HVAC Synergy: Engineering Performance Studies of Chiller Refrigerant Conversion Strategies

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After 1995, CFC refrigerants will no longer be manufactured in the United States, Large commercial buildings cooled by centrifugal chillers comprise an electric utility sector that will be strongly affected, and are the subject of considerable concern. Such concern is especially pronounced, as most options available to convert chillers to use new alternative refrigerants, result in diminished energy performance.

Although rarely done, it is possible to improve the energy performance of centrifugal chillers, at the time of conversion to an alternative refrigerant. The trick is to replace the chiller compressor and motor with new, smaller capacity components. Such conversions are known as driveline conversions with capacity reductions. There are, however, significant market barriers to the widespread adoption of such conversions.

In response to these barriers, the authors developed a program known as HVAC Synergy. This program was designed to encourage owners of large buildings to first implement cooling load reducing measures, and then re-engineer HVAC systems to meet such reduced cooling loads.

Because the feasibility of driveline conversions with capacity reductions is not well understood, the paper details an engineering study which quantifies the energy performance and cost of chiller refrigerant conversion options. Five representative chillers were each modeled under five different conversion scenarios. The chiller efficiency impacts and conversion costs of each scenario were also analyzed in order to draw general conclusions regarding the applicability of driveline conversions as an element of the HVAC Synergy strategy. The paper concludes that driveline conversions with capacity reductions can be implemented to achieve significant improvements in chiller efficiency.

Introduction

The Termination of CFC Production

After 1995, CFC refrigerants (including R-11 and R-12) will no longer be manufactured in the United States. Virtually all major electric utility sectors will be affected to some extent, but perhaps, the commercial buildings sector has been the subject of greatest concern. Only 6% of commercial buildings in the United States are cooled with central chillers, either solely or in combination, but because they are for the most part large buildings, they represent 27.1% of the nation's commercial building floorspace (Energy Information Administration 1991). The largest of these buildings are cooled using centrifugal chillers, of which about 80% are charged with CFC refrigerants (Lindsay 1993). As such, this paper is concerned with centrifugal chillers located in commercial buildings.

Centrifugal Chiller Options

In the face of the termination of CFC production, owners of centrifugal chillers charged with CFCs have three legitimate options:

1. adopt an aggressive refrigerant management plan and maintain chillers with the original refrigerant,

2. replace with new chillers that use alternative, non-CFC refrigerants,

3. convert chillers to alternative, non-CFC refrigerants.

Owners of relatively new chillers may select the first option, also known as "contain/maintain," and monitor the status of CFC refrigerant supplies and prices. This option should not impact energy use, although it will become increasingly expensive to implement, and does present the risk that eventual shortfalls in CFC supplies could lead to disruptions of chiller service.

Owners of chillers near the end of their service life may choose to remove them and install new chillers charged with non-CFC refrigerants. Since chillers from the early 1970's exhibited efficiencies in the range of 0.8 kW/ton to 1.0 kW/ton when new (and may tend to be even less efficient due to age), today's water cooled centrifugal chillers are rated in a range of 0.54 kW/ton - 0.65 kW/ton. Investments in new chillers may be returned in energy savings in three years or less (Smithart 1993).

In between the maintain and replace options—and note that this is a wide range without any sharply defined boundaries-is the conversion option. Chiller conversions fall into one of three categories: (1) simple, (2) "optimized," or (3) driveline.

In a simple conversion, only chiller materials that are incompatible with the new refrigerant are changed. These changes include normal chiller rebuild materials (gaskets, seals, and bearings), as well as electric motor windings in hermetic units (where the motor is exposed to the refrigerant). Because most alternative refrigerants are less efficient than the CFC refrigerants they replace (Smithart and Crawford 1993), chillers that have been the subject of simple conversions typically exhibit lower full load capacity (3% - 15%) and efficiency (3%-9%) than before the conversion. The cost of a simple conversion is usually about 20% to 30% of the cost of a new chiller (Ostman 1993).

"Optimized" conversion is an industry term that is typically used to describe a refrigerant conversion approach designed to minimize the loss in capacity that occurs in the simple conversion case, and as such, only represents optimization in a narrow sense. It should be noted that this optimization does not attempt any improvements of related systems and building components (e.g., cooling towers, air distribution, building envelope, etc.). The additional mechanical modifications associated with such conversions may include gear changes, impeller trimming, and orifice/float changes. In general, "optimized" conversions result in relatively less performance degradation (on the order of 0% - 5% of capacity and 2% - 4% efficiency), and cost about 40% - 60% of the cost of a new chiller (Ostman 1993).

Driveline conversions replace the entire motor and compressor driveline assembly, and provide a new package of micro-processor controls. These conversions have the potential to eliminate the performance penalty of a refrigerant conversion, but also impose the highest cost: about 60% - 80% of the cost of a new chiller (Ostman 1993).

Although it is widely believed that chiller conversions always lead to a loss of chiller efficiency, there is a way to convert chillers to non-CFC refrigerants with a substantial increase in efficiency. The trick is to combine either an "optimized" or a driveline conversion with a significant reduction in chiller capacity.

The reason why chiller capacity reductions may lead to efficiency improvements is simple. The efficiency of the chiller is strongly dependent on the heat exchange surfaces (evaporator, condenser, cooling tower) that transfer energy into and out of the chiller. The more heat transfer surface per full load compressor capacity, the more efficient the chiller. If the chiller full load capacity is reduced, but the associated heat transfer surfaces remain constant, the heat transfer surfaces then "look" larger in comparison to the compressor.

An example of a driveline conversion with a substantial capacity reduction was performed at the Bank of America building in San Francisco, where a 1,750 ton chiller, with a full load efficiency of 0.85 kW/ton, was converted to an alternative refrigerant. The converted chiller was derated to 1035 tons, and exhibited a full load efficiency of 0.628 kW/ton (Randazzo 1994).

Although it would seem that "optimized" or driveline conversions with capacity reductions offer an opportunity to achieve abundant energy savings, only a handful of such conversions with capacity reductions have been performed at the time of writing. To the authors' experience, and that of others (Lovins 1992), there are a number of barriers to building owners and mangers adopting this CFC remedy on a widespread basis, including:

1. A preference for simple solutions to CFC phaseout related problems;

2. A preference for low first cost solutions, especially if the benefits of more costly options are not well explained;

3. A reluctance to endorse chiller capacity reductions.

The first two barriers are similar, and are virtually identical to the classic issue of first cost versus lifetime savings. While some sophisticated owners will recognize the benefits of this strategy and make appropriate investments, most are not expected to do so. Utility DSM programs may address such barriers with carefully structured incentives designed to "buy down" investments to an acceptable payback for the owner.

To overcome the latter barrier often requires more than simple financial incentives. Building owners and managers may perceive that reducing chiller capacity will present additional risk, while offering little or no benefit. There is no question that these parties are under enormous pressure to maintain comfort, even during extremely hot weather. Furthermore, they often have little or no monitored data from which to determine what their peak cooling demands actually are. As such, they tend to adopt the philosophy that "more is better."

Despite such widespread beliefs, achieving deep cuts in chiller capacity is often technically feasible. Most buildings present ample opportunities to cost-effectively reduce cooling load by upgrading building systems such as lighting and HVAC distribution. Additionally, many existing chillers were substantially oversized when originally installed. Regardless of the basis for capacity reduction, the authors have found that only by presenting decision makers with rigorous engineering studies documenting their cooling load, will the decision makers feel comfortable selecting a unit smaller than their existing one.

Demonstrating the benefits of this approach is just as important. Reduced utility costs may or may not be of interest to owners and managers of buildings where the tenants pay the utility bills. Solutions that ease CFC related risks may only be perceived as only a tangible benefit to those owners and managers that are concerned about such issues and are planning ahead. Again, only by providing comprehensive analytical support that demonstrates the benefits of this approach, can a utility DSM program address such issues.

The HVAC Synergy Program Concept

In order to overcome the barriers listed in the above section and achieve comprehensive energy savings at the time of chiller replacement or refrigerant conversion, Robertson, Wolpert, and Stein have been working to develop the HVAC Synergy DSM program concept and address the large number of issues it raises. (Wolpert, J.S. and C. Robertson 1991. Personal communications with Nick Dedominicis and others at the Competitek Fourth Annual Member's Forum. Snowmass, CO. October 24-27, 1991),(Robertson, Wolpert, and Stein 1992; 1993; Stein, Robertson, and Wolpert 1993). The program follows 7 steps:

1. Identify building owners or managers who are motivated to either replace or convert chillers in response to the CFC phaseout.
2. Conduct a comprehensive building analysis, which includes lighting, HVAC, appliances, building shell, and building use schedules.
3. Upgrade building systems that impact cooling loads. In most cases these upgrades are lighting retrofits, but other opportunities to reduce cooling loads, such as window films, may be pursued as well.
4. Re-engineer HVAC systems to reflect reductions in cooling load. There are usually numerous opportunities to improve the efficiency of both HVAC distribution and auxiliary systems.
5. Treat the cooling plant. Either the existing chiller is converted to an alternative refrigerant, or is replaced with a new high efficiency chiller. Either way, the chiller plant is accurately sized to the building's cooling load with a prudent safety margin.
6. Commission new building systems and evaluates savings.
7. In the case of utility-supported programs, pay incentives to participants equivalent to some portion of the cost of designing, purchasing, and installing the energy efficiency measures.

At the time of writing, programs based on this concept are being fielded by five utilities, and a sixth has received commission approval for a series of case studies. Most of these utilities include chiller replacements as well as optimized and driveline conversions in their programs. While the energy performance improvement gained by replacing an old inefficient chiller with a new high efficiency chiller is well understood, the energy performance improvement gained by implementing a driveline conversion with capacity reduction is not well understood. As such, this paper is largely concerned with driveline conversions, although data are also presented regarding simple and "optimized" conversions.

Driveline Conversion Feasibility Study

In order to support the implementation of the HVAC Synergy Strategy, an engineering study was performed to quantify the energy performance and cost of a number of chiller refrigerant conversion options. Five representative chillers charged with R-11 were modeled under a variety of conversion scenarios, including driveline conversions with and without capacity reductions. The chiller efficiency impacts and conversion costs of each scenario were also analyzed in order to draw general conclusions regarding the applicability of driveline conversions as an element of the HVAC Synergy Strategy.

Methodology

Select Baseline Chillers

Five chillers, charged with CFC-11 refrigerant, were selected to represent actual machines that are typically found in the field.

Characterize Baseline and Converted Chillers

The five chillers were analyzed in regard to six different scenarios, including:

1. present operation with CFC-11 (not including any degradation due to age);
2. a typical low cost simple conversion to HCFC-123;
3. a typical moderate first cost conversion to HCFC-123, "optimized" to minimize capacity loss;
4. a driveline conversion to HCFC-123 that minimizes capacity and efficiency losses;
5. a driveline conversion to HCFC-123 with 33% capacity reduction;
6. a driveline conversion to HCFC-123 with 50% capacity reduction.

For each analysis, the following was documented:

1. the efficiency, condenser water temperatures, and capacity exhibited by the converted chillers at full-load and part-load (including IPLV). Such performance characteristics were generated using a proprietary computer simulation model developed by a major chiller manufacturer;
2. an estimate of the cost of such conversions.

Results

Baseline Chiller Selection

In selecting baseline chillers, it was necessary to focus on characteristics which were likely to have a significant impact on energy performance (Table 1). As such, the following parameters were settled upon:

1. Chiller capacity—Since the relative performance changes were not expected to significantly vary with size, the machines selected were all rated at 250-ton full-load capacity.

Table 1. Baseline Chiller Characteristics

Chiller Type	Design	Rated Capacity	Age
"B"	open drive	250 tons	1992
"B"	open drive	250 tons	10 yr. old
"B"	open drive	250 tons	20 yr. old
"A"	hermetic, gear drive	250 tons	10 yr. old
"C"	hermetic, direct drive	250 tons	20 yr. old

2. Machine types—Three types of machines were selected for analysis.
   a. gear-driven hermetic: the motor is included in the refrigerant system and the impeller wheel is run at a different speed than the motor, denoted as type A.
   b. open—drive: the compressor motor is external to the sealed refrigeration system (connected by a shaft and seal arrangement), denoted as type B.
   c. hermetic with inter-stage cooling of the refrigerant gas, denoted as type C.
3. Age of machines–Since more recent chillers tend towards higher original efficiency (i.e., the industry has gradually provided higher-efficiency units), a range of ages was included. Three type B units were selected to span the typical age range with a new (1992), a 10 year old, and a 20 year old chiller included. The remaining two chillers were selected to represent a 10 year old type A and a 20 year old type C model.

Energy Performance of Baseline and Converted Chillers

Baseline Chiller Performance. The performance, when new, of the selected machines with R-11 was chosen to represent the baseline condition. This was a conservative assumption as the analysis did not account for any degradation in performance due to age. The efficiency and water temperatures exhibited by these machines were characterized at Air-Conditioning and Refrigeration Institute operating conditions (ARI 1992), as well as at part-load conditions. In developing the part-load operating characteristics (and thus the Integrated Part-Load Values, IPLV) the entering condenser water temperature (ECWT) was allowed to drop with falling load as this reflects the more common field usage (as opposed to constant ECWT). These baseline efficiencies and temperatures were generated using a proprietary computer simulation model developed by a major chiller manufacturer.

As shown in Table 2, the design performance of recent centrifugal chiller models is more efficient than that of older models. Type B was compared over a range of vintages, but the principle still holds true for the others as well. The full load efficiency of the Type B units ranged from 0.664 kW/ton for the newest unit to 0.776 kW/ton for the 20 year old unit. Note that this trend holds true for the IPLV values as well.

Table 2. Baseline Chiller Performance

Age	Rating Point	kW/ton
New (1992)	Full load	0.664
Type B	IPLV	0.641
max. kW = 166		
10 Yr. Old	Full load	0.704
Type B	IPLV	0.686
max. kW = 176		
20 Yr. Old	Full load	0.776
Type B	IPLV	0.743
max. kW = 194		
10 Yr. Old	Full load	0.688
Type "A"	IPLV	0.630
max. kW = 172		
20 Yr. Old	Full load	0.844
Type "C"	IPLV	0.769
max. kW = 211		

The full-load and IPLV efficiencies of all five chillers are portrayed in Figure 1. Note that the differences between design types (as reviewed in the Discussion section) are not meant to imply inherent performance differences, but largely reflect how results vary with different starting selections.

Simple Conversion Chiller Performance. The simple conversion, which is the easiest and least expensive of the five conversion options, also results in fairly large losses in efficiency and capacity when compared to the baseline R-11 case. As shown in Table 3 and Figure 2, capacity losses for these selections range from 13. 6% to 15.2 %, while reductions in full-load efficiencies range from 4.5% to 9.1%. It is of interest to note that since the fill-load capacities have dropped, and the efficiency expressed in kW/ton has increased (reflecting worsened efficiency), in most cases the full-load kW values are lower (decreasing from 6.2% to 11.3%). While worsened efficiency results in a higher kW consumption for a given tonnage throughout most of a chiller's range, most converted units exhibit a lower peak load kW value when compared to the baseline unit. Of course, if the baseline unit (i.e., operation with R-11) never achieved full-loading, then this theoretical reduction in maximum kW would never be realized by the utility. On the other hand, if the baseline unit did operate at peak capacity, the converted unit would not maintain comfort, unless accompanied by cooling-load-reducing measures.

Optimized Conversion Chiller Performance. The characteristics of the optimized conversions, along with the baseline characteristics, are presented in Table 4. As shown by these data, the optimized cases for the selections presented here did not exhibit capacity and efficiency much different from the simple conversions. This may have been partly due to the particular machines selected for this study, as the authors have seen elsewhere optimized conversions that compared more favorably with baseline performance. Even these more favorable optimized conversions, however, still exhibited diminished full-load efficiency and capacity when compared to the basecase (e.g., loss of capacity and efficiency in the 4% - 5% range).

Driveline Conversion Without Capacity Reduction Performance. Unlike the simple and optimized conversions discussed above, the driveline conversions reported here were engineered to maintain full-load capacity. As shown in Table 5, the changes in full-load efficiencies, expressed in the kW/ton, ranged from 0%, in the case of the 10-year-old Type B unit, to 16.1% worse in the case of the 10-year-old Type A unit. In no cases was the efficiency improved (Figure 3).

Driveline Conversion With Capacity Reduction Performance. The last category of conversions investigated were those involving driveline replacements along with substantial downsizing (33% and 50%) of the chiller. While this strategy has not been a popular one for conversions to date, it is a feasible engineering solution, and a few such conversions have been successfully accomplished. By planning the driveline conversion based on a

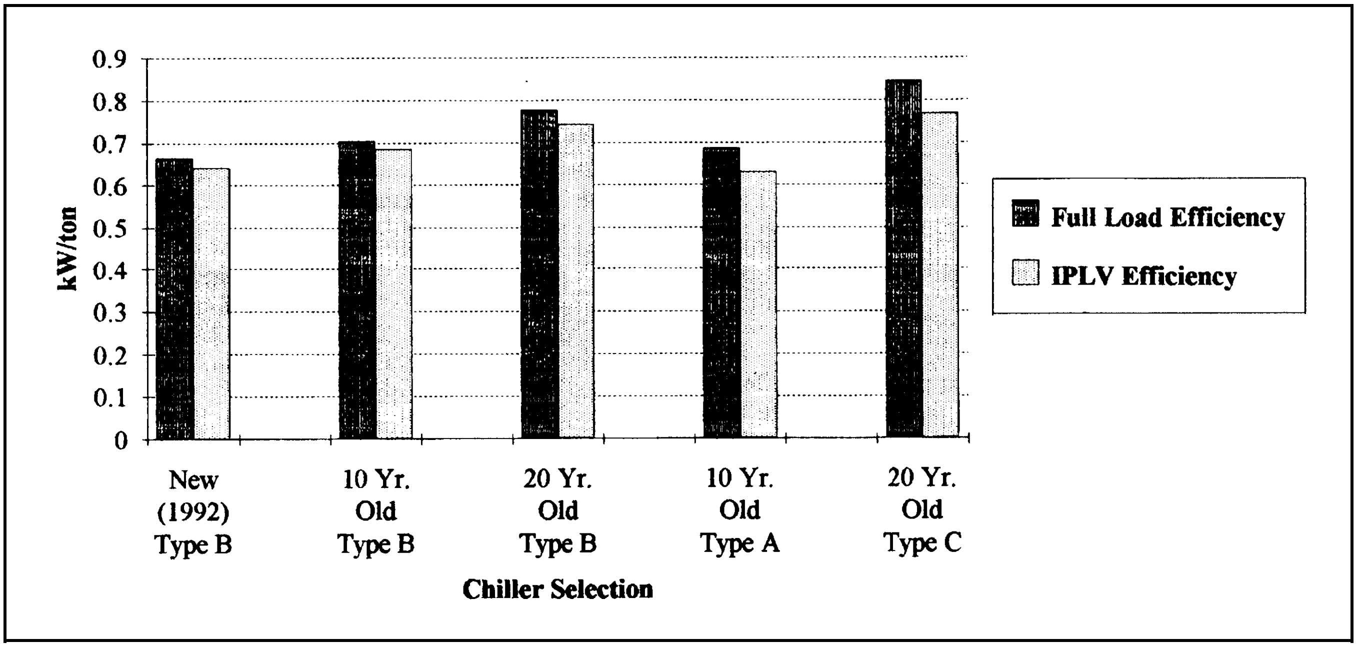

Figure 1. Baseline (R-11) Chiller Performance

Table 3. Simple Conversion Performance

Chiller Selection: R-11 to R-123	Capacity				Performance			
					Full Load		IPLV	
	tons	% chg.		% chg.	kW/ton	% chg.	kW/ton	% chg.
1992 Type B								
baseline, R-11	250	n.a.	166	n.a.	0.664	n.a.	0.641	n.a.
simple conversion	216	-13.6	154	-7.2	0.713	7.4	0.679	5.9
10 Yr. Old Type B								
baseline, R-11	250	n.a.	176	n.a.	0.704	n.a.	0.686	n.a.
simple conversion	212	-15.2	156	-11.3	0.736	4.5	0.727	6.0
20 Yr. Old Type B								
baseline, R-11	250	n.a.	194		0.776	n.a.	0.743	n.a.
simple conversion	220	-12	181	-6.7	0.823	6.1	0.769	3.5
10 Yr. Old Type A								
baseline, R-11	250	n.a.	172	n.a.	0.688	n.a.	0.630	n.a.
simple conversion	243	-2.8	175	1.7	0.720	4.7	0.684	8.6
20 Yr. Old Type C								
baseline, R-11	250	n.a.	211	n.a.	0.844	n.a.	0.769	n.a.
simple conversion	215	-14	198	-6.2	0.921	9.1	0.855	11.2

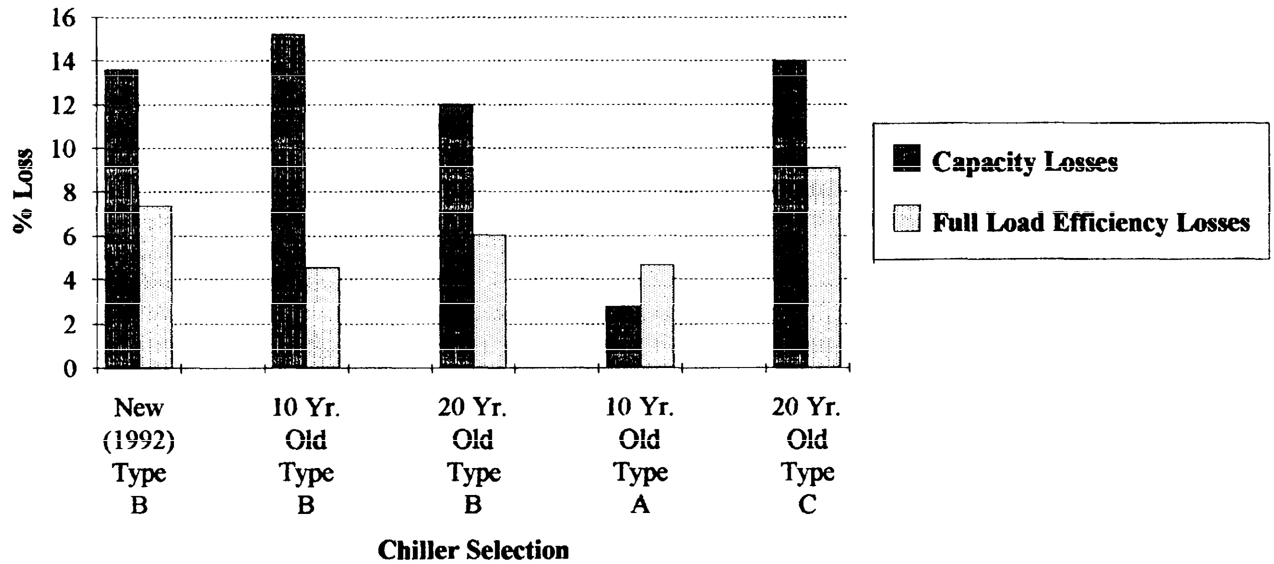

Figure 2. Simple Conversion Performance

Table 4. Optimized Conversion Performance

Chiller Selection: R-11 to R123	Capacity		Performance					
					Full Load		IPLV	
	tons	% chg.	kW	% chg.	kW/ton	% chg.	kW/ton	% chg.
1992 Type B								
baseline, R-11	250	n.a.	166	n.a.	0.664	n.a.	0.641	n.a.
"optimized" conversion	217	-13.2	157	-5.4	0.724	9.0	0.734	14.5
10 Yr. Old Type B								
baseline, R-11	250	n.a.	176	n.a.	0.704	n.a.	0.686	n.a.
"optimized" conversion	212	-15.2	156	-11.3	0.736	4.5	0.727	6.0
20 Yr. Old Type B								
baseline, R-11	250	n.a.	194	n.a.	0.776	n.a.	0.743	n.a.
"optimized" conversion	222	-11.2	188	-3.1	0.847	9.1	0.801	7.8
10 Yr. Old Type A								
baseline, R-11	250	n.a.	172	n.a.	0.688	n.a.	0.630	n.a.
"optimized" conversion	250	0	190	10.5	0.760	10.5	0.687	9.0
20 Yr. Old Type C								
baseline, R-11	250	n.a.	211	n.a.	0.844	n.a.	0.769	n.a.
"optimized" conversion	218	-12.8	212	0.5	0.973	15.3	0.902	17.3

Table 5. Driveline Conversion Without Capacity Reduction Performance

Chiller Selection: R-11 to R123	Capacity tons	Capacity % chg.	Full Load kW	Full Load % chg.	Full Load kW/ton	Full Load % chg.	IPLV kW/ton	IPLV % chg.
1992 Type B								
baseline, R-11	250	n.a.	166	n.a.	0.664	n.a.	0.641	n.a.
driveline (s), full tons	250	0	176	6.0	0.704	6.0	0.681	6.2
10 Yr. Old Type B								
baseline, R-11	250	n.a.	176	n.a.	0.704	n.a.	0.686	n.a.
driveline (l), full tons	250	0	176	0.0	0.704	0.0	0.696	1.5
20 Yr. Old Type B								
baseline, R-11	250	n.a.	194	n.a.	0.776	n.a.	0.743	n.a.
driveline (l), full tons	250	0	206	6.2	0.824	6.2	0.766	3.1
10 Yr. Old Type A								
baseline, R-11	250	n.a.	172	n.a.	0.688	n.a.	0.630	n.a.
driveline (l), full tons	244	-2.4	195	13.3	0.799	16.1	0.773	22.7
20 Yr. Old Type C								
baseline, R-11	250	n.a.	211	n.a.	0.844	n.a.	0.769	n.a.
driveline (l), full tons	250	0	216	2.4	0.864	2.4	0.826	7.4

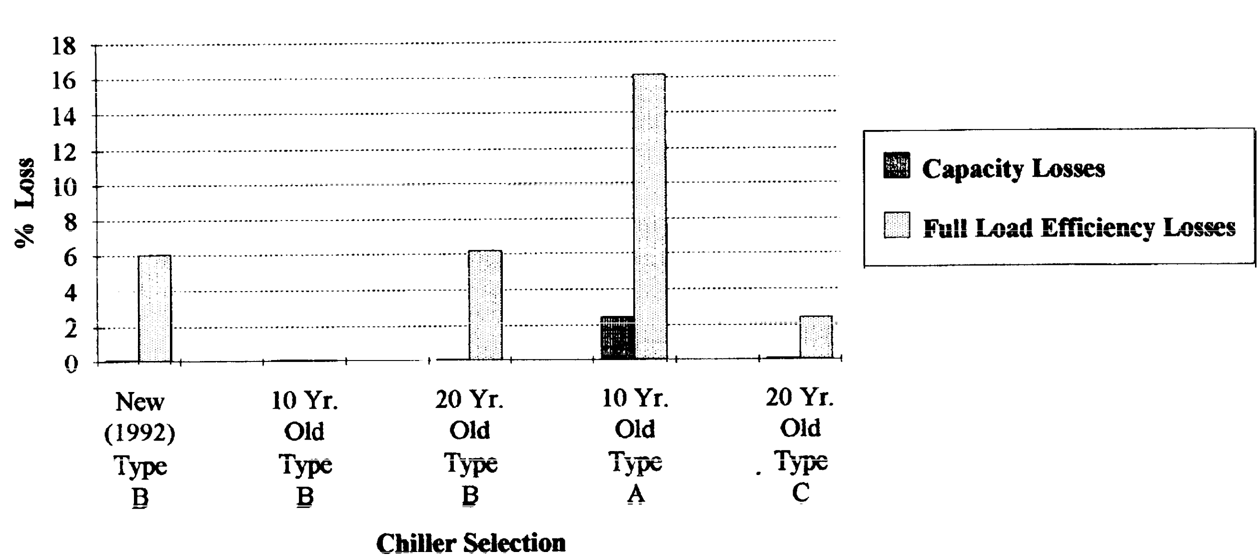

Figure 3. Driveline Conversion Without Capacity Reduction Performance

reduced capacity, the full-load and IPLV efficiencies are greatly improved. For example, improvements in full-load efficiency, as shown in Table 6, ranged from 7.6% to 19.5% for the 33% capacity reduction scenarios, and 31.4% to 41.2% for the 50% capacity reduction scenarios. In addition, the maximum kW dropped significantly, ranging from 36.2% to 46.9% for the 33% capacity reduction scenarios, and 65.7% to 70.6% for 50% capacity reduction scenario (Figure 4).

Lastly, the characteristics of all the conversion scenarios are portrayed in Table 7, in order to give an overview of all combinations.

Cost of Refrigerant Conversions

The cost to convert centrifugal chillers varies from job to job, reflecting the influence of a number of variables. Among some of the significant influences are the types of unit, the age and conditions, the local service organizations' rates and familiarity with conversions, and building access to name a few. While these costs are somewhat variable, useful generalizations can be made as shown in Table 8.

For reference, it is noted that a new machine of comparable capacity to the baseline unit (250 tons) would cost in the range of $60,000 to $70,000.

Table 6. Driveline Conversion With Capacity Reduction Performance

Chiller Selection: R-11 to R-123	Capacity		Efficiency					
			Full Load				IPLV	
	tons	% chg.	kW	% chg.	kW/ton	% chg.	kW/ton	% chg.
1992 Type B								
baseline, R-11	250	n.a.	166	n.a.	0.664	n.a.	0.641	n.a.
driveline, 33% reduct.	165	-34	100	-39.8	0.606	-8.7	0.575	-10.3
driveline, 50% reduct.	125	-50	53	-68.1	0.424	-36.1	0.466	-27.3
10 Yr. Old Type B								
baseline, R-11	250	n.a.	176	n.a.	0.704	n.a.	0.686	n.a.
driveline, 33% reduct.	165	-34	106	-36.2	0.642	-8.8	0.61	-11.1
driveline, 50% reduct.	125	-50	55	-66.9	0.440	-37.5	0.454	-33.8
20 Yr. Old Type B								
baseline, R-11	250	n.a.	194	n.a.	0.776	n.a.	0.743	n.a.
driveline, 33% reduct.	165	-34	109	-43.8	0.661	-14.8	0.632	-14.9
driveline, 50% reduct.	125	-50	60	-69.1	0.480	-38.1	0.432	-41.9
10 Yr. Old Type A								
baseline, R-11	250	n.a.	172	n.a.	0.688	n.a.	0.630	n.a.
driveline, 33% reduct.	165	-34	105	-39.0	0.636	-7.6	0.601	-4.6
driveline, 50% reduct.	125	-50	59	-65.7	0.472	-31.4	0.482	-23.5
20 Yr. Old Type C								
baseline, R-11	250	n.a.	211	n.a.	0.844	n.a.	0.769	n.a.
driveline, 33% reduct.	165	-34	112	-46.9	0.679	-19.5	0.622	-19.1
driveline, 50% reduct.	125	-50	62	-70.6	0.496	-41.2	0.513	-33.3

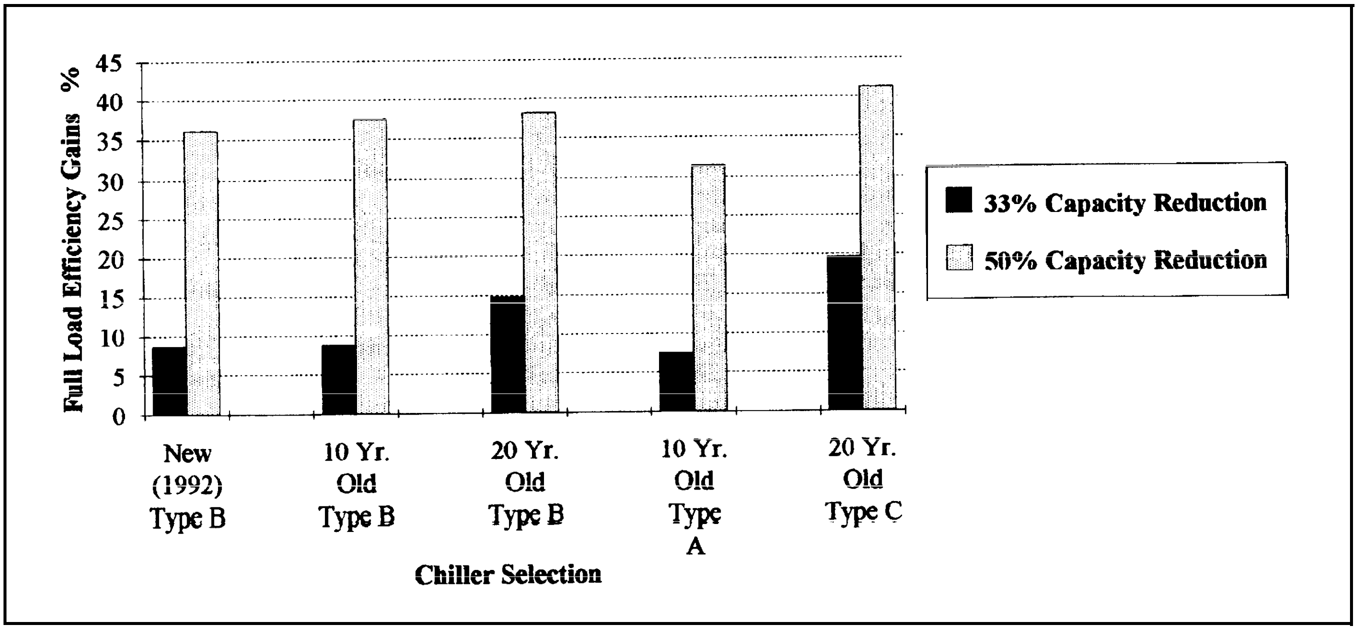

Figure 4. Driveline Conversion With Capacity Reduction Performance

Discussions

1. Simple and optimized conversions nearly always result in some loss of efficiency and capacity. The quantity of such losses is difficult to generalize at this time, and should be evaluated for each chiller on a case-by-case basis.

2. Driveline conversions without capacity reduction make it possible to maintain existing chiller capacity, although there is generally some loss in efficiency. Again, the quantity of such efficiency losses is difficult to generalize, and should be evaluated for each chiller on a case-by-case basis.

3. Driveline conversions combined with capacity reductions can be implemented to achieve significant improvements in chiller efficiency. The extent of such improvements may not be generalized at this time, but they appear to be both large, and strongly dependent on the amount of capacity reduction. The greater the capacity reduction, the greater the improvement in performance.

4. Driveline conversions combined with capacity reductions may also achieve additional savings by reducing both the flow and the energy consumption of chiller auxiliaries, such as pumps and cooling tower fans. In some cases, such reductions might not be achieved without a price, however, as they might reduce the converted chiller efficiencies shown in the above analysis. Achieving the optimum balance between chiller efficiency and reductions in chiller auxiliary power is beyond the scope of this paper, but may be taken up by the authors in a future paper.

5. The cost of chiller conversions varies widely, and should be evaluated on a case-by-case basis. In general, if only minor capacity reductions are acceptable, optimized conversions cost more than simple conversions, and driveline replacements cost more than optimized conversions. However, significant capacity reductions make it possible to reduce the cost of the driveline conversion. In many cases, the cost of the driveline conversion with capacity reduction costs less than an optimized conversion. As such, many building owners are likely paying for more expensive conversions that result in less efficient chillers. Of course, this analysis does not include the cost of the cooling-load reducing measures that may be required in order to achieve such capacity reductions.

6. While a determination of the cost-effectiveness of the above conversion scenarios is beyond the scope of this paper, the large improvements in efficiency coupled with reduced chiller conversion cost indicate a strong potential for cost-effective applications. The authors hope others will take the information presented and apply it to their particular cost and benefit circumstances.

7. The authors propose that the driveline conversion with capacity reduction strategy presents an excellent opportunity for electric utilities to leverage the CFC phaseout in order to achieve significant energy savings in the commercial buildings sector. We further propose that the HVAC Synergy program, when

Table 7. All Options Conversion Performance

Chiller Selection: R-11 to R-123	Capacity		Performance					
			Full Load				IPLV	
	tons	% chg.	kW	% chg.	kW/ton	% chg.	kW/ton	% chg.
1992 Type B								
baseline, R-11	250	n.a.	166	n.a.	0.664	n.a.	0.641	n.a.
simple conversion	216	-13.6	154	-7.2	0.713	7.4	0.679	5.9
"optimized" conversion	217	-13.2	157	-5.4	0.724	9.0	0.734	14.5
driveline (s), full tons	250	0	176	6.0	0.704	6.0	0.681	6.2
driveline (s), 33% reduct.	165	-34	100	-39.8	0.606	-8.7	0.575	-10.3
driveline (s), 50% reduct.	125	-50	53	-68.1	0.424	-36.1	0.466	-27.3
10 Yr. Old Type B								
baseline, R-11	250	n.a.	176	n.a.	0.704	n.a.	0.686	n.a.
simple conversion	212	-15.2	156	-11.3	0.736	4.5	0.727	6.0
"optimized" conversion	212	-15.2	156	-6.0	0.736	4.5	0.727	6.0
driveline (l), full TR	250	0	176	6.0	0.704	0.0	0.696	1.5
driveline (s), 33% reduct.	165	-34	106	-36.2	0.642	-8.8	0.61	-11.1
driveline (s), 50% reduct.	125	-50	55	-66.9	0.440	-37.5	0.454	-33.8
20 Yr. Old Type B								
baseline, R-11	250	n.a.	194	n.a.	0.776	n.a.	0.743	n.a.
simple conversion	220	-12	181	-6.7	0.823	6.1	0.769	3.5
"optimized" conversion	222	-11.2	188	-3.1	0.847	9.1	0.801	7.8
driveline (l), full tons	250	0	206	6.2	0.824	6.2	0.766	3.1
driveline (s), 33% reduct.	165	-34	109	-43.8	0.661	-14.8	0.632	-14.9
driveline (s), 50% reduct.	125	-50	60	-69.1	0.480	-38.1	0.432	-41.9
10 Yr. Old Type A								
baseline, R-11	250	n.a.	172	n.a.	0.688	n.a.	0.630	n.a.
simple conversion	243	-2.8	175	1.7	0.720	4.7	0.684	8.6
"optimized" conversion	250	0	190	10.5	0.760	10.5	0.687	9.0
driveline (l), full tons	244	-2.4	195	13.3	0.799	16.1	0.773	22.7
driveline (s), 33% reduct.	165	-34	105	-39.0	0.636	-7.6	0.601	-4.6
driveline (s), 50% reduct.	125	-50	59	-65.7	0.472	-31.4	0.482	-23.5
20 Yr. Old Type C								
baseline, R-11	250	n.a.	211	n.a.	0.844	n.a.	0.769	n.a.
simple conversion	215	72	198	-6.2	0.921	9.1	0.855	11.2
"optimized" conversion	218	74.4	212	0.5	0.973	15.3	0.902	17.3
driveline (l), full tons	250	100	216	2.4	0.864	2.4	0.826	7.4
driveline (s), 33% reduct.	165	-34	112	-46.9	0.679	-19.5	0.622	-19.1
driveline (s), 50% reduct.	125	-50	62	-70.6	0.496	-41.2	0.513	-33.3

Table 8. Estimated Conversion Costs

Machine Type	Conversion Type	Estimated Cost $ ("000)
Open Drive	simple	12.5 - 19
	"optimized"	25 - 38
	driveline, full tons	37.5 - 50
	driveline, 33% red.	27 - 35
	driveline, 50% red.	21 - 28
Hermetic	simple	25 - 38
	"optimized"	37.5 - 50
	driveline, full tons	37.5 - 50
	driveline, 33% red.	27 - 35
	driveline, 50% red.	21 - 28

integrated into electric utility DSM portfolios, provides an excellent vehicle to encourage such driveline conversions.

8. The energy performance of the conversion scenarios characterized in this paper were modeled with a single chiller manufacturer's software and products. Future papers are expected which utilize software and products from other manufacturers.

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