THE EVOLUTION OF HVAC EFFICIENCY

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ABSTRACT

This paper discusses the growth in energy efficiency of air conditioning equipment over the last 25 years, looking specifically at the growth in its largest residential and commercial sector products - unitary products and centrifugal chillers. Also discussed are the theoretical and practical limits on efficiency. Finally, the paper will discuss the environmental benefits of these efficiency gains in HVAC equipment over the past 25 years.

HISTORICAL PERSPECTIVE OF EFFICIENCY GROWTH IN HVAC EQUIPMENT

Unitary Products

Unitary air-conditioners and heat pumps constitute the largest product line in residential air conditioning equipment. The United Nations Environment Programme (UNEP) estimate for the worldwide installed cooling capacity of unitary products is 410 x 10^6 tons (1,450 x 10^6 kW) [UNEP, 1995].

Over the past 25 years, the HVAC industry has made significant improvements in the efficiency of unitary products. Figures 1 and 2 show this dramatic growth in the shipment-weighted average efficiencies of unitary air conditioners and unitary heat pumps from 1976 through 1995. It should be noted that in 1981, the efficiency rating criterion for unitary products was changed from the energy efficiency ratio (EER) to the seasonal energy efficiency rating (SEER). Although both are expressed in the same units of measure (Btuh/watt), the two are measured over different operating conditions and therefore are not directly comparable. EER is calculated at a single temperature condition, whereas SEER is calculated over a range of operating conditions that more accurately reflect the conditions over an entire cooling season. Therefore, to accurately assess the growth in efficiency, we must break this data into two separate segments.

Looking at the EER data from 1976 to 1980, we see that the efficiency of unitary air conditioners increased 7.4% over this 4-year period. Their shipment-weighted EER jumped from 7.03 to 7.55. Over the same period, unitary heat pumps had a slightly larger increase of 9.3%, jumping from an EER of 6.87 to 7.51. Looking at the SEER data from 1981 through 1995, we see an even greater rate of improvement in the shipment-weighted SEER of unitary equipment. Over this 14-year period, the efficiency of unitary air conditioners increased overall by 37%, going from a SEER of 7.78 to 10.68. Over the same period, the efficiency of unitary heat pumps had a 42% leap in SEER, rising from 7.70 to 10.97.

However, it should be noted that the above efficiency values are on a shipment-weighted basis. Units with considerably higher efficiencies were also available during the respective time periods, but at higher prices.

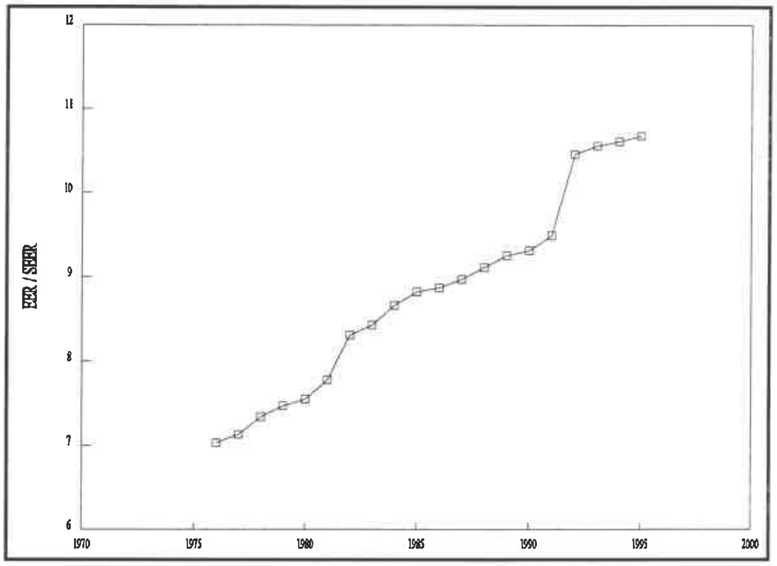

Figure 1. Shipment-weighted Average Efficiencies of Unitary Air Conditioners
Data from 1976 through 1980 are EER values.
Data from 1981 and afterwards are SEER values.

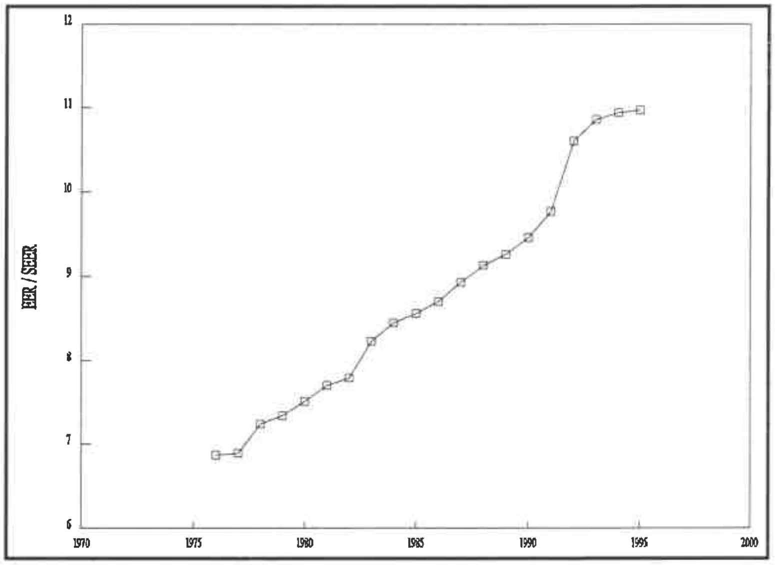

Figure 2. Shipment-weighted Average Efficiencies of Unitary Heat Pumps
Data from 1976 through 1980 are EER values.
Data from 1981 and afterwards are SEER values.

How were these drastic improvements made?

Much of the growth in equipment energy efficiency can be attributed to motor and compressor efficiency improvements. Electric motors used today to drive compressors and to circulate air have higher efficiencies than those used in previous years. Compressor design improvements also have made marked improvements in system efficiency. In 1988, the scroll compressor was introduced into unitary products in the U.S. Since then, more products have adopted the scroll compressor. This revolutionary compressor design provided performance improvements over traditional reciprocating compressors. Improvements in system controls, dual speed motors, heat exchangers, and other improvements also contributed to the enhanced efficiency of unitary products over the last 20 years.

Can we expect even higher efficiency units in the future?

Actually, those units are already on the market today. Top of the line unitary products can achieve efficiencies of yust under 18 SEER. However, market forces for unitary products have not greatly supported the added cost of these higher efficiency units. Growth in the weighted average shipment efficiency can be expected to gradually increase each year. However, it is apparent that, given relatively low energy costs and the lack of consumer rebates or other incentives, there is little consumer demand for the more expensive, top-of-the-line high efficiency units.

Centrifugal Chillers

In the commercial air conditioning sector, centrifugal chillers account for 70% of the global installed cooling capacity, which has been estimated at 60 x 10^6 tons (211 x 10^6 kW) [Fischer 1991]. Improvements in their efficiencies over the past 20 years have been spectacular, as seen in the data supplied by one manufacturer and presented in Figure 3. In the U.S., chiller efficiencies are usually expressed in terms of power input divided by cooling capacity in kilowatts per ton of refrigeration (kW/ton). Therefore, the lower the kW/ton value, the better the efficiency. This is an inverse relationship of what is normally expressed as efficiency. An efficiency of 0.50 kW/ton is equivalent to a COP of 7.03.

Figure 3 depicts the average design efficiencies of centrifugal chiller from a representative U.S. manufacturers over the last 20 years. It should be noted that this manufacturer's chiller efficiencies were several years ahead of its competitors in the early years. However, by 1996 most of its competitors had closed that gap. Therefore, the efficiency presented for 1996 is representative of the U.S. industry average. From these charts, we see that over the past 20 years average efficiencies of centrifugal chillers have increased by 34%, jumping from a COP of 4.24 (0.83 kW/ton) to 5.67 (0.62 kW/ton).

Comparing Figure 3 to Figures 1 and 2, we see that the growth rate for centrifugal chillers has taken on a completely different profile from that of the unitary products. Instead of the steady year-to-year growth rate of unitary products, for centrifugal chillers we see a rapid rise in the early years and less and less growth with each succeeding year.

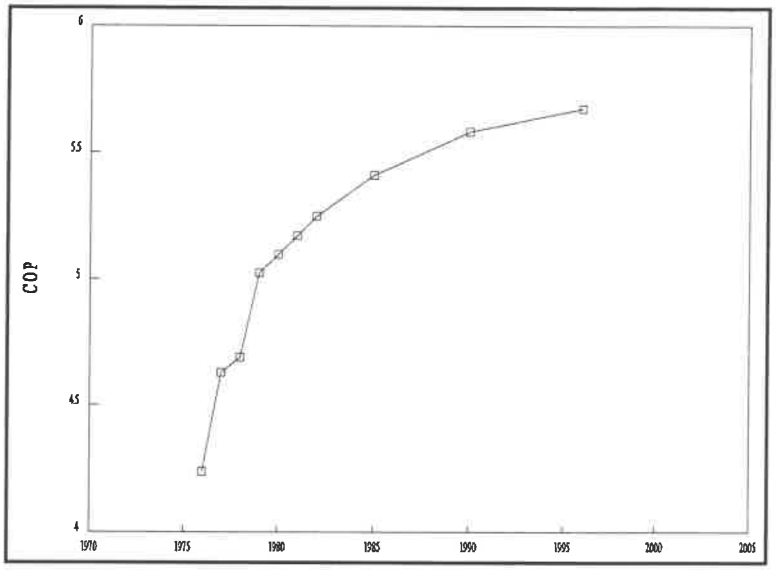

Figure 3. One Manufacturer's Average Design Efficiencies of Centrifugal Chillers (COP)

MAXIMUM ATTAINABLE EFFICIENCIES

What's in store for the future? Are we approaching a limit on the efficiency of centrifugal chillers?

The efficiency limit of the Carnot cycle is the maximum ideal limit on efficiency. The Carnot cycle consists of isentropic compression and expansion and isothermal evaporation and condensation. These are idealistic processes with no irreversible losses. In practice, this is not achievable because of irreversible losses in the compression and expansion of the gas, pressure drops in the lines, and other losses in the heat rejection and absorption processes due to non-uniform temperature throughout the heat exchangers. For cooling cycles, the Carnot efficiency is defined in terms of the absolute temperatures of the evaporator (T_c) and condenser (T_h), as follows:

$$COP_{Carnot} = \quad T_c/(T_h - T_c) \qquad \text{(Eq. 1)}$$

Assuming ARI standard rated conditions for chillers, T_h is 95°F (555 °R or 308 K) and T_c is 44°F (504 °R or 280 K). This gives a Carnot COP of 9.88, or an equivalent chiller efficiency of 0.355 kW/ton. Centrifugal chillers are the among the most efficient cooling systems available. Today's top of the line centrifugal chillers have efficiencies around 0.50 kW/ton or a COP of roughly 7.0. At ARI rated conditions, this is about 70% of the ideal Carnot efficiency.

For comparison purposes, we can calculate the ideal Carnot efficiency for unitary products. At ARI rated conditions, T_h is 95°F (555 °R or 308 K) and T_c is 45°F (505 °R or 281 K). This gives an ideal Carnot COP of 10.1. A COP of 10.1 is equivalent to an EER of 34 Btuh/watt. The most efficient unitary products have SEERs in the 15 to 17 range. As noted earlier, EER and SEER are not directly comparable. However, if we compare the Carnot efficiency in EER to the SEER of the most efficient unitary products, we see that unitary products are currently only at 50% of the maximum ideal Carnot efficiency.

Unitary products and centrifugal chillers each have radically different profiles for efficiency growth over time. However, Figures 1, 2, and 3 reflect the average efficiencies of what was sold and not the best efficiencies available. The market forces for the two product lines are vastly different. In the residential sector, first cost is the driving market force for small unitary products. This encourages purchase of economical units rather than the most efficient models. In the commercial sector, operating cost is a dominant driving force. This encourages purchases of the higher efficiency units.

The Trane Company examined these losses and made projections on practical efficiency improvements for R-123 chillers. For large chillers, efficiency can be improved by perhaps another 4.0%. For smaller chillers, efficiency gains can be as much as 7.5% [Glamm 1996]. Several suggested improvements are summarized in Table 1.

Compressor improvements: Compressor improvements are achievable on smaller sized units and could provide the largest efficiency gain for those units. Suggested improvements include the use of movable guide vanes and diffuser walls (to provide variable flow path geometry and improve impeller efficiency levels at off-design conditions); use of highly machined parts in place of cast parts (thinner impeller blades and extra fine surface finish could also reduce viscous losses).

Table 1. Possible Efficiency Gains from Technological Improvements in Centrifugal Chillers

Improvement	Large Chillers	Small Chillers
Compressor Efficiency	0%	3%
Subcooling	1.5%	1.5%
Spray Evaporators	1.0%	1.0%
Motor Efficiency	0.5%	1.0%
Motor Cooling	0.8%	0.8%
Piping Losses	0.2%	0.2%
Total	4.0%	7.5%

[Source: Glamm, 1996]

Subcooling: Adding subcoolers provides the next greatest possible improvement in efficiency.

Heat exchanger improvements: Successful application of liquid spray evaporators to low pressure chillers could reduce losses caused by liquid static head in the bundle and vapor pressure drop from flow through the bundle.

Hermetic motor improvements: Large centrifugal chillers are already using hermetic electric motors that are 93 to 94.5% efficient. However, stator resistance losses might be reduced by increasing the copper density in the stator through slot geometer changes or by reducing the thickness of wire insulation.

Motor cooling: Some efficiency might be gained by pumping the refrigerant through the motor to remove heat by routing the vapor back to the condenser instead of to the compressor, thereby preventing additional superheat prior to the compression process.

Reducing piping losses: Pressure drop losses in suction lines, discharge lines and suction baffles in the evaporator could be reduced by using computer simulations with the latest computational fluid dynamics codes to design improved vapor flow paths.

With all these improvements, the best efficiency for centrifugal chillers would end up near 0.465 kW/ton or a COP of 7.5. This is 76% of the theoretical ideal Carnot efficiency.

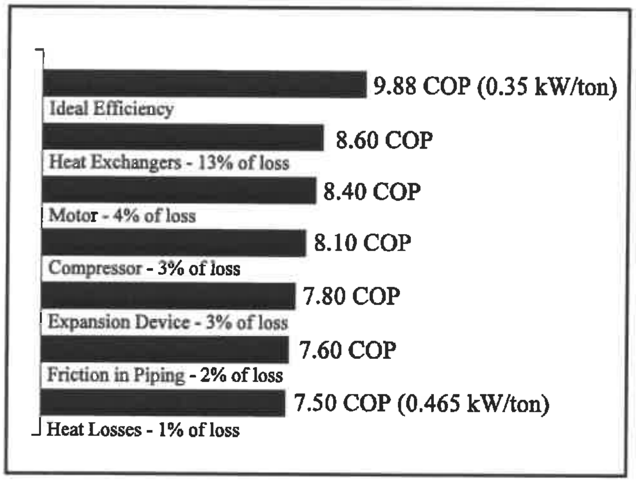

Figure 4. Centrifugal Chillers
-- Losses which cannot be reasonably overcome

ARE FULL-LOAD SEASONAL EFFICIENCY MEASUREMENTS APPROPRIATE?

The efficiency of air-conditioning and refrigeration can be measured in several ways. The easiest method is steady state, which is the efficiency obtained when the equipment is allowed to run at a steady, full load. This is analogous to an auto running at a steady highway speed. A more realistic indicator is a seasonal efficiency measurement. This is analogous to an automobile's stop-and-go driving. For chillers, this seasonal efficiency is call IPLV, Integrated Part Load Value. This measure reflects the fact that the chiller is usually working at less than its full load. The current IPLV formulas in the chiller rating standards (ARI Standards 550, 560 and 590) imply many assumptions.

The IPLV formula in use today was revised in 1992, and reflects best practices at that time. More recent data about the operation of chillers and HVAC systems have shown its limitations. It has been proposed that the IPLV formula be updated to reflect how chillers are applied today. Some of the improvements to the formula suggested:

- ASHRAE temperature bin method used
- the weather is assumed to be USA city weighted average, not Atlanta
- building type is weighted average of various building types
- operation is weighted average of 12 hours/day, 5 day/week & also 24 hours/day, 7 days/week
- chiller operates at outdoor temperatures above & also below 55°F
- entering condenser water temperature and partial loads are based on weather data for type building operation, not fixed incremental values
- weightings are based on weighted averaging of ton-hours, not a straight average of hours

As a result of this revised formula, chiller efficiency would be higher than what is generally now recognized. For example, Figure 5 shows that chiller performance can be as much as 9% more than in computed from the present IPLV formula, for the case shown.

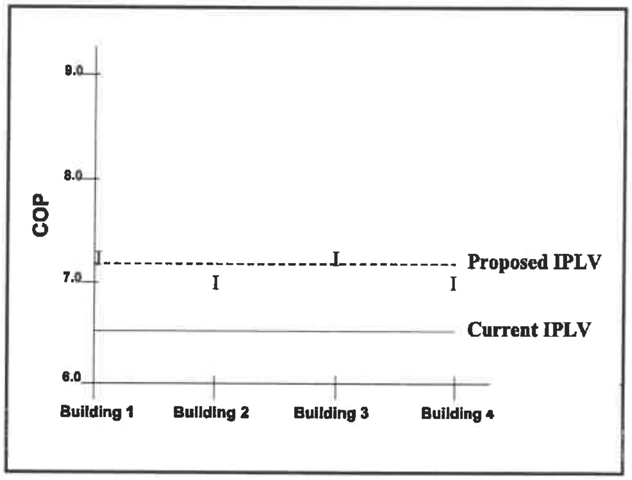

Figure 5. Are Seasonal Efficiency Factors Representative?

ENVIRONMENTAL BENEFITS OF INCREASED EFFICIENCY OF HVAC EQUIPMENT

Use of air-conditioning and refrigeration equipment potentially contributes to global warming through a direct effect and an indirect effect. The direct effect results from the eventual release of the refrigerant and its inherent global warming potential. The indirect effect, or energy consumption effect, results from the release of greenhouse gases in the combustion of fossil fuels to generate the power needed to run the equipment over its useful life. The sum of these two global warming effects is known as the "total equivalent warming impact" or TEWI.

Within the U.S., new manufacturing techniques and servicing practices, which prohibit venting of refrigerants to the atmosphere, have greatly reduced the direct greenhouse gas contributions of refrigerants, while increased equipment operating efficiencies over the past 20 years have reduced the indirect greenhouse gas contribution. Please note that the indirect effect greatly outweighs the direct effect greenhouse contributions. Therefore TEWI, not the refrigerant's global warming potential, should be used to evaluated global warming impacts of alternatives.

TEWI is dependent on the specific refrigerant applications. Typical assumed values for residential split system air conditioners and low-pressure centrifugal chillers are presented in Table 2.

Table 2: Typical TEWI Assumptions for Specific Applications

<table>
<tr><th></th><th colspan="2">Residential Split-System Air Conditioner
1995 | 1970</th><th colspan="2">Low-Pressure Centrifugal Chiller
1995 | 1970</th></tr>
<tr><td>Service Life (yrs)</td><td colspan="2">13 to 20</td><td colspan="2">25 to 30</td></tr>
<tr><td>Operation [a] (hrs/yr)</td><td colspan="2">1200</td><td colspan="2">2190</td></tr>
<tr><td>Refrigerant</td><td>R-22</td><td>R-22</td><td>R-123</td><td>R-11</td></tr>
<tr><td>Refrigerant GWP [b]</td><td>1700</td><td>1700</td><td>93</td><td>4000</td></tr>
<tr><td>Efficiency [c]</td><td>10.6 SEER</td><td>7.0 SEER</td><td>0.6 kW/ton</td><td>0.82 kW/ton</td></tr>
<tr><td>Charge</td><td>2.1 lb/ton</td><td>2.5 lb/ton</td><td>2 lb/ton</td><td>2 lb/ton</td></tr>
<tr><td>Make-up Rates [d]</td><td>2%</td><td>10%</td><td>0.75%</td><td>15%</td></tr>
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Notes:
[a] Approximately equivalent full load operation.
[b] 100-year iteration values (ARTI Refrigerant Database)
[c] Power requirements and system efficiency terms are consistent with those associated with the specific type of equipment. Values are reflective of median capabilities and not the best available technologies.
[d] As a result of today's regulations, it is expected that equipment manufactured in the future will have dramatically lower make-up requirements due to smaller refrigerant charges, tighter manufacturing tolerances, and revamped field service practices.

The TEWI of a given application is also influenced by its geographic location, since the regional fuel mix and the overall efficiency of the power plant producing power for the equipment contributes to the indirect global warming contribution. The U.S. national average for electrical conversions factor in 1995 was estimated at 0.674 Kg CO_2/kWh. In 1970, the national average CO_2 emission per kWh generated was estimated at 20 to 25% higher than the 1995 average.

Figures 6 and 7 utilize the data presented in Table 2 to calculate TEWIs for a typical 2.5 ton unitary air conditioner and a 300-ton centrifugal chiller of 1995 verses 1970. The overall TEWI contribution has significantly decreased on a unit basis over this twenty-five year period. Not only has the direct contribution become a smaller percentage of the contribution, but the overall TEWI has also been reduced.

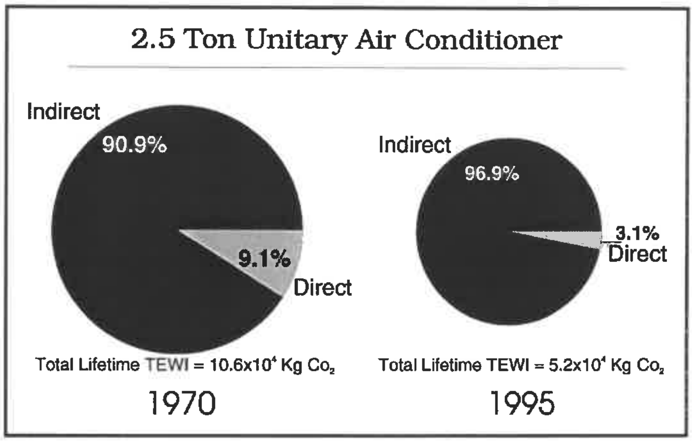

Figure 6.

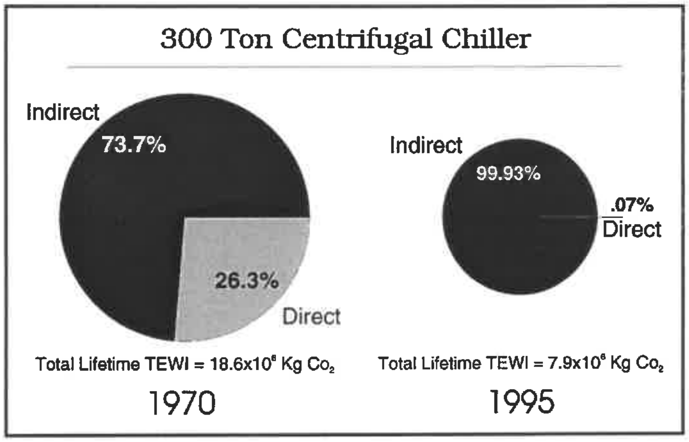

Figure 7.

CONCLUSIONS

Over the past 25 years, significant improvements have been made in the efficiencies of air-conditioning equipment.

For unitary products, there still appears to be room for added efficiency improvements, provided that consumers are willing to pay considerably higher initial costs for higher efficiency products.

However for centrifugal chillers, the efficiency improvements already achieved have pushed technology close to its practical limit and substantial increases in efficiency may not be practical.

For air-conditioning applications, the direct contribution to TEWI is a small portion of the total. Therefore, system efficiency is more important than the GWP of the working fluid. Greenhouse warming contributions from air-conditioning systems are primarily a function of the carbon dioxide emitted during the generation of electricity that drives the equipment.

For today's air-conditioning applications, 97 to 99^+% of the TEWI is due to the release of carbon dioxide formed during generation of power over the lifetime of the equipment. Hence, focusing only on the working fluid offers little opportunity to reduce greenhouse gas emissions. The steps that manufacturers have taken, and continue to take, to reduce the direct contribution (e.g., system tightening, revamped service practices, etc.) only influence a small portion of the total TEWI.

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