerants. The top efficiencies for actual products indicate the state of the art and suggest limits to attainable efficiencies, since manufacturers have incorporated most practical options to boost efficiencies. Full exploitation of the best current R-123 performance over the currently recommended minimum efficiency offers avoided requirement for 13 gas, 2 coal, or 1 nuclear generating unit(s) per year worldwide. These quantities would increase by a factor exceeding 20 for replacement of all existing centrifugal chillers with models matching the best currently available efficiency.

4. ADDITIONAL BENEFITS FROM IMPROVED EFFICIENCY

Chiller efficiency improvement offers a number of additional environmental (and cost) benefits beyond significant potential to reduce GHG emissions. While COPs at full load and IPLVs at standardized rating conditions indicate relative performance among different chillers, neither measure accurately predicts performance for specific applications with varying operating and

Table 1. Benefits from Chiller Efficiency Upgrade from Standard 90.1 Minimum Allowed Efficiency to Best Available Centrifugal Chiller Based on Representative Building Simulation for Hong Kong Climate

reduction (%)	item
3.4	• cooling tower water usage, chemical treatment, and blow-down disposal
18	• overall cooling system energy use • energy-related greenhouse gas emissions • atmospheric pollutants from electricity generation • generating fuel imports
22	• peak electricity demand • required electricity generating, transmission, and distribution system capacities • heat dissipation requirements and noise emanation for transformers (especially noteworthy for those located indoors) • in-building or central plant wiring and switchgear capacities
96	• refrigerant-related greenhouse gas emissions compared to centrifugal chillers using R-134a

weather conditions. Annual simulations, therefore, more accurately indicate performance for specific applications. They consider climate and load profiles, number and sizing of the chillers, distribution burdens, and operating control sequences.

Simulations for a representative building in Hong Kong for the “typical” and “best” equipment showed system efficiencies (including pumps and other accessories) of 8.3 (0.42 kW/RT) and 10.1 (0.35 kW/RT), respectively (Calm, 2007). The actual chillers modeled had COPs of 6.10 (0.577 kW/RT) and 7.85 (0.448 kW/RT) with corresponding IPLVs (for actual equipment selections) of 7.24 (0.486 kW/RT) and 9.13 (0.385 kW/RT), respectively. The simulations modeled a typical arrangement of three equally sized chillers with optimized operation in each case. The reason the annual efficiencies exceeded the ratings despite addition of system burdens is improved performance at part-load operation, which the IPLVs significantly under-predict for the chosen systems with Hong Kong weather data. Table 1 summarizes the implications of the simulation results.

Although not elaborated herein, the price premiums for efficiency improvement are cost effective on a life-cycle basis with reductions in energy costs. The specific payback period depends on the extent of efficiency improvement, but payback periods of less than three years commonly result with efficiency upgrades of 10% or more depending on local utility rates.

Some individuals argue that the very-best performers are expensive despite life-cycle cost advantages. Factoring in the environmental and social cost savings of increased chiller efficiency makes the cost differences a financial bargain. Even closing the gap by only 50% between the current average and state-of-the-art efficiency levels, a common choice of discerning buyers, yields very attractive environmental and economic benefits.

5. CONCLUSIONS

The analyses summarized in this paper indicate significant potential to reduce greenhouse gas emissions and atmospheric pollutants by upgrading chiller efficiency levels. The studies also indicate potential for corresponding reductions in peak electricity demand, potentially avoiding the need for 13 additional gas, 2 coal, or 1 nuclear generating unit(s) per year on a worldwide basis. Additionally, the upgrades identified offer potential reductions in water usage, chemical treatment for cooling towers, and required fuel imports.

REFERENCES

American Society of Heating Refrigerating, and Air-Conditioning Engineers (ASHRAE), 2007, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, ANSI/ASHRAE/IESNA Standard 90.1-2007, ASHRAE, Atlanta, GA, USA, and the Illuminating Engineering Society of North America (IESNA), New York, NY, USA, table 6.8.1C.

Calm, J. M., Wuebbles, D. J., and Jain, A. K., 1999, "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(2):439-474.

Calm, J. M., 2005, "Comparative Efficiencies and Implications for Greenhouse Gas Emissions of Chiller Refrigerants," *Proceedings of the Fourth International Symposium on Non-CO_2 Greenhouse Gases* (NCGG-4, Utrecht, The Netherlands, 2005.07), Vereniging van Milieukundigen [VVM, Netherlands Association for Environmental Professionals], Den Bosch, The Netherlands; Millpress Science Publishers, Rotterdam, The Netherlands; 671-680; 2006, *International Journal of Refrigeration,* 29(5):833-841.

Calm, J. M., 2007, "Centrifugal Chiller Efficiency — Benefits Beyond Reduced Operating Costs," *Proceedings of the International Conference on Climate Change* (ICCC, Hong Kong, 2007.05), Hong Kong Institution of Engineers (HKIE), Hong Kong (in press).

Calm, J. M., and Hourahan, G. C., 2007, "Refrigerant Data Update," *Heating/Piping/Air Conditioning Engineering*, 79(1):50-64.

Daniel, J. S., Solomon, S., and Albritton, D. L., 1995, "On the Evaluation of Halocarbon Radiative Forcing and Global Warming Potentials," *Journal of Geophysical Research*, 100(D1): 1271-1285.

Energy Information Administration (EIA), 2006, *Annual Energy Review 2005*, report DOE/EIA-0384(2005), U.S. Department of Energy, Washington, DC, USA.

Intergovernmental Panel on Climate Change (IPCC) and the Technology and Economic Assessment Panel (TEAP), 2005, *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons*, Cambridge University Press, Cambridge, UK.

WMO, 2007. *Scientific Assessment of Ozone Depletion: 2006*, report 50, World Meteorological Organization (WMO) Global Ozone and Research Monitoring Project, Geneva, Switzerland; United Nations Environment Program (UNEP), Nairobi, Kenya; National Oceanic and Atmospheric Administration (NOAA), Washington, DC, USA; National Aeronautics and Space Administration (NASA) Office of Earth Science, Washington, DC, USA; and European Commission, Research Directorate General, Brussels, Belgium.

United Nations Environment Programme (UNEP), 2007a, *2006 Assessment Report of the Technology and Economic Assessment Panel*, UNEP Ozone Secretariat, Nairobi, Kenya.

United Nations Environment Programme (UNEP), 2007b, *2006 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee — 2006 Assessment*, UNEP Ozone Secretariat, Nairobi, Kenya.

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