Electric Chiller Handbook

EPRI

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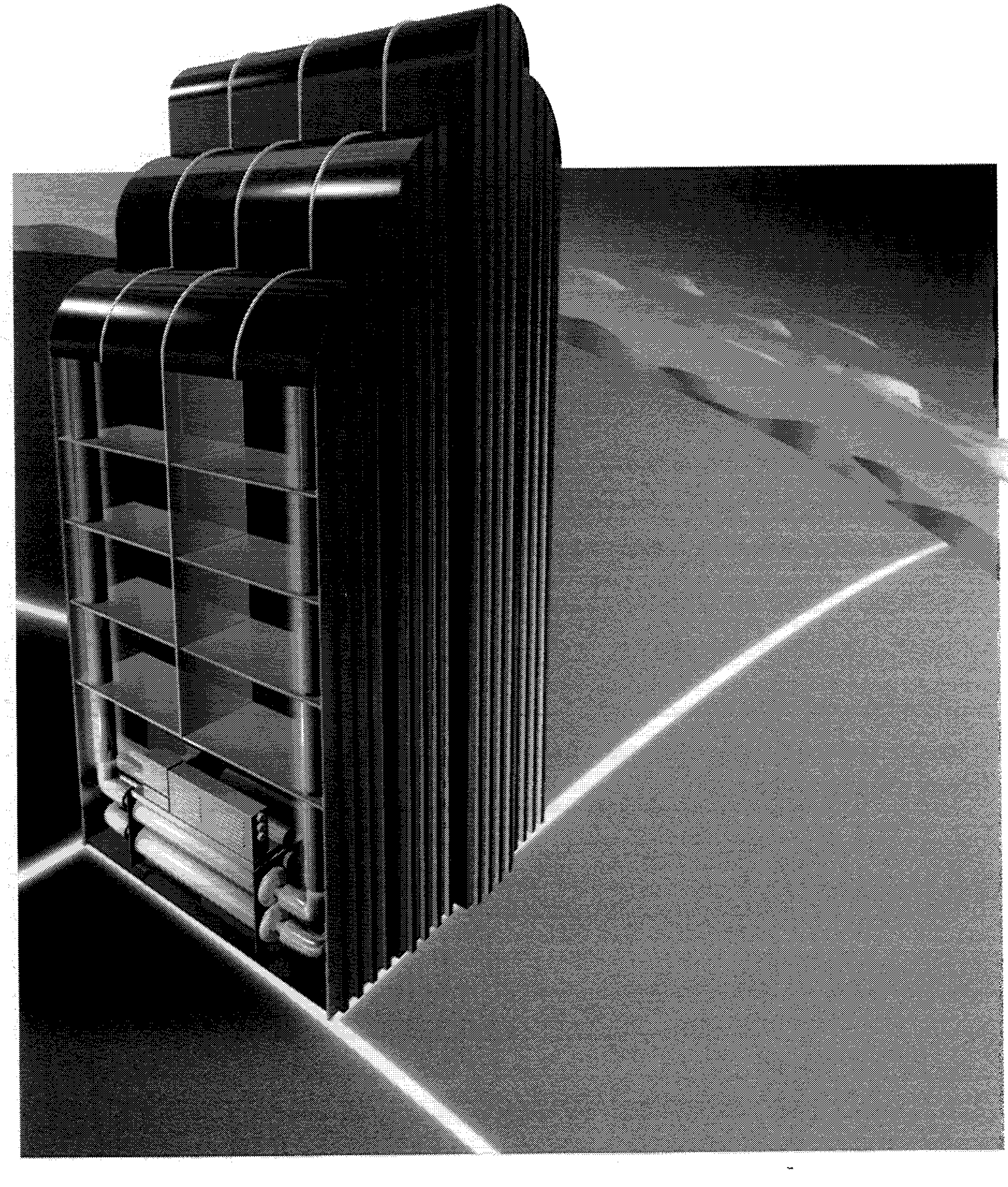

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REPORT SUMMARY

Electric Chiller Handbook

Electric chillers have dominated the market for large commercial cooling systems due to their history of reliable, economical operation. This handbook provides a comprehensive guide for use in selecting chillers for commercial cooling needs. Key issues include chiller availability, rated performance, future viability of various refrigerant options, the cost-effectiveness of alternative chillers, and chilled-water system optimization.

INTEREST CATEGORIES

HVAC
Building systems and analysis tools

KEYWORDS

Air conditioning
Commercial buildings
Load management
Energy efficiency
Cool storage
Demand-side planning

BACKGROUND With the present phaseout of chlorofluorocarbon (CFC) and coming phaseout of hydrochlorofluorocarbon (HCFC) refrigerants, chiller manufacturers are rapidly changing the features and performance of their products and owners are accelerating replacement of existing chillers. Users and system designers thus need up-to-date information on applying and selecting cost-effective chiller systems.

OBJECTIVE To develop a comprehensive handbook that helps utility technical and marketing staff, their customers, and design professionals evaluate and select the best options for chilled water systems in commercial buildings.

APPROACH Investigators used a variety of industry data sources to develop market share information for electric and gas chiller systems and to determine applications according to building type, age, and region. Discussions with chiller manufacturers provided information on product availability, performance, and ownership cost. Using EPRI's COMTECH software, investigators performed comprehensive cost analyses for placement of large and small chillers in three representative cities. Case studies of actual installations support these analyses.

RESULTS EPRI's *Electric Chiller Handbook* provides a single source of current information on all major issues associated with chiller selection and application. Key issues include chiller availability and markets, rated performance, future viability of various refrigerant options, the cost-effectiveness of alternative chillers, and chilled-water system optimization. The handbook also describes available hardware, outlines the features and costs of gas-fired competitive systems, and provides methods and comparisons of life-cycle costing of various chiller system options.

Analyses of chiller features and economics show that electric chillers are preferable to gas chillers in the large majority of applications, consistent with current market trends. Furthermore, today's chillers offer a wide range of efficiencies and refrigerant options to serve cooling system needs for the 20-year lifetime of the chiller. Finally, new higher-efficiency models of electric chillers offer very attractive paybacks.

EPRI PERSPECTIVE The end of CFC production as of December 31, 1995, ensured the movement away from chlorine-containing refrigerants. During this time of accelerated chiller system replacement, electric utilities can be a valued source of information for customers selecting new systems. This handbook provides the most up-to-date system selection information and will be revised as new options become available. The handbook is one component of EPRI's extensive information and software addressing commercial cooling issues. EPRI's *Commercial Cooling Updates*, for example, discuss a wide range of commercial cooling concerns and provide numerous case studies. These updates are available through the EPRI Distribution Center.

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Introduction

Electric chillers dominate the space cooling market for large commercial buildings. In 1992, about 94% of large water chillers shipped in the United States had electric drives, with the balance being primarily gas-fired technologies (EPRI 1993e). For this report, a large chiller is defined to have a capacity greater than or equal to 100 tons. The two primary types of gas-fired technologies that compete with electric motor-driven chillers are absorption and engine-driven systems.

For comparison, shipments of large electric centrifugal and screw chillers declined slightly (0.9% per year) during the time period of 1986 to 1992 (estimated shipments in 1992 were 2950 units compared to 1986 shipments of 3113). Competing gas-fired absorption chillers showed an increase in shipments during this same period, increasing at an annual rate exceeding 9% (total shipments in 1992 estimated at 307 units compared to 180 in 1986).

Much of the chiller shipment market is currently being driven by the CFC production ban that took effect at the end of 1995. As a result, the pace of electric chiller replacements and/or retrofits is expected to continue at a strong pace. By some estimates, there are approximately 80,000 electric chillers in the United States that use CFC-11 or CFC-12 (production of both was banned after 1995). Estimates suggest that 15,000 to 20,000 of these chillers will be converted or replaced to operate with alternative refrigerants by the end of 1995 (News 1995b). These numbers suggest that perhaps 60,000 to 65,000 CFC electric chillers will still face retrofit, replacement, or continued operation with CFCs at the end of 1995.

During this time of high sales activity, electric utility personnel have an opportunity to assist building owners with the chiller selection process. To provide valuable assistance, it is important that utility personnel have accurate technical and economic information for electric as well as competing gas systems. The intent of this *Handbook* is to fulfill this information need.

1.1 OBJECTIVE

The objective of the *Electric Chiller Handbook* is to provide utility marketing managers, market planners, and account representatives with information to assist their commercial building customers with the selection of water chillers.

The *Handbook* is targeted for systems in the range of 100 to 2000 tons of cooling[1] and is intended to address the selection of electric chillers with either centrifugal or screw compressors. These electric systems frequently compete with natural gas-fired absorption or engine-driven technologies, and competitive issues are presented. Information in the *Handbook* includes

- Market Breakdown of Installed Chiller Base and Recent Sales Trends
- Technology Descriptions for Both Electric and Gas Chillers
- Manufacturers and Product Offerings
- Selection and Optimization Criteria
- Chiller Economics

The focus of the *Handbook* is on chiller selection. Other components in the chiller plant (e.g., cooling towers, condensers, pumps, and piping) are described for completeness. However, detailed reference data (e.g., manufacturers and product offerings) for these ancillary systems are not included.

In some cases, chillers beyond the target size range (100 to 2000 tons) are discussed. For example, in the market analysis much of the available data does not report chiller size, and systems outside the 100-to 2000-ton-size range are undoubtedly included. For product offerings, chillers beyond the upper size range are included if these large chillers are part of a family of products that covers the target size range.

Table 1-1. Handbook Sections

1 *Introduction*
2 *Chiller Market*
3 *Description of Chiller Systems*
4 *Product Offerings*
5 *Selection Factors*
6 *Optimization*
7 *Chiller Economics*

1.2 ORGANIZATION

The *Handbook* is comprised of seven sections as shown in Table 1-1. A bibliography and supporting appendices are included for additional reference.

Following the introduction, an overview of the chiller market in the United States is provided in Section 2. This market analysis includes a discussion of the installed chiller population by number of buildings and cooled floor space. Breakdowns by building size, geographic region, and building age are included. The market analysis also includes a summary of chiller sales trends over the past 25 years for both electric and gas systems.

Sections 3 and 4 describe typical water chiller systems. A technical overview of common electric and gas systems is included in Section 3, and chiller product offerings by vendor are listed in Section 4. The chiller technologies examined in greatest detail are listed in Table 1-2.

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[1] One ton of cooling = 12,000 Btu/h

Table 1-2. Chiller Technology Focus for this Report

Primary Power Source	*Technology*
Electric	Centrifugal Compressor Screw Compressor
Gas	Absorption (Direct-Fired, Double-Effect) Engine-Driven

Sections 5 and 6 cover selection factors and optimization issues. In Section 5, the significant issues involved in chiller plant design are discussed. Variables such as cost (e.g., first, operating, and maintenance), refrigerant options, performance (e.g., part-load efficiency), and physical characteristics are examined. In Section 6, several strategies for optimizing chilled water systems are discussed. These strategies are summarized relative to specific utility and building owner objectives. To provide a practical perspective, Section 6 includes recent case studies involving chiller installations.

The final section includes an economic analysis of chiller options based on the COMTECH™ [2] computer program. Chillers near 200 and 700 tons are examined based on the parameters shown in Table 1-3.

Table 1-3. Parameters Used for Chiller Economics

Parameter	*Variation*
Chiller Type	[1] Electric Centrifugal, Standard Efficiency [2] Electric Centrifugal, High Efficiency [3] Gas Engine, Screw Compressor [4] Gas Absorption
Building Type	[1] Office [2] Retail [3] Health Facility [4] School
Cities	[1] Los Angeles [2] Chicago [3] Atlanta

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[2] COMTECH™ is an interactive screening tool developed by the Electric Power Research Institute for evaluating the cost impacts of various commercial building technologies.

2

Chiller Market

The U.S. Department of Energy (DOE 1994) reports that there are approximately 4.8 million commercial buildings[3] in the United States with a total floor space of nearly 68 billion ft^2. Figure 2-1 shows the distribution by number and floor space as a function of building size. As indicated in Figure 2-1, 95% of all commercial buildings are under 50,000 ft^2, accounting for just over half of the total commercial building square footage.

In recent years, the U.S. DOE has surveyed building owners and managers to determine a wide variety of characteristics for this commercial building stock, including the prevalence of chillers.

Based on this DOE data, the installed chiller base can be examined as a function of the following variables

- Building Size
- Geographic Region
- Building Age

2.1 CHILLERS BY BUILDING SIZE

Approximately 3% of the 4.8 million commercial buildings have chillers (DOE, 1994)[4]. Because chillers dominate installations in larger buildings, the fraction of floor space cooled by chillers is significantly higher (19%).

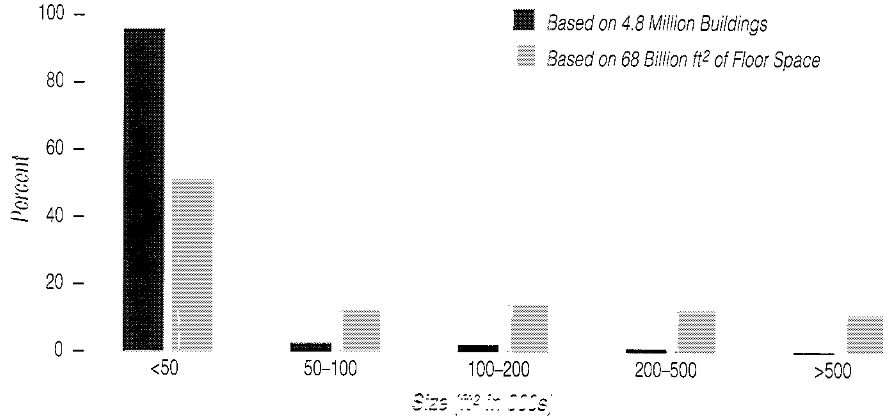

Figure 2-1. Commercial Building Inventory
Source: DOE/EIA (1994)

[3] Defined as a non residential, non agricultural, non industrial building larger than 1000 ft^2.

[4] These statistics include both gas and electric chillers installed in buildings greater than 1000 ft^2. In some cases, buildings may have multiple chillers. The number of chillers installed per building is not reported in the DOE (1994) reference.

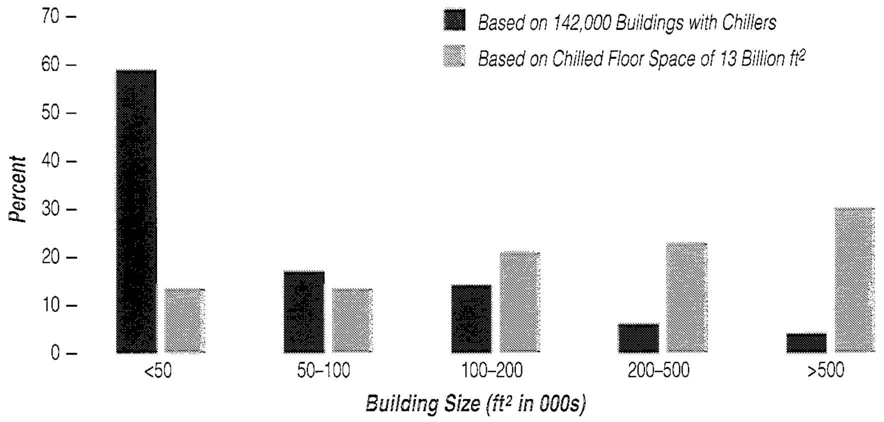

Figure 2-2. Chiller Distribution by Building Size
Source: DOE/EIA (1994)

Figure 2-2 shows chiller installations as a function of building size. As indicated, 59% of all chillers are installed in buildings under 50,000 ft^2. The majority of these chillers in small commercial buildings are likely to be electric-powered systems with reciprocating compressors[5]. Water chillers with centrifugal and screw compressors generally have higher capacities and are thus suited for large buildings (>50,000 ft^2). Buildings above 50,000 ft^2 are reported to have 41% of all chillers and 87% of all chilled building floor space.

2.2 CHILLERS BY GEOGRAPHIC REGION

Figures 2-3 and 2-4 illustrate the distribution of chillers for various geographic locations (see Figure 2-5 for regional

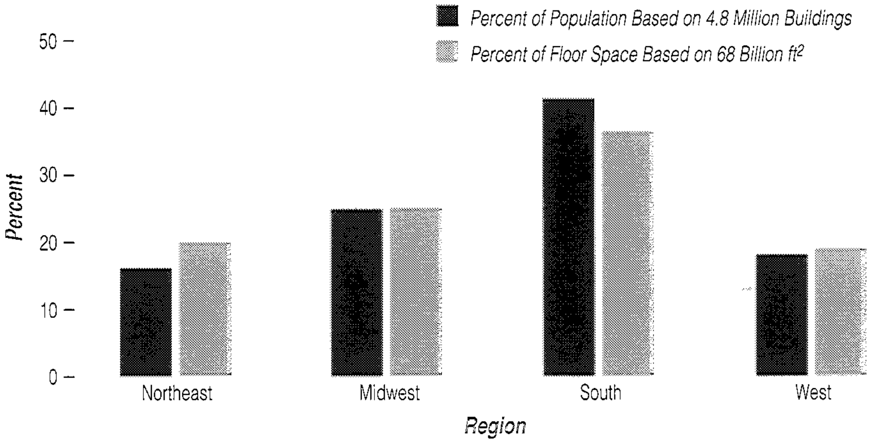

Figure 2-3. Building Breakdown by Region
Source: DOE/EIA (1994)

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[5] Quantitative data on energy source for chillers and compressor style not reported in the DOE (1994) reference.

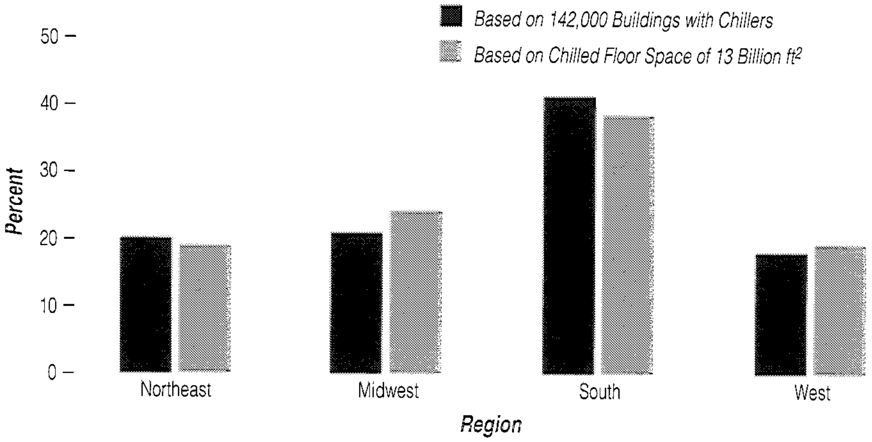

Figure 2-4. Chiller Distribution by Region
Source: DOE/EIA (1994)

boundaries). The southern region of the United States has just over 40% of all commercial buildings and slightly under 40% of the estimated floor space for the entire country (Figure 2-3). The chiller inventory in the South closely follows the building inventory (Figure 2-4).

A comparison of Figures 2-3 and 2-4 reveals that the regional building breakdown data compares within two percentage points to the regional distribution data (Figure 2-4), with the exception of the population in the Northeast (16% of buildings, 20% of chillers) and the population in the Midwest (25% of buildings, 21% of chillers).

2.3 CHILLERS BY BUILDING AGE

The pie charts in Figures 2-6 and 2-7 provide insights into the relationship of building age and chiller installations. Of the 142,000 buildings with chillers, approximately 36% were constructed prior to 1960, which represents 22% of the total floor space conditioned by chillers. For buildings constructed in the 1960s, the percentage of buildings with chillers closely matches the floor space percentage (25% with chillers, 23% of floor space). In the 1970s, the percentage of chilled floor space exceeded the population percentage (19% of buildings with chillers, 26% of chilled floor space). A similar disparity occurred in the 1980s

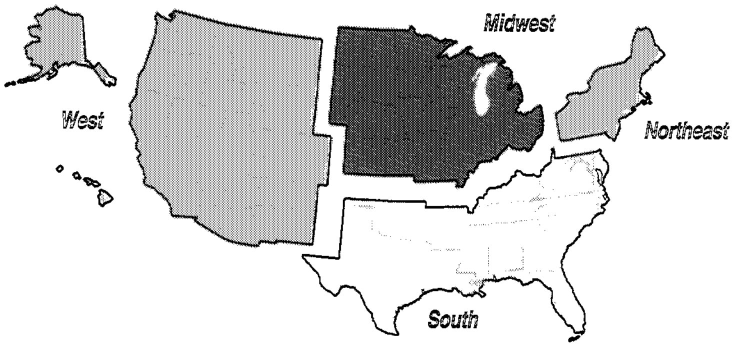

Figure 2-5. Regional DOE/EIA Boundaries

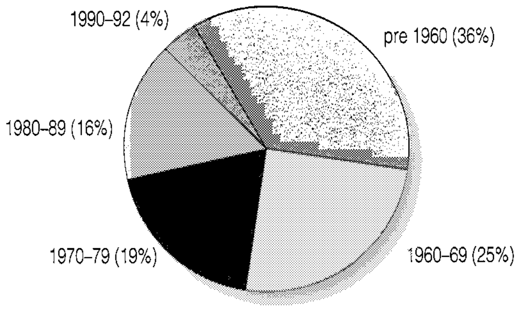

Figure 2-6. Buildings with Chillers by Building Construction Date
Source: DOE/EIA (1992)
Base: 142,000 Buildings with Chillers

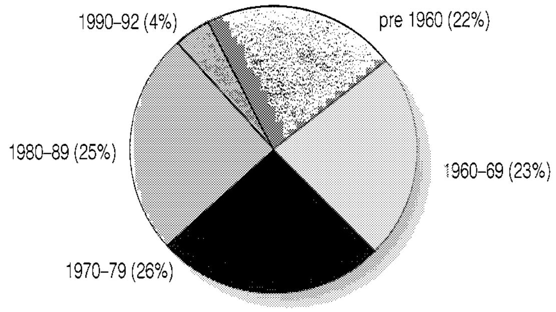

Figure 2-7. Chilled Floor Space by Building Construction Date
Source: DOE/EIA (1992)
Base: 13 Billion ft^2 Cooled by Chillers

(16% of buildings with chillers, 25% of chilled floor space). From 1990 to 1992, the percentages have been similar at 4% each.

Through the end of the 1980s, the data in Figures 2-6 and 2-7 suggests that chillers were being installed in larger buildings over time. This trend explains a generally increasing percentage of chilled floor space and a generally declining percentage of buildings with chillers. After 1990, the percentages have been similar (4%).

Building age data can provide an indication for chiller replacement trends. For example, for the three decades from 1960 to 1989, the number of buildings with chillers declined from 25% to 19% to 16% (Figure 2-6). This data implies that the number of first-time chiller replacements should also decline as chillers reach the end of their useful life (typically in the range of 20 to 30 years). This conclusion, however, does not account for replacements due to other reasons (e.g., CFC curtailments), nor does it include second-time chiller replacements that might occur in older buildings.

As noted in the following section, chiller shipments are actually rising sharply, and buyers are facing considerable lead times for new electric and gas chillers. This recent buying trend is undoubtedly driven by a combination of factors, including replacement of older

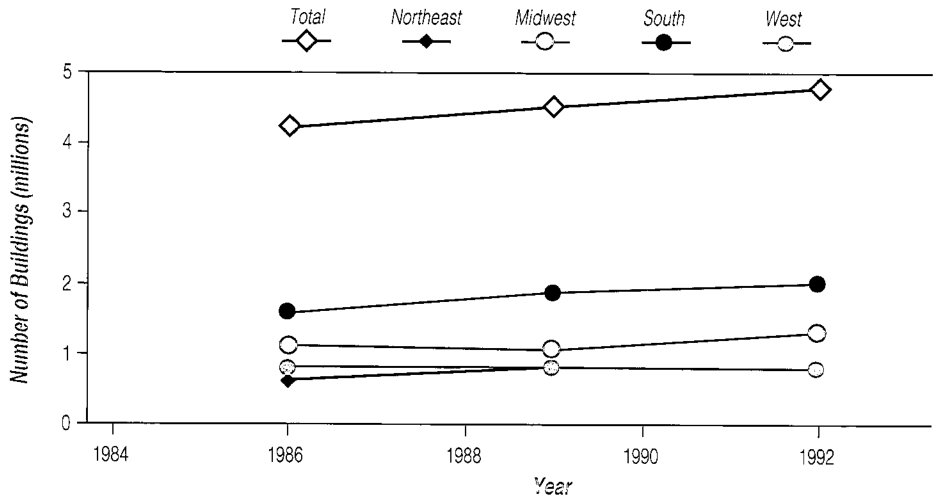

Figure 2-8. Commercial Building Growth
Source: DOE (1994)

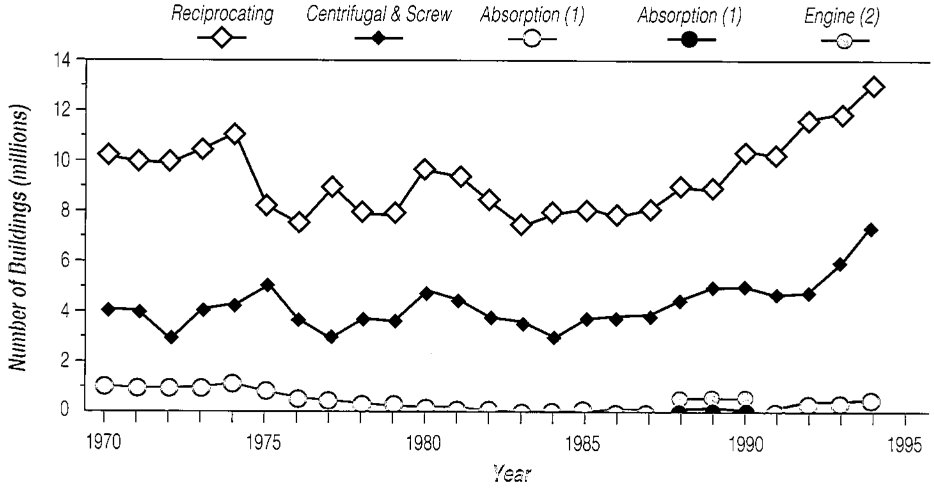

Figure 2-9. Chiller Shipment Trends (all sizes)
Source: [1] News (1993) and News (1995a) [2] AGA (1994)

chillers near the end of their useful life, replacement of younger CFC chillers with non-CFC alternatives, and the purchase of chillers for new installations.

2.4 COMMERCIAL BUILDING GROWTH AND CHILLER SHIPMENT TRENDS

Chillers are purchased for new construction and replacement needs. For new construction, chiller demand is most closely correlated with commercial building growth patterns. A recent six-year period (1986–1992) for this growth is shown in Figure 2-8, which indicates that the total commercial building population grew at an annual rate of 2.5% (4.2 to 4.8 million). The largest growth rate (3.8%) occurred in the south (Figure 2-5 for boundaries), which is also the region with the largest building population (nearly two million buildings in 1992).

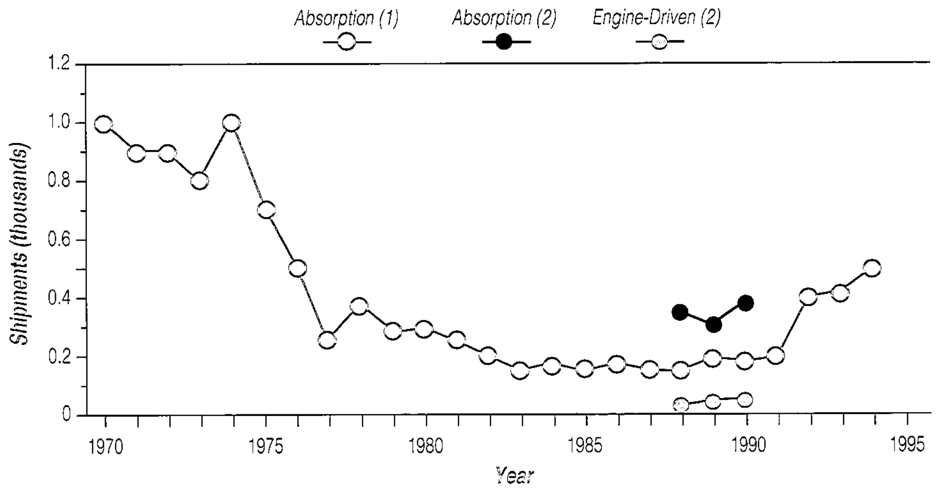

Figure 2-10. *Gas Chiller Shipments*
Source: [1] News (1993) and News (1995a) [2] AGA (1994)

Replacement chiller purchases have accelerated in recent years due to the CFC production ban that takes effect at the end of 1995. This production ban has prompted many CFC chiller owners to retire chillers early and replace these machines with non-CFC alternatives. Early retirement of CFC machines combined with demand for expected replacements (i.e., those chillers at the end of their economic life) and new construction have caused a noticeable and sustained upturn in shipments (Figure 2-9). As indicated in Figure 2-9, electric chiller shipments are about one order of magnitude greater than gas chillers[6]. However, gas chiller shipments, particularly for absorption technologies, are increasing sharply (Figure 2-10).

It is important to note that the shipment data in Figures 2-9 and 2-10 are based largely on data supplied by manufacturers to the American Refrigeration Institute (ARI) and subsequently released to various trade publication (e.g., the *Air Conditioning, Heating and Refrigeration News*). The data in Figures 2-9 and 2-10 cover both large and small systems. For comparison, shipment data for larger chiller systems (>100 tons) are shown in Figure 2-11.

Figure 2-11 suggests that shipments of gas-fired absorption systems are rebounding and beginning to capture a larger share of the large chiller market. For the period 1986–1992, shipments of electric centrifugal and screw chillers declined slightly (0.9% per year) from 3113 to 2950 units. Over this same period, absorption shipments increased from 180 to 307 (9.3% average annual increase). The number of commercial buildings grew at an average annual rate of 2.5% for this same six-year period.

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[6] Data for engine-driven and absorption systems from AGA (1994) covers systems above 15 tons.

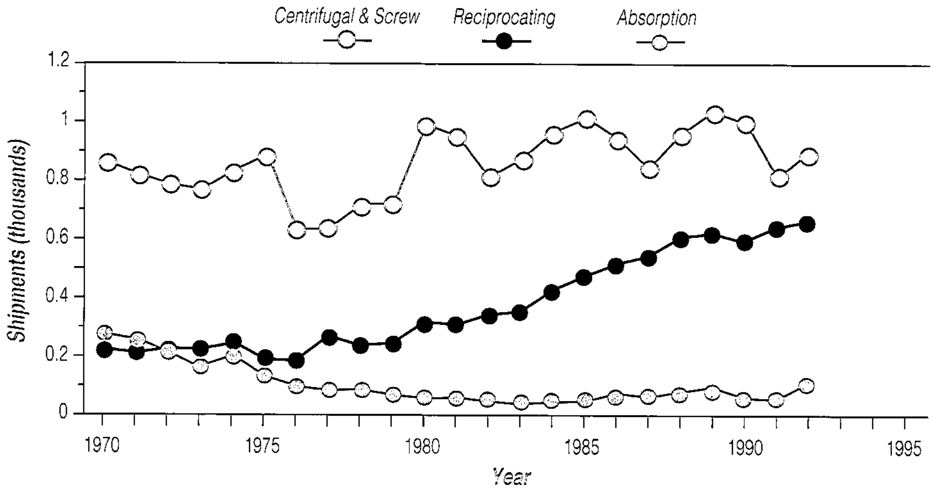

Figure 2-11. *U.S. Chiller Shipments (>100 tons)*

3

Chillers & Chilled-Water Systems

A chilled-water system provides cooling by extracting energy (i.e., heat) from a building and transferring this energy to the outside environment, generally through a cooling tower. A diagram of a basic chilled-water system with a single chiller[7] is shown in Figure 3-1. The chilled-water system is comprised of three main elements

- Chiller
- Chilled-Water Loop
- Condenser-Water Loop

The chiller is typically packaged and supplied by the manufacturer as a single skid-mounted unit. The chiller contains the condenser and evaporator components that are connected in the field to the condenser- and chilled-water loops, respectively. The chilled-water loop connects the chiller to the building, and includes a chilled-water pump, miscellaneous piping, and an air-handling unit. The condenser-water loop connects the chiller to the cooling tower, and includes a condenser pump and miscellaneous piping.

A variety of energy sources can be used to drive the chiller cycle (e.g., electricity, natural gas, diesel fuel, or steam). Electric, gas, steam, and other types of chillers all represent alternative methods of producing the chilled water. Each type may be used as the chiller element in Figure 3-1. Regardless of chiller type, the components and functions of the chilled-water loop and condenser cooling-water loop remain the same.

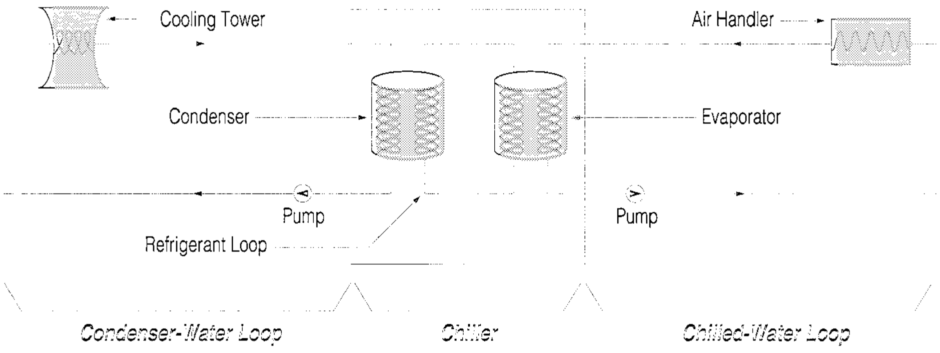

Figure 3-1. Chilled-Water System

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[7] Chilled-water systems frequently contain multiple chillers.

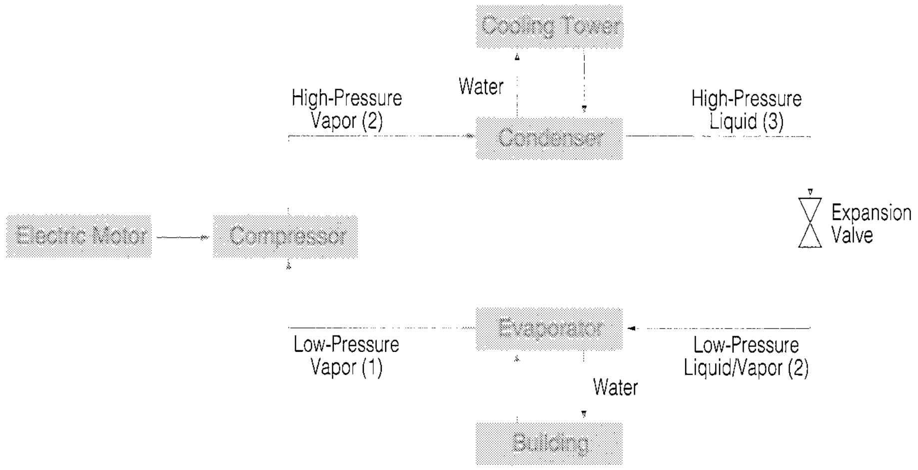


Figure 3-2. Electric Chiller Diagram

3.1 ELECTRIC CHILLERS

Electric chillers use a vapor compression refrigeration cycle, also known as a two-phase mechanical refrigeration cycle, for transferring heat. A diagram for a typical water-cooled electric chiller is shown in Figure 3-2. The chiller includes an electric motor, a refrigeration compressor, a condenser, an evaporator, an expansion valve, and controls. A photograph of a typical water-cooled electric chiller is shown in Figure 3-3.

For smaller chillers (up to 250 tons), an air-cooled condenser is often used rather than a water-cooled arrangement as shown in Figure 3-2. Air-cooled condensers use one or more fans, instead of a cooling tower, to cool the hot refrigerant vapor. For an air-cooled system, the condenser and fan(s) are typically supplied as a single unit and located remotely from the chiller. Similarly evaporative condensers can replace the cooling tower and condenser water loop.

The electric chiller vapor compression cycle operates in the following manner (numbered items in Figure 3-2 correspond to the following explanations):

1. The compressor is used to compress the low-pressure refrigerant vapor to a high-pressure vapor. An electric motor powers the refrigeration compressor.
2. The high-pressure refrigerant vapor is cooled and condensed to a high-pressure liquid in the condenser. The condenser removes heat from the refrigerant and rejects it through a condenser cooling-water loop to the cooling tower.
3. An expansion valve or pressure reducer is used to lower the pressure of the liquid refrigerant that passes into the evaporator.
4. In the evaporator, the low-pressure liquid refrigerant vaporizes, removing heat from the chilled water. The low-pressure refrigerant vapor then returns to the compressor inlet.

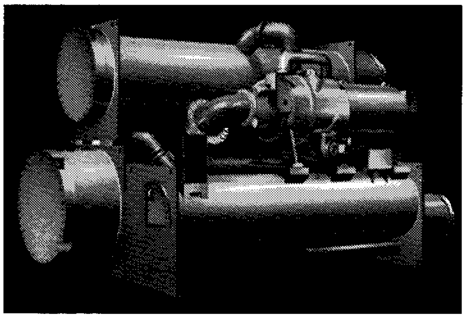


Figure 3-3. Electric Chiller
Source: Carrier Corporation

3.1.1 REFRIGERANTS

Numerous refrigerants have been developed for vapor compression systems, primarily halogenated carbon compounds (also called halocarbons) having specific thermodynamic, physical, and chemical properties that make them suitable for use as refrigerants in vapor compression cycles. Compressors and chillers are typically designed around the thermodynamic characteristics and physical properties of a specific refrigerant.

In the past, the majority of refrigerants used in electric chillers were CFCs (chlorinated-fluorocarbons). In the case of electric chillers configured with centrifugal compressors, approximately 80% were designed to use CFC-11. About 15% of these centrifugal chillers used CFC-12, and the balance used a mix of refrigerants, including CFC-113, CFC-114, and CFC-500 (EPRI, 1990a).

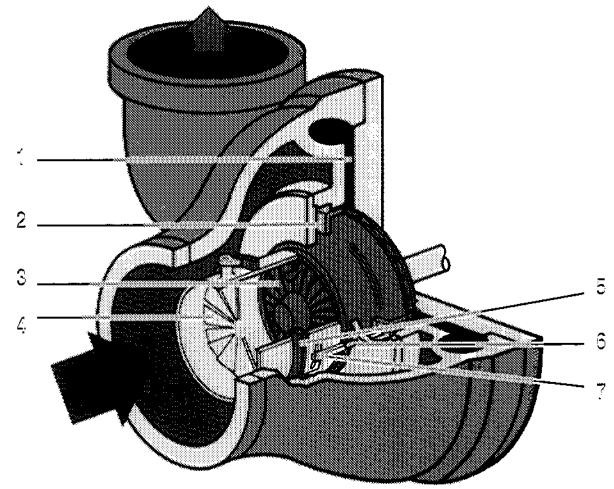
The recent concerns over the Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) of CFC refrigerants has led to production bans on CFCs and to the introduction of alternative refrigerants. These alternatives include HCFCs (hydro-chlorinated-fluorocarbons) and HFCs (hydro- fluorocarbons) with much lower ODP and GWP levels. A comparison of ODP and GWP levels for various CFCs and possible replacements is shown in Table 3-1. Note that a suggested replacement for CFC-11 is HCFC-123, and a possible replacement for CFC-12 is HFC-134a (EPRI 1995d).

3.1.2 COMPRESSORS

Electric chillers are typically classified by the type of refrigeration compressor used. Three types of compressors are commonly used in electric chiller applications: centrifugal, screw, and reciprocating. A fourth type, the scroll compressor, is less frequently used, and a fifth type, the hydraulic compressor, is under development. A comparison of centrifugal, screw, and reciprocating compressors is presented in Table 3-2, and a discussion of each is presented in the following sections.

Centrifugal Compressors

Centrifugals are the most common type of compressor used for electric chillers. Figure 3-4 diagrams a typical centrifugal compressor. Centrifugal compressors are turbo-machines, rather than positive-displacement devices. Pressure and flow of the refrigerant is developed by means of a rotating impeller. Refrigerant vapor enters the compressor near the center of the impeller. The vapor is spun out from the center of the impeller and compressed by centrifugal forces.



1. Diffuser Opening
2. Diffuser Ring
3. Compressor Impeller
4. Variable Inlet Guide Vanes
5. Coordinating Ring
6. Actuating Rods
7. Program Cams

Figure 3-4. *Typical Centrifugal Compressor*
Source: Carrier Corporation

Table 3-1. Refrigerant Properties

Refrigerant	*Components*	*Typical Use*	*ODP*	*GWP*
Traditional Refrigerants in Use				
R-11	CFC-11	most centrifugal chillers (low-pressure)	1.00	1.00
R-12	CFC-12	commercial & residential refrigeration centrifugal chillers (med-pressure) auto a.c.	1.00	2.09
R-22	HCFC-22	direct expansion a.c. (heat pumps, etc.) screw compressors centrifugal chillers (high-pressure)	0.06	0.43
R-500	CFC-12/HFC-152a	centrifugal chillers (med-pressure)	0.70	1.60
R-502	HCFC-22/CFC-115	commercial refrigeration	0.20	1.30
R717	ammonia	industrial refrigeration	0.00	0.00
New Refrigerants in Use				
R-134a	HFC-134a	CFC-12 compressors	0.00	0.34
R-123	HCFC-123	CFC-11 compressors	0.02	0.02
R-401A	HCFC-22/124/HFC-152a	CFC-12 retrofit in comm'l refrigeration	0.03	0.27
R-402A	HFC-125/HCFC-22/R-290	R-502 retrofit in existing equipment	0.02	0.58
R-404A	HFC-125/143a/134a	R-502 alternative	0.00	0.68
R-407A	HFC-32/125/134a	R-502 retrofit in existing equipment	0.00	0.49
R-407C	HFC-32/125/134a	R-22 alternative	0.00	0.39
R-408A	HFC-125/143a/HCFC-22	R-502 retrofit in existing equipment	0.03	0.78
R-409A	HCFC-22/124/142b	CFC-12 retrofit in comm'l refrigeration	0.05	0.31
R-507	HFC-125/143a	R-502 alternative	0.00	1.02
Refrigerants Under Consideration				
R-32	HFC-32	blends	0.00	0.15
R-124	HCFC-124	blends	0.02	0.12
R-125	HFC-125	blends	0.00	1.00
R-143a	HFC-143a	blends	0.00	1.10
R-152a	HFC-152a	blends	0.00	0.04
R-290	propane	blends	0.00	0.00
R-410A	HFC-32/125	R-22 alternative	0.00	1.02
R-410B	HFC-32/125	R-22 alternative	0.00	1.02

Source: EPRI (1995d) and EPRI (1993c)

Table 3-2. Comparison of Compressor/Chiller Types

	Compressor Type		
Characteristic	*Centrifugal*	*Screw*	*Reciprocating*
Compressor Operation	turbo-machine	positive-displacement	positive-displacement
Available Sizes (tons)	80-10,000	40-1250	15-300
Common Applications (tons)	200-2,000	150-400	50-200
Full-Load Efficiency (kW/ton)	0.50-0.70	0.60- 0.75	0.90-1.00
Refrigerant	HCFC-123 HCFC-22 HFC-134a —	— HCFC-22 HFC-134a ammonia	— HCFC-22 HFC-134a ammonia
Turndown	20-40% of full load	10-20% of full load	20-30% of full load
Capacity Control Method	• inlet guide vanes • variable freq. drive • hot gas by pass	• slide valves • variable freq. drive • hot gas by pass	• cylinder unloaders • hot gas by pass
Noise/Vibration	medium	medium-high	low
Motor Speed (max rpm)	3,600	3,600	3,600
Compressor Speed (max rpm)	3,600-35,000	3,600	3,600
Drive Type	• open • semi-hermetic	• open • semi-hermetic • hermetic	• open • semi-hermetic • hermetic
Condenser Cooling	water or air	water or air	water or air
Advantages	• high full-load efficiency • reliable	• small • light weight	• low first cost • parts & service readily available • reliable
Disadvantages	• surge at low loads • small sizes are expensive to purchase	• low full-load efficiency • lube oil separation required	• low efficiency

Source: E-Source (1995), EPRI (1995d), EPRI (1993c), Haines (1994), and Manufacturers' Literature

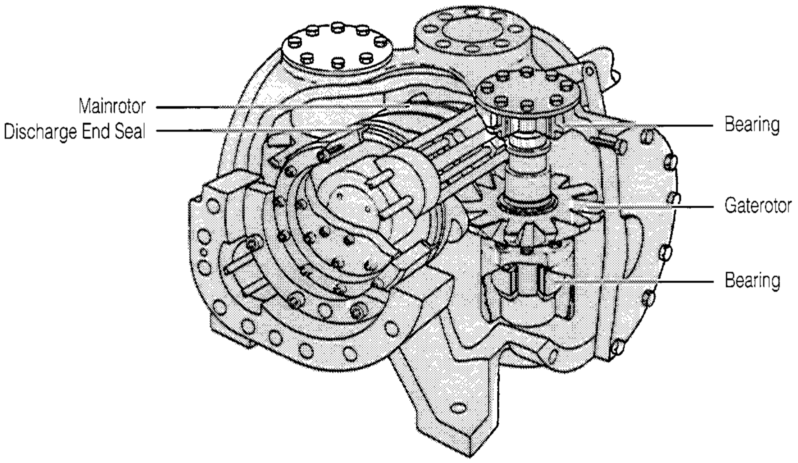


Figure 3-5. Typical Single-Screw Compressor Design
Source: ASHRAE (1992)

Centrifugal compressors may use single-stage compression (with single impellers and speed-increasing gear drives) or multistage compression (with multiple impellers and direct drives). Capacity control is achieved through adjustment of inlet guide vanes or motor speed. Centrifugal compressors are commonly used for chillers with capacities above 200 tons.

Screw Compressors

The use of screw compressors for electric chillers is increasing. Screw compressors are displacing smaller centrifugal compressors and reciprocating compressors. Screw compressors are positive-displacement devices available in single-screw or twin-screw designs. The single-screw design consists of a helical main rotor and two star wheels or gate rotors. A typical single-screw compressor design is illustrated in Figure 3-5. The twin-screw design consists of two inter-meshing helical gears. In both designs the refrigerant vapor is compressed between the tightly sealed, rotating components. Capacity control is achieved through adjustment of slide vanes and motor speed. Screw compressors are commonly used on chillers with 150- to 400-ton capacities.

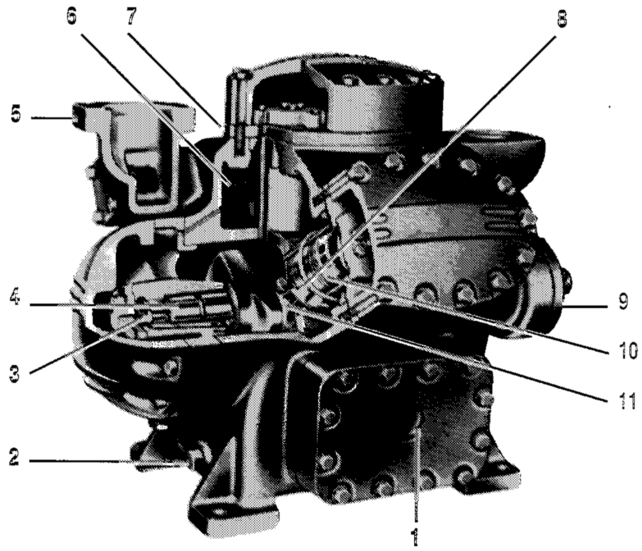
Reciprocating Compressors

A typical reciprocating compressor design is illustrated in Figure 3-6. Reciprocating compressors are positive-displacement devices. The refrigerant is compressed by a number of single-acting pistons operating in cylinders. Designs are available with 1 to 12 cylinders. Capacity control is accomplished through cylinder unloading and motor speed control. Reciprocating compressors are commonly used on chillers with 50- to 200-ton capacities.

3.1.3 ELECTRIC MOTORS

Approximately 94% of all chillers are powered by electric motors (EPRI, 1993e). Compressors may be connected to electric motors through the use of belt-drives, direct-drives, or gear-drives (transmissions). Gear-drives are used when the electric motor speed must be matched to the compressor speed. Speed-increasing transmissions are commonly used between electric motors and centrifugal compressors. When a direct-drive is used, the motor is often connected to the compressor drive-shaft through a flexible metal coupling that reduces vibration and alignment problems.

Electric motors are available in a range of efficiencies. For standard efficiency open-drive motors in the size range from



1. Oil level sight glass
2. Oil drain
3. Reversible oil pump
4. Statically and dynamically balanced crankshaft
5. Unrestrictive suction gas inlet
6. Fine-mesh suction screen
7. Precision ground valve plate assembly with Swedish steel ring valves
8. Internal capacity control system
9. Time-proven shaft seal assembly
10. Removable cylinder liners
11. Forged-steel connecting rods with replaceable bearing inserts

Figure 3-6. *Typical Reciprocating Compressor Design*
Source: Carrier Corporation

3 to 100 hp, efficiencies range from 80% to 92% (ASHRAE 1992). High-efficiency electric motors above 100 hp typically have efficiencies of 95-96%.

The relatively large electric motors used with chillers almost always use three-phase power. Electric motors up to 500 hp are generally wired to 480-VAC or 575-VAC electrical supplies. Above approximately 500 hp, motors are frequently wired to three-phase power at 2300 VAC or 4160 VAC. Electric motors are controlled using motor starters, contactors, and current-limiting devices. Power factor[8] control capacitors may be required if the power factor is below 0.8. Low power factor often results when motors are oversized or are operated under part-load conditions. Adjustable speed drives can be used to control motor speed and reduce power consumption.

Three general motor configurations are available for electric chillers: hermetic, semi-hermetic, and open-drive. Each is discussed in the following sections.

Hermetic

Hermetic designs integrate the compressor and electric motor. The compressor and motor components are on the same shaft and are contained in a sealed housing to prevent refrigerant loss. Refrigerant leakage is minimized as there are no seals around rotating shafts. Since hermetic motors are cooled by the refrigerant, motor heat is removed by the condenser and does not have to be removed from the equipment room through ventilation. Hermetic designs protect the motor from dust and dirt and are more efficient at part-load operation. Hermetic designs are more difficult to repair in the event of a motor failure as the refrigerant must be removed or isolated.

Semi-hermetic

Semi-hermetic designs have separate housings for the compressor and motor. The housings have matching flanges and seals to prevent refrigerant leakage. Seals around the rotating compressor and motor shafts are, therefore, not required.

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[8] Power factor is a unitless value between 0 and 1, and is the ratio of real to apparent power.

Open-Drive

Open-drive designs use an electric motor coupled to the compressor through a flexible coupling, gear drive, or belt drive. A shaft seal on the compressor must be provided to prevent refrigerant leakage. Refrigerant does not have to be removed when the motor is repaired. Open-drive designs allow for a wider range of choices for motor size, type, and efficiency. In addition, the motors on open-drives are commonly available and are easier to repair. Motors have common NEMA frame designations with standardized mounting and interface configurations, electrical connections, and drive-shaft connections.

3.1.4 CONDENSERS

The condenser cools and condenses the hot, compressed refrigerant vapor after it leaves the compressor. Condensers may be air-cooled, water-cooled, or evaporatively cooled.

Air-Cooled Condensers

The air-cooled condenser is essentially a refrigerant-to-air heat exchanger. The refrigerant passes through finned tubes, and electric fans are used to blow air across them. Air-cooled condensers are often used on screw and reciprocating chiller packages up to about 400 tons. They are also used on small centrifugal chillers. Air-cooled condensers may be integral to the chiller package or remotely located. When remotely located, the refrigerant is pumped to the air-cooled condenser and then back to the chiller package. Air-cooled condensers are also common on smaller-packaged rooftop chillers.

Water-Cooled Condensers

Water-cooled condensers are usually shell and tube heat exchangers. The refrigerant vapor is circulated through the shell, and the cooling water is circulated through the tubes. Heat is removed from the refrigerant by the cooling water at the condenser and rejected at a cooling tower or fluid cooler.

Water-cooled condensers are used on centrifugal, reciprocating, and screw chillers. Water-cooled condensers are often mounted on the chiller package next to the evaporator, but they may also be remotely located.

Evaporatively Cooled Condensers

In an evaporatively cooled condenser, the refrigerant is circulated through a tube coil. Water is sprayed on the tube coils, and a fan draws air across the coils and sprays. As the water evaporates, it removes heat from the tube coils and refrigerant.

3.1.5 PRESSURE REDUCERS

A pressure-reducing device, such as an expansion valve, is located in the refrigerant line between the condenser and evaporator. Its function is to convert the high-pressure refrigerant liquid to a low-pressure mixture of liquid and vapor.

3.1.6 EVAPORATORS

The evaporator is a device for exchanging heat between the low-pressure liquid/vapor refrigerant and the chilled-water loop. The low-pressure refrigerant is evaporated, removing heat from the chilled water. Evaporators are generally one of two types: flooded or direct-expansion. Both types are essentially tube and shell heat exchangers. In flooded evaporators, the chilled water flows through the tubes and the refrigerant flows through the shell. A straight-through design is often used with removable water boxes to aid in tube cleaning. In direct-expansion evaporators, the refrigerant flows through the tubes and the chilled water flows through the shell. A U-tube design is often used. Baffles control the flow of chilled water around the tubes.

3.1.7 CONTROLS AND OPTIONS

The majority of electric chiller packages have integral control panels, although large chillers may have custom-built or remotely located controls. Controls typically include devices for monitoring compressor operation, controlling compressor startup and shutdown, interfacing with the chilled-water loop, and interfacing with the condenser cooling-water loop. Electric chiller control panels typically include oil pressure gage, suction pressure gage, discharge pressure gage, run-time indicator (hour meter), compressor motor starter and overload protection devices, compressor sequencing or short-cycle prevention timers, control relays for condenser pump, control relays for chilled-water pump, and controls for the cooling tower fan.

Electric chillers are available with a variety of options. Most options depend on the type of chiller and some are offered only by specific manufacturers. Common options include condenser size and type, evaporator size, compressor refrigerant, compressor unloading method, relay packages, adjustable speed drives, control enclosure type, gage packages, and remote-control packages.

3.2 GAS-FIRED CHILLERS

There are two main types of gas chillers: absorption and engine-driven.

3.2.1 ABSORPTION CHILLERS

Absorption chillers are based on an absorption, or heat-activated, thermodynamic cycle. A two-component fluid is circulated in the absorption cycle. One component, the refrigerant, is alternately absorbed and desorbed from the second component, the absorbent. Two common fluid pairs are water (refrigerant) with lithium bromide (absorbent) and ammonia (refrigerant) with water (absorbent).

The absorption process occurs in a section of the chiller referred to as the absorber, and the desorption step occurs in a section referred to as the generator. Absorption chillers include condenser and evaporator sections much like electric chillers (see Figure 3-2). However, absorption chillers can include additional condenser sections that are combined with additional generator sections. Each set of generators and condensers is referred to as an effect (e.g., single-effect or double-effect). In general, chiller efficiencies improve with additional effects.

Heat is added, either directly or indirectly, to the generator to desorb the refrigerant. Direct-fired chillers use a natural-gas-fired burner to provide heat, and indirect-fired units use hot water, steam, or waste heat. A photograph of a direct-fired, double-effect absorption chiller is shown in Figure 3-7.

Table 3-3 compares the operating and performance characteristics of single-, double-, triple-, and quadruple-effect absorption chillers. The single-effect and

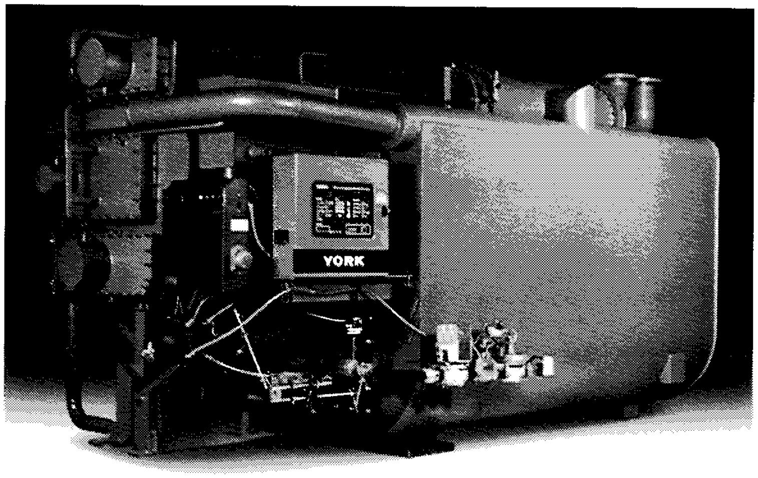


Figure 3-7. York Model YPC-DF Absorption Chiller
Source: York International Corporation

double-effect systems are commercially available, while the triple- and quadruple-effect units are currently under development.

Single-Effect

A single-effect absorption refrigeration cycle is diagrammed in Figure 3-8. The system operates in the following manner:

1. In the evaporator, cool liquid refrigerant is expanded and sprayed on the chilled-water evaporator coils.
2. The liquid refrigerant is evaporated with heat liberated from the chilled-water loop, thus cooling the chilled water.
3. In the absorber, the refrigerant vapor is cooled and condensed by the cooling tower water. The liquid refrigerant is then absorbed by an absorbent solution.
4. The refrigerant/absorbent solution is pumped to the generator.
5. In the generator, heat is added and the refrigerant is evaporated from the absorbent. The concentrated absorbent solution is returned to the absorber section, and the refrigerant vapor travels to the condenser.
6. In the condenser, the refrigerant vapor is cooled and condensed. Heat is removed by the condenser-water loop and rejected to the cooling tower. The cool liquid refrigerant is returned to the evaporator section, and the process repeats.

Double-Effect

Double-effect absorption chillers incorporate two generator and condenser sections as diagrammed in Figure 3-9. The system operates much like the single-effect system, with the following modifications:

Table 3-3. Comparison of Absorption Chiller Types

Type	*COP*	*Availability*	*Size (tons)*	*Refrigerant/ Absorbent Pair*	*Generator Temp. (°F)*	*Fuel Type*	*Applications*
Direct-Fired, 1-effect	0.48-0.62	in production	3-5	ammonia/water	180-240	natural gas	residential, small commercial
Direct-Fired, 2-effect	0.92-1.04	in production	20-1100	water/ lith. bromide	200-400	natural gas	commercial
Indirect-Fired, 1-effect	0.60-0.70	in production	5-1660	water/ lith. bromide	180-210	hot water, steam	commercial
Indirect-Fired, 2-effect	1.15-1.20	in production	100-1700	water/ lith. bromide	350	hot water, steam, exh.	commercial
3-effect	1.50-1.70	in development	—	water/ lith. bromide	400	natural gas, steam, exh.	—
4-effect	2.00	concept	—	water/ lith. bromide	500	natural gas, steam, exh.	—

Source: AGCC (1995a) and ASHRAE (1995)

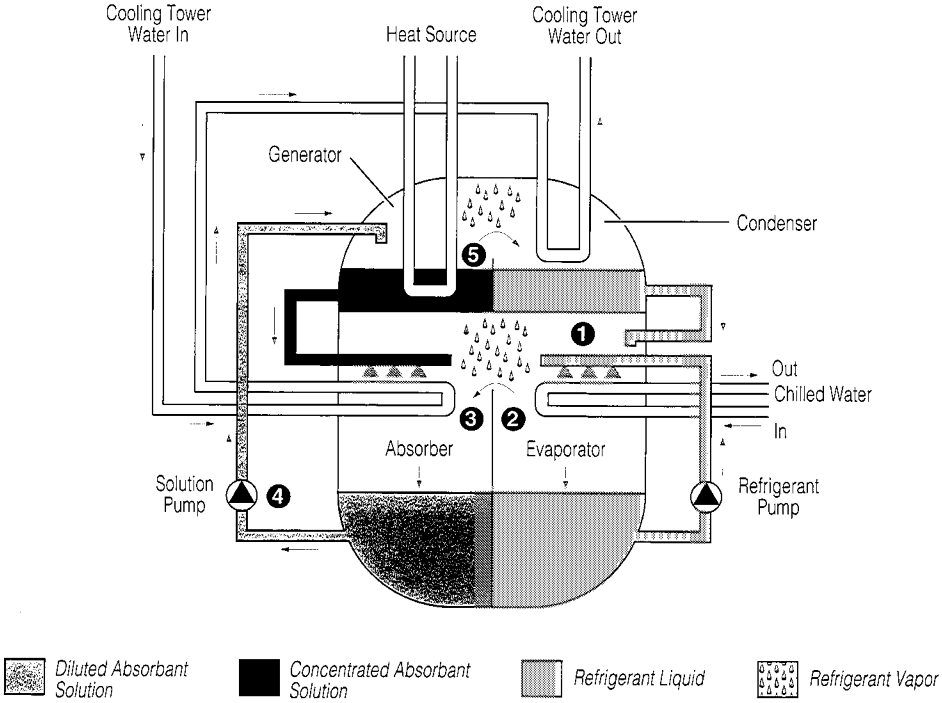


Figure 3-8. Single-Effect Absorption Cycle

1-4. Similar to single-effect operation as discussed above.

5. From the solution pump, the refrigerant/absorbent mixture enters the primary generator. Heat is added to vaporize the refrigerant, and the concentrated absorbent flows to the secondary generator. The refrigerant vapor passes to the primary condenser.
6. In the primary condenser, the refrigerant vapor is cooled and condensed. Heat is removed by a closed-loop heat exchanger that transfers energy between the primary condenser and the secondary generator sections. The condensed refrigerant travels to the secondary condenser.
7. In the secondary generator, additional refrigerant is evaporated using heat from the closed-loop heat exchanger connected to the primary condenser. Concentrated absorbent solution moves from the secondary generator to the absorber section, and the refrigerant vapor travels to the secondary condenser.
8. In the secondary condenser, refrigerant vapor from both the secondary and primary condensers is cooled and condensed. Heat is rejected to the cooling tower. The cool liquid refrigerant is returned to the evaporator, and the process repeats.

Developments in Triple-Effect and Quadruple-Effect

Triple-effect and quadruple-effect absorption chillers are being developed. Triple-effect machines are nearing market introduction, while quadruple-effect machines are in the early stages of development.

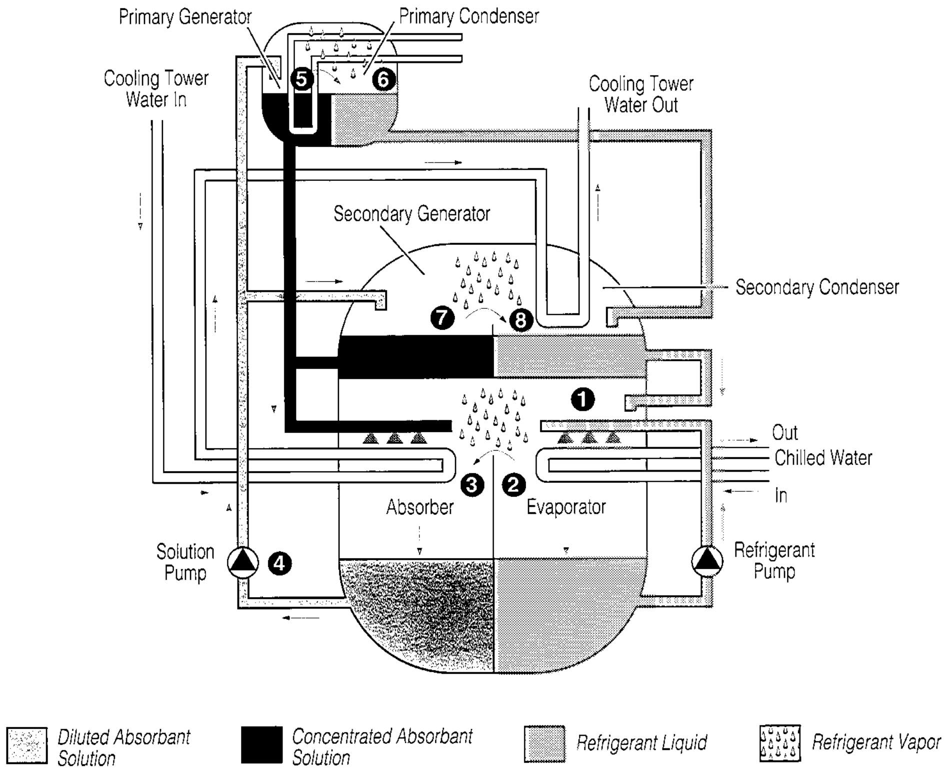


Figure 3-9. Double-Effect Absorption Cycle

These machines are expected to have significantly higher efficiencies compared to existing single- and double-effect chillers. For comparison, triple-effect machines are anticipated to have efficiencies, as expressed in terms of Coefficient of Performance (COP), of 1.5 or greater. This efficiency indicates that these machines will be on the order of three times more efficient than single-effect machines (typical COP near 0.5) and approximately 50% more efficient than double-effect chillers (typical COP near 1.0).

Controls and Options

The control, safety, and system integration features of absorption chillers are similar to those of electric chillers. These include controls for startup, shutdown, interface with the chilled-water loop, and interface with the condenser-water loop. In addition, absorption chillers include motor starters for the solution pump, burner or steam modulation controls, and indicators for refrigerant/absorbent temperature and pressure. Refrigerant loss must be monitored to prevent crystallization of the absorbent (lithium bromide).

3.2.2 GAS ENGINE-DRIVEN CHILLERS

Gas engine-driven chillers are based on vapor compression refrigeration cycles. A natural gas-fired internal-combustion engine is used to power the compressor. With the exception of the gas engine and its ancillary components and controls, gas engine-driven chillers are similar in design and operation to electric chillers. The description of the vapor compression cycle presented in Figure 3-2 is also applicable to gas engine-driven chillers, with substitution of a gas engine for the electric motor. In addition, the basic

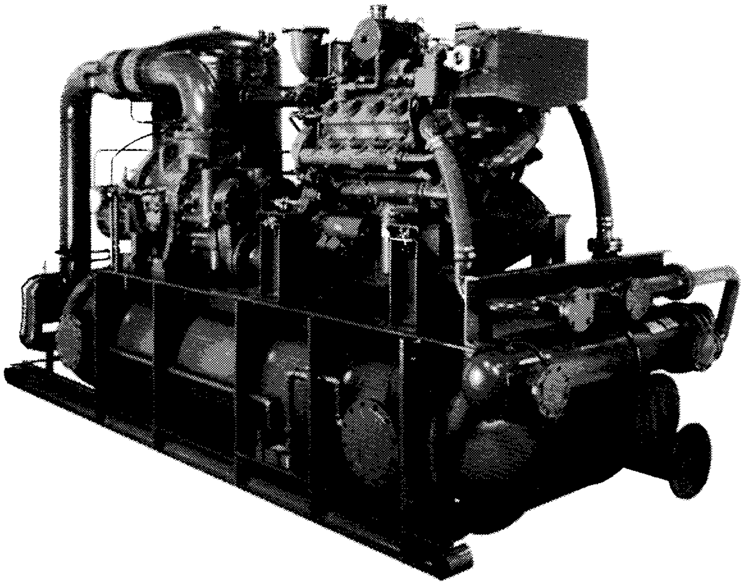


Figure 3-10. Representative Engine-Driven Chiller
Source: Tecogen

components of a gas engine-driven chiller are similar and include refrigerant, compressor, gas engine drive, condenser, pressure reducer, evaporator, and controls. The engine and compressor components are generally mounted on a single skid, although for large chillers the engine components may be mounted on a separate skid. Figure 3-10 shows a representative gas engine-driven chiller.

Gas-engine-driven chillers are available that use centrifugal, screw, and reciprocating compressors. Gas engine-driven chillers are available from a number of manufacturers in sizes ranging from 15 to 4000 tons. Large gas engine-driven chillers are usually custom built. Depending on chiller size and compressor type, air-cooled or water-cooled packages are offered. COP values typically range from 0.8 to 2.4 (AGCC 1995). To increase capacity and provide redundancy and flexibility, gas engine chillers are often packaged with two compressors and two gas engine drives.

Although many of the components of a gas engine-driven chiller are similar to those of an electric chiller, some specific differences must be considered. Gas engines, ancillary components, and controls are discussed in the following sections.

Gas Engines

Gas engine-driven chillers typically use natural-gas-fired, spark-ignited, internal-combustion engines. Both naturally aspirated and turbo-assisted models are in use. Natural-gas-fired engines are available from a variety of manufacturers in sizes from 50 to 2000 hp. Both automotive-derivative gas engines (e.g., Tecodrive) and industrial gas engines (e.g., Caterpillar, Waukesha, and Cummins) are in use.

A primary consideration in the use of gas engine drives is matching the engine and compressor speeds. Smaller gas engines are generally operated at 1800 to 3600 rpm at full speed, while larger gas engines operate at 1000 to 1500 rpm at full speed. Reciprocating compressors and screw compressors with design speeds of 1200 to 1800 rpm can be driven directly from the gas engine. Screw compressors and centrifugal compressors with design speeds of 3,600 to 15,000 rpm are connected to the gas engine drive through a transmission consisting of a series of speed-increasing gears. Centrifugal or electric clutches are sometimes used between the engine and transmission.

Gas engines are available with speed-control packages. Engine speed is typically modulated between full speed (1800 rpm) and idle speed (1000 rpm). A minimum engine speed (idle speed) must be maintained to assure proper lubrication and operation of the coolant system. Chiller output can be modulated through a combination of engine speed control and standard compressor capacity control (e.g., unloaders, slide valves, and inlet vanes).

Compressors

Gas engine-driven chillers are defined by the type of compressor used. Gas engine-driven chillers are available with centrifugal, reciprocating, and screw compressors. Screw and reciprocating compressors predominate. Centrifugal compressors with gas engine drives are available in larger capacities and as custom-engineered systems. Many of the compressor characteristics, such as refrigerant type, capacity control method, and compressor speed, remain the same regardless of whether a gas engine or electric motor is used to drive the chiller.

Ancillary Components

Gas engine-driven chillers are usually larger and heavier than electric chillers of the same capacity. Weight, size, noise, and vibration considerations may limit installation options. Ventilation must be provided to control radiated heat from the engine and exhaust systems. The engine jacket cooling water must be cooled; this is generally accomplished using an air-cooled radiator. In some cases, energy may be recovered from the cooling water and used for other purposes.

Exhaust silencers or mufflers are required and sound-dampening enclosures may be necessary. Depending on local air quality regulations, lean-burn engines or catalytic converters may be required to meet emissions levels for carbon monoxide, nitrogen oxides, and hydrocarbons. When speed-control packages are used, the installation of automatic air-to-fuel ratio control packages may be necessary to maintain low emissions levels over the entire range of loads and engine speeds.

Controls and Options

Gas engine-driven chiller packages are equipped with options and controls similar to those of electric chillers.

The control, safety, and system integration features of gas engine-driven chillers are also similar to those of electric chillers. Again, these include controls for startup, shutdown, interface with the chilled-water loop, and interface with the condenser-water loop. In addition, gas engine-driven packages include engine diagnostic and safety systems, electronic ignition, and speed-control packages. Standard options on gas engine-driven chillers include exhaust and engine jacket water heat-recovery systems, sound attenuation enclosures, automatic lubrication oil makeup systems, emissions control packages, air or evaporatively cooled condensers, remote radiators, and outdoor enclosures.

3.3 ADDITIONAL CHILLER SYSTEM COMPONENTS

As indicated in Figure 3-1, a number of other components are, in addition to the chiller itself, required to complete the chilled-water system. In the following sections, the components of the chilled-water loop (evaporator loop), the condenser cooling-water loop (condenser loop), and the air distribution system are discussed.

3.3.1 CHILLED-WATER LOOP

The chilled-water loop is diagrammed in Figure 3-11. The chilled-water loop circulates chilled-water between the chiller and remotely located air-handling units. Its purpose is to remove heat from the air in the building and transfer it to the refrigerant in the

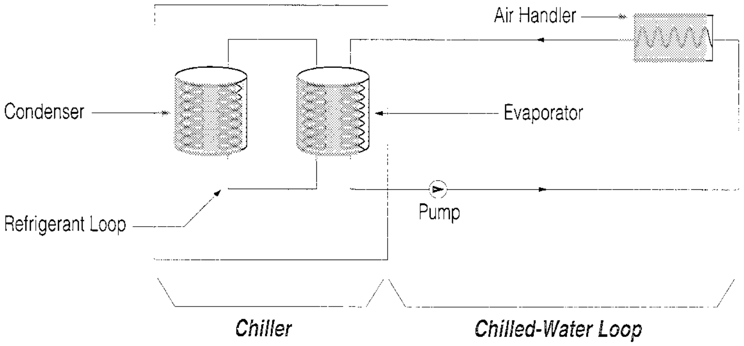


Figure 3-11. *Chilled-Water Loop*

chiller. The chilled-water loop consists of the evaporator, pump, piping, and air-handling units.

Evaporator

Evaporators are refrigerant-to-chilled-water heat exchangers. They are generally included as part of the chiller package.

Pumps

The pumps used to circulate chilled water are almost always centrifugal pumps. The water enters a centrifugal pump near the center of a rotating impeller. The impeller forces the water out from the center to the outside, increasing its pressure. The water is collected and directed to the pump outlet.

Pumps are selected to meet the flow and pressure requirements of the system. The pump is selected to sustain the design flow rates with pressure drops from the chiller, supply and return piping, valves, and air-handling units. In addition, high-static pressure heads must be overcome in multistory buildings. Pumps are generally placed upstream of the chiller.

Depending on chilled-water loop piping layout and control strategy, multiple pumps may be used. Variable speed drives and throttling may be used to increase pumping system efficiency.

Chilled-water pumps and chillers may be configured in a number of ways. Systems with one chiller and one chilled-water pump are generally configured as constant flow systems that use three-way valves and bypass lines at each air-handling unit to maintain a constant total flow. Variable flow systems use multiple compressors and multiple chilled water pumps with staged operation or variable speed drives. Two-way valves are used at the air-handling units. A system bypass line may be required to maintain a minimum flow through the chillers. Pumps and chillers can be manifold and cross connected to provide greater operating flexibility and reliability.

One chilled-water pumping scheme that has become popular uses two piping loops with separate pumps for each loop. The primary loop uses constant speed pumps to circulate water through the chiller. The pumps in the primary loop are high flow rate, low-pressure pumps. The output of the chillers and pumps in the primary loop is matched to the total demand of the secondary loop. The secondary loop uses variable speed pumps to circulate water through the air-handling units and the bulk of the piping system. The pumps in the secondary system are lower flow rate, higher pressure pumps. Each air-handling unit has a two-way modulating valve to adjust chilled-water flow through the unit. The speed of the pumps in the secondary loop is adjusted to precisely match the chilled-water flow with the demand requirements of the air-handling units.

Piping

The chilled-water piping loop supplies all of the air-handling units with chilled water and returns the water to the chiller. Chilled-water loops consist of supply piping and return piping that may be configured in several ways: out-and-back (lowest first cost, highest pumping cost), reverse-return (highest first cost, intermediate pumping cost), or double-loop (intermediate first cost, lowest pumping cost).

Chilled-water loops are often integrated with heating-water loops and may be configured as two-, three-, or four-pipe systems. In two-pipe systems, one pipe is used as the chilled-water supply and the other is used as the chilled-water return. The same piping system can be used in the winter to supply hot water for heating, in which case simultaneous cooling and heating (or reheat) is not possible with the two-pipe system. The three-pipe system uses one pipe for the chilled-water supply, one pipe for the heating-water supply, and the third pipe as a common return. Three-pipe systems have low efficiencies and are not commonly used. Four-pipe systems have separate supply and return loops for chilled and hot water.

The chilled-water piping system consists of piping, check valves, control valves strainers, and fittings. In addition, bypass lines and expansion tanks may be required. Depending on system configuration, pipe diameters at the chiller are large. Progressively smaller diameters are used as the chilled-water system divides and connects to the air-handling units. Large-diameter piping is often made of black steel with threaded or flanged fittings. Small-diameter piping to air-handling units often uses copper tubing and soldered connections.

3.3.2 AIR DISTRIBUTION SYSTEM

Chilled water is circulated in a piping system to remotely located air-handling units located in or near the conditioned space. The chilled water flows through a series of finned coils in the air-handling unit. A fan or blower is used to move air past the coils, transferring heat from the conditioned air to the chilled water. The air-handling unit may provide temperature, humidity, and ventilation control functions. In addition to the chilled-water piping system, a system of ductwork may be necessary to provide adequate air distribution, circulation, and ventilation. The design and extent of the system of ductwork depends on the type of air-handling unit, the layout of the building, and the air distribution and ventilation requirements of the conditioned space.

Chilled-water systems commonly use two types of air-handling units: central air-handling units or room air coils. Each is discussed below.

Central Air-handling Units

A central air-handling unit is a large water-to-air heat exchanger that also provides air distribution functions. The central air-handling unit consists of a finned-coil heat exchanger, a blower, and connection points for air supply and return ductwork. It is connected to the chiller with chilled-water supply and return piping. Central air-handling units are available for applications requiring 1,000 to over 50,000 cfm.

The central air-handling unit is usually remotely located from the chiller in an equipment room near the conditioned space. Ductwork delivers conditioned air to the building space. Air distribution may be through a single duct, double duct (with separate heating and cooling ducts), or a triple-duct system. Temperature is controlled at the air handler by mixing hot and cold air supplies.

With a variable air volume (VAV) system, the temperature in various building zones is controlled with terminal units located in the conditioned space. These terminal units control temperature by varying the air volume.

Room Air Coils

A room air coil consists of small, self-contained water-to-air heat exchanger with an integral fan. No ductwork is connected to the room air coil, although it may be concealed behind wall or ceiling grills. The room air coil may be able to provide both cooling and heating functions. Designs are available that use two-, three-, and four-pipe water distribution systems.

Room air coils are used to provide conditioned air to individual rooms with flow requirements of 100 to 1000 cfm. Room air coils are commonly used in hotels, motels, and apartment buildings. Air temperature is controlled by variation of the chilled-water flow through the room air coil. When not in use, the air room coil fan and chilled-water flow can be turned off (Carrier, 1989). A separate system of ductwork may be required to provide adequate ventilation in buildings with energy-efficient envelopes.

3.3.3 CONDENSER-WATER LOOP

The condenser-water loop is diagrammed in Figure 3-12. The condenser cooling water loop circulates water between the chiller and the cooling tower. Its purpose is to remove heat from the refrigerant. The condenser cooling-water loop consists of the condenser, pump, piping, and cooling tower.

Condenser

The condenser is a heat exchanger used to transfer heat from the refrigerant to the condenser cooling water. Air-cooled, water-cooled, and evaporatively cooled condensers are used on chillers. The condenser may be located on the chiller package (typical of water-cooled and packaged air-cooled chillers) or remotely located (typical of air-cooled chillers and evaporatively cooled chillers). When the condenser is remotely located, refrigerant is piped from the compressor outlet to the condenser.

Pump

Centrifugal pumps are used for circulating condenser cooling water between the chiller and the cooling tower. Condenser cooling-water pumps, condensers, and cooling towers may be arranged in a one-to-one configuration or alternatively manifold and cross connected to yield greater operating flexibility and reliability. Staged operation of multiple condenser pumps may be used. Variable speed drives on condenser-water pumps are rarely used. Some systems are arranged with all chiller condensers connected in series and one pump operating at a constant flow rate. Although this allows staged operation of the chillers, a high pumping cost is incurred.

Piping

A single loop consisting of supply piping and return piping is used to connect the chiller condenser and cooling tower. Generally, black steel piping is used. Depending on cooling tower type, water

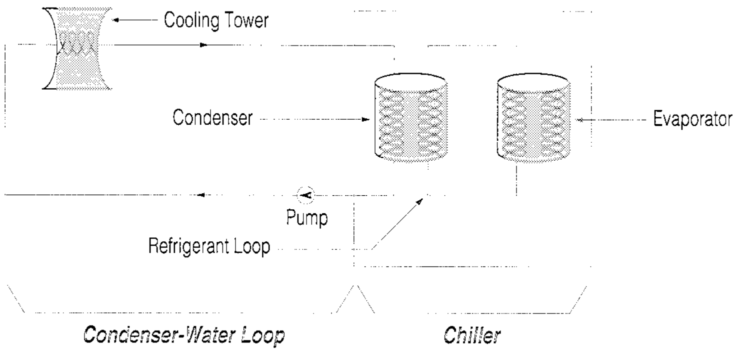


Figure 3-12. Condenser-Water Loop

must be continually added to the condenser cooling water loop to make up evaporative and blowdown losses. Since the condenser cooling water loop is an open system, chemicals must be constantly added to the water to prevent microbiological growth and corrosion.

Cooling Towers and Fluid Coolers

Cooling towers (and fluid coolers) reject heat from the chiller. This heat includes the heat removed from the chilled-water loop, as well as heat added during the refrigeration cycle. In addition, heat from a hermetic or semi-hermetic electric motor or gas engine drive can be rejected through the cooling tower. The cooling tower must be sized to reject the heat from all of these sources.

A rule of thumb often used for sizing cooling towers for electric chillers assumes a chiller efficiency of 0.88 kW/ton and 15,000 Btu/h of heat rejection for each ton of cooling capacity. For more-efficient chillers, this sizing guideline generally results in an oversized cooling tower. For less-efficient chillers, a larger cooling tower may be required. It should be noted that chillers with lower COP values (lower efficiencies) reject more heat per ton of cooling, and thus require proportionately larger cooling towers. Table 3-4 presents heat-rejec-

Table 3-4. Relative Cooling Tower Sizes

Chiller Type (ton)	*Efficiency (kW/ton)*	*COP*	*Heat-Rejection Rate (Btu/ h/ton)*	*Relative Cooling Tower Size (CT ton/Chiller)*
Electric Chillers				
centrifugal	0.60	5.86	14,000	0.93
centrifugal	0.71	4.95	14,400	0.96
centrifugal	0.88	4.00	15,000	1.00
screw	0.68	5.17	14,300	0.95
reciprocating	0.82	4.29	14,800	0.99
Gas Engine-Driven Chillers				
centrifugal	1.95	1.80	16,000	1.07
screw	2.13	1.65	16,400	1.09
reciprocating	2.51	1.40	17,100	1.14
Absorption Chillers				
DF, 2-effect	3.52	1.00	22,200	1.48
IF, 1-effect	5.02	0.70	26,600	1.77

Notes:

1. For engine-driven systems, 60% of the input energy is assumed to be rejected by the cooling tower.
2. For absorption systems, 85% of the input energy is assumed to be rejected by the cooling tower.

Source: AGCC (1995a) and EPRI (1993c)

tion data and relative cooling tower size for several types of electric and gas chillers.

When a cooling tower is used, the condenser water is sprayed or dripped from the top of the tower. A fill material may be used to increase the evaporation rate. Air moves past the fill material and a portion of the water is evaporated. The evaporation of the water provides latent cooling. In addition, some sensible cooling by the moving air also occurs, depending on ambient conditions. Evaporated water is continually replaced. The water must be treated to prevent corrosion, fouling, and microbiological growth.

Cooling towers usually use mechanical draft (fan) designs. Mechanical draft cooling towers with single fans are available as single units up to about 800 tons. Larger-capacity cooling towers are built using smaller, individual cooling towers, each with an individual fan.

Mechanical-draft designs may be forced draft, where air is pushed through the fill material, or induced draft, where air is pulled through the fill material. Forced-draft designs generally use axial or centrifugal fans located below the fill. Forced-draft designs are commonly used for cooling towers with capacities of 100 to 400 tons. Induced draft designs use propeller fans located above the fill. Induced-draft designs are commonly used on cooling towers with capacities of 400 to 800 tons. The preferred design configuration is chosen after considering capacity, space limitations, ambient conditions, load pattern, and cost.

One alternative to open-loop cooling towers for heat rejection is a closed-loop fluid cooler. In a closed-loop fluid cooler, the condenser water (or other fluid) circulates through a closed loop and passes through coils in the fluid cooler. Water is sprayed from the top of the fluid cooler onto the coils and evaporates, removing heat from the condenser water. A centrifugal fan is used to blow air from the bottom of the fluid cooler past the cooling coils. Water sprayed on the coils provides latent cooling, and air blown past the coils provides some sensible cooling. Depending on cooling load requirements, the fluid cooler can be operated without the water spray. Glycol solutions may be used in the condenser loop instead of water. Even though the condenser-water loop is closed, treatment must be provided to prevent corrosion and fouling.

3.4 THERMAL ENERGY STORAGE SYSTEMS

Gas and electric chilled-water systems are typically sized and controlled to operate on demand to building cooling loads. Operation in this manner generally results in the majority of operations during daytime hours. In the case of electric chillers, daytime operation coincides with peak electric energy rates, and may also produce high electric demand charges as chillers respond to high cooling demands (e.g., cooling on hot summer days).

Thermal Energy Storage (TES) systems can be implemented with conventional electric chilled-water systems to help reduce energy costs (EPRI, 1990b). TES systems shift energy consumption to off-peak periods, and thus help minimize peak energy use and energy demands. A typical TES system is diagrammed in Figure 3-13. It consists of an electric chiller and a thermal mass, in this case a tank of water. The chiller is used to cool the thermal mass during off-peak periods (e.g., at night). Depending on design, daytime cooling loads can be met using the thermal mass only (full storage), or a combination of the chiller and the thermal mass (partial storage).

Three types of TES systems are in common use: water, ice, and eutectic salts. Each is discussed below.

3.4.1 WATER TES

Water TES systems utilize one or more tanks of chilled water as the thermal storage mass. The water is chilled to temperatures of 40–46°F, and is used to produce supply air as cool as 55°F.

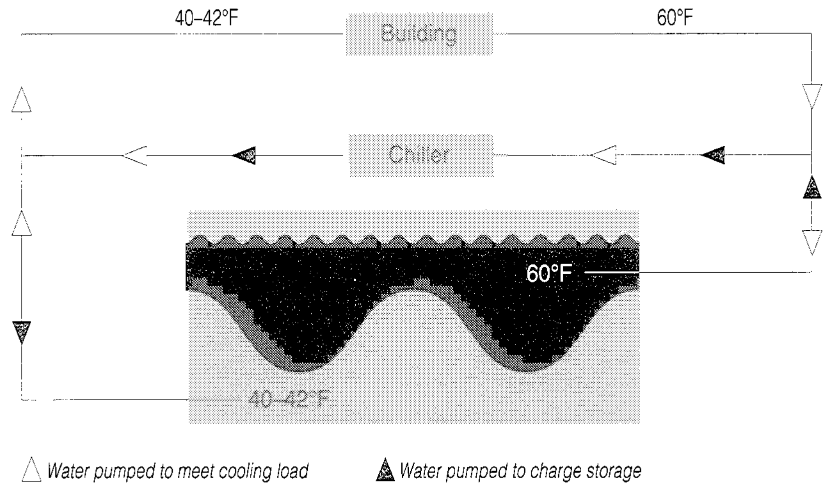


Figure 3-13. Typical Thermal Energy Storage System
Source: EPRI (1990b)

Water is able to provide approximately one ton-hour of cooling per 11.4 ft^3 of storage. Water TES systems can achieve system efficiencies of 0.7–0.9 kW/ton, which is competitive with many conventional electric chilled-water systems. Over 150 water TES systems were in operation at the end of 1990 (EPRI, 1992c).

3.4.2 ICE TES

Ice TES systems use an ice-water mixture for the thermal mass. Ice TES systems produce an ice slurry in the range of 32–35°F, which can be used to produce supply air in the range of 43–47°F.

Due to the latent heat of fusion, ice TES systems have relatively high storage capacities compared to water systems. An ice TES system can provide approximately one ton-hour of cooling per 1.5 ft^3 of storage, which is an order of magnitude higher than water TES systems. Due to the higher capacity, ice TES systems can have smaller duct work, smaller fans, and fewer air-handling units compared to water TES designs. Ice TES systems typically have system efficiencies of 0.9–1.2 kW/ton (EPRI 1989). Over 1000 ice TES systems were in operation at the end of 1990 (EPRI 1992d).

3.4.3 EUTECTIC SALT TES

Like ice TES systems, eutectic salt TES systems provide cooling by taking advantage of the latent heat of fusion. However, unlike ice, eutectic salts freeze at temperatures above 32°F (e.g., 41°F or 47°F). The eutectic salts are usually contained in individual plastic containers packed in concrete storage tanks. The tanks are filled with chilled water. When building cooling is required, chilled water is circulated through the tanks to the air-handling units. When the storage is charged, water from the chiller is circulated through the tanks to cool the containers.

Eutectic salt TES systems provide approximately one ton of cooling per 2.5 ft^3 of storage. TES systems based on 47°F eutectic salts can produce supply air as cold as 55°F, and those using 41°F salts can produce supply air in the range of 49–51°F. Over 80 eutectic salt TES systems were in operation at the end of 1990 (EPRI 1992e).

4

Vendor & Product Information

Figure 4-1 shows the capacities commonly available for gas and electric chillers in the range of 100 to 2000 tons. It should be noted that for electric- and engine-driven chillers, equipment above 2000 tons is available, often as custom-engineered products.

In the United States electric chillers are manufactured by five companies: Carrier, McQuay, Trane, York, and Dunham-Bush. Each has standard product lines in centrifugal, screw, reciprocating and/or scroll chillers covering a range of sizes. In addition, custom chillers are offered for applications with capacity requirements above approximately 3000 tons. Table 4-1 presents data for electric chiller products currently available from U.S. manufacturers.

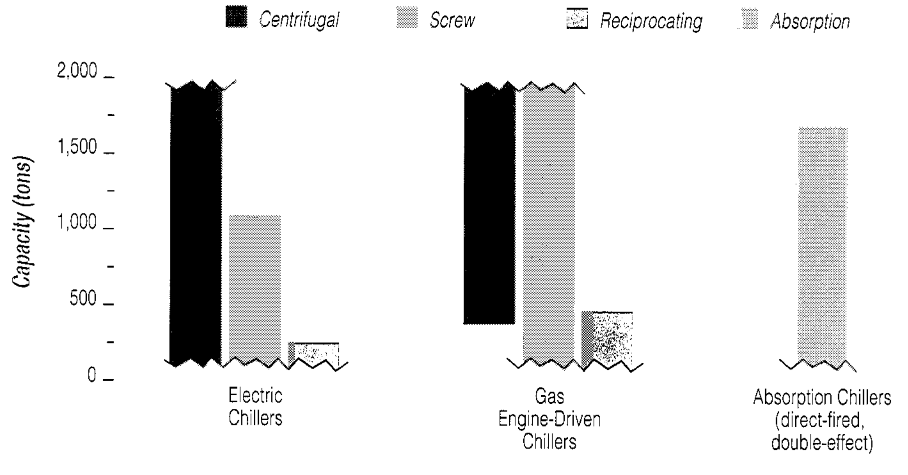


Figure 4-1. Chiller Capacities
Source: E-Source (1995), and Manufacturers' Literature

Direct- and indirect-fired absorption chillers are manufactured by American Yazaki, Carrier, McQuay, Trane, and York. Table 4-2 presents data for double-effect, direct-fired absorption chiller products currently manufactured by U.S. companies.

Depending on the vendor, gas-engine-driven chillers are available with centrifugal, screw, or reciprocating compressors as standard products in a range of sizes. In addition, custom-engineered gas engine-driven chillers are offered by several vendors to meet the requirements of high-capacity applications. Gas engine-driven chillers are offered by York, GASAIR, Alturdyne, Hercules Energy Products, Sierra Power, and

Table 4-1 Electric Chiller Products

Mfg.	*Capacity (tons)*	*Compressor Type*	*Efficiency (kW/ton)*	*Model Designation*	*Refrigerant Options*
Carrier	200-600	Centrifugal	0.60-0.68	19XL	HFC-134a
	300-580	Centrifugal	0.55-0.59	19XT	HFC-134a
	500-1000	Centrifugal	0.60-0.64	19EF	HFC-134a
	800-2300	Centrifugal	0.58-0.63	19EX	HFC-134a
	800-2300	Centrifugal	0.54-0.59	17EX	HFC-134a
	160-350	Screw	0.61-0.66	23XL	HCFC-22
	15-250	Reciprocating	0.70-0.75	30HR	HCFC-22
Dunham-Bush	50-1000	Screw	0.67-0.74	WCFX	HCFC-22
	2-130	Reciprocating	0.87-0.97	WCDR	HCFC-22
McQuay	170-550	Centrifugal	0.60-0.75	PF4	HFC-134a
	170-1200	Centrifugal	0.58-0.79	PE4	HFC-134a
	110-250	Screw	0.76-0.77	155A	HCFC-22, HFC-134a
	20-240	Reciprocating	0.85-0.93	WHR	HCFC-22, HFC-134a
Trane	165-1350	Centrifugal	0.49-0.81	CVHE	HCFC-123
	190-1400	Centrifugal	0.49-0.68	CVHF	HCFC-123
	130-450	Screw	0.70-0.75	RTHA	HCFC-22
York	250-800	Centrifugal	0.550.69	YT	HCFC-123
	600-1600	Centrifugal	0.58-0.68	YK	HCFC-22, HFC-134a
	125-675	Screw	0.67-0.69	YS	HCFC-22
	3-240	Reciprocating	0.85-0.90	YCW	HCFC-22

Note: Efficiency measured at full load

Source: E-Source (1995) and Manufacturers' Literature

Tecogen. These companies generally purchase compressors and gas engines from various manufacturers and assemble them into gas engine-driven chiller packages. Table 4-3 presents data for gas engine-driven chiller products currently offered by U.S. manufacturers. Additional vendor information is presented in Appendix B.

Table 4-2. Absorption Chiller Products (Direct-Fired, Double-Effect)

Manufacturer	Capacity (tons)	Chiller Type	Efficiency (COP)	Model Designation	Refrigerant Pair
American Yazaki	30-100	Double-Effect	0.95-1.00	CH-L	Water & Lithium Bromide
Carrier	135-1000	Double-Effect	0.97	16 DF	Water & Lithium Bromide
McQuay	100-1500	Double-Effect	1.00	DC-11U	Water & Lithium Bromide
Trane	100-1100	Double-Effect	0.97-1.04	ABDL	Water & Lithium Bromide
York	170-1000	Double-Effect	0.92-1.00	ParaFlow	Water & Lithium Bromide

Source: AGCC (1995) and Manufacturers' Literature

Table 4-3. Gas Engine-Driven Chiller Products

Manufacturer	Capacity (tons)	Compressor Type	Efficiency (COP)	Model Designation	Refrigerant Options
Alturdyne	30-300	Reciprocating	1.32-1.52	WW	HCFC-22, HFC-134a, ammonia
	200-1040	Screw	1.32-1.52	WW	HCFC-22, HFC-134a, ammonia
GASAIR	75-470	Reciprocating	1.44	RXL	HCFC-22, HFC-134a, ammonia
	100-2000	Screw	1.64	SXL	HCFC-22, HFC-134a, ammonia
	500-2000	Centrifugal	1.83	CXL	HCFC-22, HFC-134a
Hercules	42-150	Reciprocating	——	——	HCFC-22
Sierra Power	50-300	Reciprocating	1.0-2.0	——	HCFC-22, HFC-134a, ammonia
	50-4000	Screw	1.0-2.0	——	HCFC-22, HFC-134a, ammonia
Tecogen	125-780	Screw	1.2-1.6	CH	HCFC-22, HFC-134a
York	400-2100	Centrifugal	1.8-2.4	CodePak	HFC-134a

Source: AGCC (1995) and Manufacturers' Literature

5

Chiller Selection

Choosing the right chiller for a commercial building can involve many aspects. Table 5-1 summarizes several key selection factors for both electric and gas chilled-water systems.

5.1 BUILDING TYPE

Although the chiller capacity is generally fixed by building size and load profile, specific requirements of each building type may make certain chiller types more suitable than others. Table 5-2 lists a number of common building types.

Table 5-1. Comparison of Chilled-Water System Selection Factors

Category	*Selection Factor*	*Electric Chillers*		*Gas Chillers*	
		Centrifugal	*Screw*	*Engine-Driven, Screw*	*Absorption, Direct-Fired, Double-Effect*
Building Type	Can meet the cooling loads of most buildings	Yes	Yes	Yes	Yes
Performance	Efficiency	High	High	Moderate	Low
Refrigerant	CFC and HCFC phase-out may affect operation	Yes	Yes	Yes	No
Physical Characteristics	Size	Average	Average	Large	Large
	Weight	Average	Average	Avg.-High	Avg.-High
	Noise	Average	Average	Avg.-High	Low
	Appearance	Good	Good	Good	Good
Cost	Equipment (chiller)	Average	Average	High	High
	Installation	Average	Average	Average	Average
	Maintenance	Low	Low	High	Low
	Energy	Average	Average	Low	Low
Air Quality	NO_x, CO, and unburned hydrocarbon emissions	Not an issue at point of use	Not an issue at point of use	May require 3-way catalyst	May require low-NO_X burner
Ancillary Items	Cooling tower size	Average	Average	Average	Large
	Water usage	Average	Average	Average	High

Table 5-2.
Common Building Types

Clinics

Education Facilities

Food Service

Hospitals

Hotels

Motels

Office Buildings

Research Facilities

Retail Stores

Shopping Centers

Supermarkets

Universities

Worship Facilities

Source: EPRI (1993d)

The specific requirements of each building influence the type of chilled-water system best suited for the application. Several design considerations for selected buildings are given in Table 5-3. As indicated, hospitals generally require space conditioning 24 hours a day and a high degree of reliability, as well as a backup system. Office buildings have high occupant densities during the day but have little use at night and on weekends. They also often require simultaneous heating and cooling to separate zones. Retail stores generally require low installed cost and the ability to meet highly varying loads (due to varying customer traffic). Educational facilities require a great deal of flexibility to serve zones (e.g., offices, gyms, and cafeterias) that have different space-conditioning requirements. They also require little or no cooling during summer months when classes are not in session.

Table 5-3. Design Considerations for Selected Buildings

	Office	*Hospital*	*Education*	*Retail*
24-hour operation		■		
High reliability		■		■
Backup		■		■
Simultaneous heating & cooling	■	■		
Highly varying loads		■		■
Zone flexibility		■	■	
Seasonal occupancy			■	
Low cost	■		■	■

Source: EPRI (1993d)

Table 5-4. Common Chiller Performance Ratings

Rating	*Use*
Full-Load Performance	Calculating Chiller Operating Cost at Full Load
Part-Load Performance	Calculating Chiller Operating Cost at Part Load
System Performance	Calculating System Operating Cost at Full or Part Load
Efficiency Standards	Sets Performance Requirements

5.2 PERFORMANCE

Chiller performance can be expressed in several ways and is commonly used to calculate and compare operating costs for various types of chillers. Table 5-4 lists key chiller performance ratings. Electric chiller efficiency is generally expressed as

$$\text{Efficiency (kW/ton)} = \frac{\text{kW of power input}}{\text{tons of cooling output}}$$

Efficiency expressed in units of kW/ton is a measure of the electric power input required to produce one ton of cooling. Lower values indicate higher efficiencies.

Electric chiller efficiency can also be expressed as a Coefficient of Performance (COP), which is the ratio of the cooling output (expressed in Btu/h) to the power input (expressed in Btu/h). Higher COP values represent higher efficiencies. COP is related to efficiency by the following formula:

$$\text{COP} = \frac{3.516}{E}$$

E = efficiency measured in units of kW/ton

COP is used as the efficiency measure for gas chillers. It should be noted that the efficiency of a gas chiller should be based on the higher heating value (HHV) and not the lower heating value (LHV) of the fuel. Gas chiller COP is calculated using the following formula:

$$\text{COP} = \frac{12{,}000}{Q}$$

Q = natural gas input measured in units of Btu/h/ton

5.2.1 FULL LOAD PERFORMANCE

Chiller performance data is provided by manufacturers at full load conditions. For electric chillers, this data is expressed in terms of efficiency measured in kW/ton, and for gas chillers this data is expressed as efficiency measured in terms of COP. Chillers are rated according to ARI Standard 550, which specifies common rating conditions at full load. Measurements are conducted at a chilled-water exit temperature of 44°F, a condenser-water inlet temperature of 85°F, and an outdoor wet bulb temperature of 78°F.

Table 5-5 compares typical full-load efficiencies and COP values for electric and gas chillers.

Table 5-5. Comparison of Full-Load Efficiencies

	Full-Load Efficiency (kW/ton)	Full-Load COP
Electric Centrifugal Chillers (std. eff.)	0.65 - 0.80	5.4 - 4.4
Electric Centrifugal Chillers (high eff.)	0.49 - 0.65	7.2 - 5.4
Gas Engine-Driven Screw Chillers	——	1.8 - 1.2
Direct-Fired, Double-Effect, Absorption	——	1.1 - 0.9

Source: AGCC (1995a) and EPRI (1993c)

Full-load efficiencies or COP values can be used to calculate annual energy consumption (electricity and natural gas) and operating costs if the load profile is known or can be estimated. The load profile shows how many hours the chiller operates at specific increments of load, usually increments of 10% of full load.

One method converts the load profile to equivalent full-load hours (EFLH). The EFLH are used in conjunction with the full-load efficiency or full-load COP to estimate annual energy consumption. An analysis based on EFLH can be used when only full-load efficiency data are available, or in cases where the chiller efficiency remains constant regardless of load. Table 5-6 shows a typical load profile converted to EFLH.

5.2.2 PART-LOAD PERFORMANCE

Electric Chillers

Electric chiller performance changes with load. Figure 5-1 shows this dependence for several chiller types. As indicated, electric chiller efficiencies tend to be highest (low kW/ton values) above approximately 30% of full load.

Part-load performance may be expressed as the integrated part load value (IPLV) evaluated at ARI standard

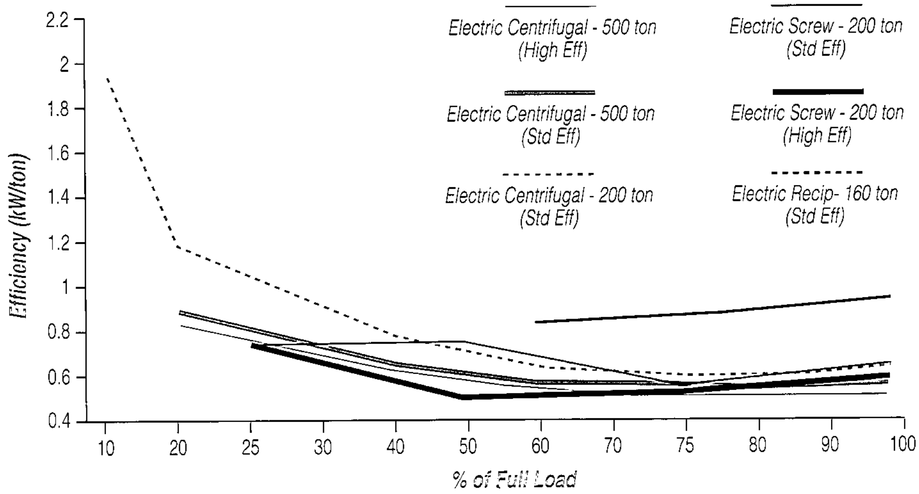


Figure 5-1. *Representative Part-Load Efficiencies for Electric Chillers*
Source: Manufacturers' Data

Table 5-6. Calculation of EFLH

(1) Load (% of Full Load)	(2) % of Operating Hours at Load	(3) Operating Hours at Load	(4) EFLH
100	2	46	46
90	3	69	62
80	5	115	92
70	15	345	242
60	30	690	414
50	20	460	230
40	15	345	138
30	5	115	34
20	3	69	14
10	2	46	5
TOTALS	100%	2300	1277

(1) = Chiller Load (in 10% increments)
(2) = Load Profile (in % of time at each load condition)
(3) = 2300 Operating Hours x (2)
(4) = (1) x (3)

EFLH = Equivalent Full-Load Hours
2300 Operating Hours Assumed

Source: AGCC (1995a) and EPRI (1993c)

conditions. The ARI conditions are 44°F chilled-water exit temperature, 85°F condenser-water inlet temperature (full load), 60°F condenser water inlet temperature (no load), and 78°F outdoor wet bulb temperature. The following formula is used to calculate IPLV (ARI 1992a):

It should be noted that the weighting factors are used to provide a basis of comparison, and do not reflect actual operating conditions. Manufacturers generally provide IPLV data, as well as full-load data, for their chiller products. IPLVs for large centrifugal and screw chillers are typically 85–91% of full-load efficiencies (EPRI 1993c).

$$\textbf{IPLV (kW/ton)} = \frac{2}{\frac{0.17}{A} \quad \frac{0.39}{B} \quad \frac{0.33}{C} \quad \frac{0.11}{D}}$$

Where: A = part-load efficiency at 100% load
B = part-load efficiency at 75% load
C = part-load efficiency at 50% load
D = part-load efficiency at 25% load

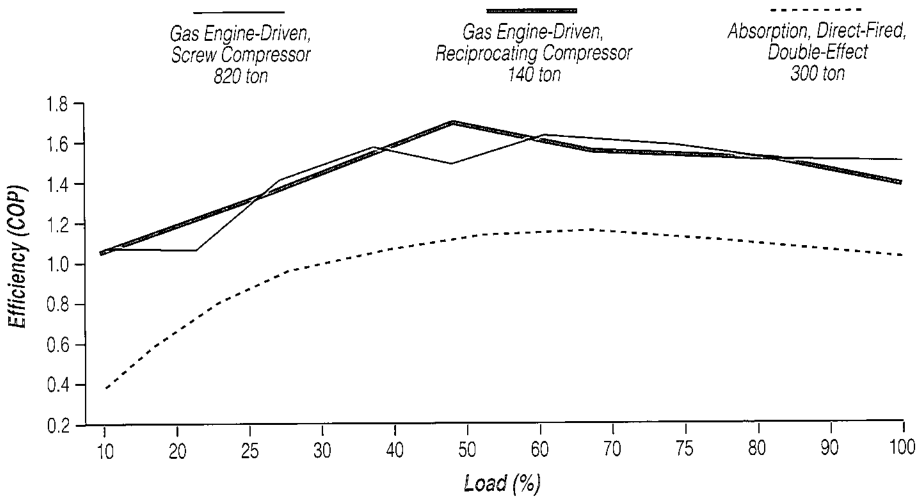


Figure 5-2. Representative Part-Load Efficiencies for Gas Engine Chillers
Source: Manufacturer's Data

Table 5-7. Ancillary Electrical Requirements

Chiller Type	*Accessories (kW/ton)*	*Cooling Tower Fan (kW/ton)*	*Condenser Water Pump (kW/ton)*	*Total (kW/ton)*
Electric Chillers				
Centrifugal (Standard Effic.)	0.00	0.02-0.10	0.04-0.06	0.06-0.16
Centrifugal (High Effic.)	0.00	0.02-0.10	0.04-0.06	0.06-0.16
Gas Engine-Driven Chillers				
Screw	0.02-0.04	0.02-0.12	0.05-0.07	0.09-0.23
Absorption Chillers				
Direct Fired, Double-Effect	0.02-0.07	0.03-0.15	0.06-0.09	0.11-0.31

Note: Table does not include chilled water pumps. Their energy requirements are similar for all systems, on the order of 0.04 kW/ton.
Source: AGCC (1994), AGCC (1995a), EPRI (1993c), and E-Source (1995)

Gas Chillers

The performance of absorption chillers and gas engine-driven chillers changes with load similar to that of electric chillers. The part-load performance of a gas engine-driven chiller reflects changes in both the engine and compressor performance with changing load. Although performance of the compressor improves with decreasing load, performance of the engine declines with decreasing load. Even though the load on the engine is less, the engine consumes more fuel per horsepower at lower loads than at higher loads. Figure 5-2 shows performance curves for two gas engine chillers and one absorption chiller.

An analog to IPLV (based on COP) can also be calculated for gas engine-driven and absorption chillers, using the following formula (ARI 1992a):

$$\mathrm{IPLV} = 0.17A + 0.39B + 0.33C + 0.11D$$

where: A=COP at 100% load
B=COP at 75% load
C=COP at 50% load
D=COP at 25% load

5.2.3 SYSTEM PERFORMANCE

Chiller efficiency or COP values can only be used to estimate the energy consumption of the chiller itself. To obtain an accurate measure of the total system operating costs, the energy consumption of ancillary equipment must also be considered. Ancillary components for complete chilled water systems include

- Chilled-water pump
- Condenser-water pump
- Cooling tower fans
- Solution pump (absorption only)
- Engine cooling equipment and controls (engine systems only)

The chilled-water pump is the same size for gas and electric chillers of the same capacity and, therefore, consumes the same amount of energy (typical values are near 0.04 kW/ton). A comparison of the remaining ancillary loads for gas and electric systems is shown in Table 5-7 (note that the accessories column covers energy-consuming equipment unique to gas-fired chilled-water systems).

Table 5-8 shows the effect on chilled-water system efficiency when ancillary equipment requirements are included (the chilled-water pump is not included in this analysis). Total average electrical requirements are used for the ancillary loads. This table shows that, as expected, system efficiency is lower than chiller efficiency when ancillary requirements are included.

5.2.4 EFFICIENCY STANDARDS

ASHRAE standards are a voluntary set of guidelines created by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. The standards are guidelines, not regulations, and only become regulations when adopted by a governing body. For chillers, the federal government recently adopted the ASHRAE guidelines for minimum efficiency as part of the U.S. Energy Policy Act of 1992 (EPAct).

The EPAct requires each state to establish a commercial building standard that meets or exceeds ASHRAE Standard 90.1 (see Table 5-9 for electric chiller ASHRAE standards). Therefore, the ASHRAE standards are now the minimum efficiency requirements for chillers. Whenever the ASHRAE standards are updated, the EPAct requires that the new standard must automatically be met.

Implementation of the federal EPAct requirements is made at the state level, through the state's building or energy codes. For water chillers, ASHRAE Standard 90.1 may be adopted in its entirety or a modified, more stringent version, may be used. For instance, state codes may give specific efficiency

Table 5-8. Typical Chilled-Water System Energy Consumption (based on chillers near 500 tons)

Chiller Type	Chiller [1] (kW/ton)	Chiller [1] (COP)	Ancillary Loads [2] (kW/ton)	System [3] (kW/ton)	System [3] (COP)
Electric					
Centrifugal (Standard Eff.)	0.68	5.17	0.13	0.81	4.34
Centrifugal (High Eff.)	0.57	6.17	0.13	0.70	5.02
Gas Engine-Driven					
Screw	—	1.70	0.15	2.22	1.58
Gas Absorption					
Direct-Fired, Double-Effect	—	1.10	0.22	3.42	1.03

[1] Chiller values include gas and electricity consumption
[2] Ancillary loads are all electric
[3] Chilled-water systems include chiller plus ancillary loads
Source: EPRI (1995g)

requirements for water chillers based on compressor type, chiller capacity, or condenser cooling method.

Efficiency requirements are enforced by state building inspectors or energy auditors at the time of construction or installation. State building codes recognize that chiller performance is not measured or calculated for each individual chiller system. However, where equipment efficiency levels are specified in the state building code, documentation must show approved data to satisfy these requirements. The necessary information can be furnished by the equipment supplier, or provided by a nationally recognized certification program, such as the program offered by Air-Conditioning

Table 5-9. ASHRAE/IES Efficiency Requirements 1,2,3

Size (tons) (kW/ton)	Maximum Full-Load Efficiency (kW/ton)	Maximum IPLV (COP)	Minimum Full-Load Efficiency (COP)	Minimum IPLV
<150	0.93	0.90	3.9	3.9
150 to 300	0.83	0.78	4.5	4.5
>300	0.68	0.66	5.2	5.3

Notes:

1. ASHRAE/IES Standard 90.1i-1993.
2. Applies to water-cooled electric chillers.
3. Efficiency measured according to ARI-550-86.

and Refrigeration Institute (ARI). The intention of the certification program is to help ensure that industry products perform as rated. On a semiannual basis, ARI publishes the "Directory of Certified Applied Air-Conditioning Products," which includes efficiency ratings for water chillers and other HVAC components (WSEO 1992, ARI 1995).

5.3 REFRIGERANT

Environmental regulations have led to production bans and phase-out schedules for CFC and HCFC refrigerants. Fortunately, a number of alternative refrigerants are now available, and chiller manufacturers have responded by developing new chiller designs for use with the new refrigerants.

5.3.1 REGULATORY ISSUES

Chlorinated-fluorocarbons (CFCs) and hydrochlorinated-fluorocarbons (HCFCs), which are widely used as refrigerants in electric chillers, have been found to promote chemical reactions that deplete ozone in the earth's upper atmosphere. In addition, they may contribute to global warming by trapping radiated and reflected heat. In response to these concerns, the international community established a protocol addressing the phaseout of CFCs and HCFCs. The initial agreement, known as the Montreal Protocol, and subsequent amendments have established a phaseout schedule. Table 5-10 shows how the United States is conforming to the international phaseout for CFC and HCFC refrigerants commonly used in chillers.

5.3.2 REPLACEMENTS

In view of the phaseout schedules imposed by these protocols, manufacturers of refrigerants have developed replacements suitable for use in most chiller applications. A number of HCFCs, HFCs (hydrofluorocarbons), and blends have been developed to immediately replace CFCs and eventually HCFCs. Notably, HCFC-123 has been developed as a substitute for CFC-11, and HFC-134a has been developed as a substitute for CFC-12. The replacements generally have lower Ozone Depletion Potential (ODP) and lower Global Warming Potential (GWP) values.

5.3.3 EFFECT ON CHILLER SELECTION

Three selection strategies that consider refrigerant type are replacement, retrofit, and use of reclaimed refrigerants.

Table 5-10. Refrigerant Phaseout Schedule

Refrigerant	*Year*	*Restrictions*
CFC-11	1996	Ban on production
CFC-12	1996	Ban on production
HCFC-22	2010	Production freeze and ban on use in new equipment
	2020	Ban on production
HCFC-123	2015	Production freeze
	2020	Ban on use in new equipment
	2030	Ban on production
HFC-134a	—	No restrictions

Source: EPRI (1995e)

New Purchases and Replacements

Electric chillers purchased for new installations or for replacement of older equipment will most likely use HCFC or HFC refrigerants. These new refrigerants are in full-scale production, and chiller manufacturers have designed chillers optimized for use with these alternative refrigerants. Production bans for HCFC-22 and HCFC-123 do not take effect until 2020 and 2030, respectively, which is past the expected service life of most chillers. Therefore, the eventual production phaseout of HCFCs should not be an overriding factor in selecting a new or replacement electric chiller today.

If a chiller that uses a CFC refrigerant is more than 20 years old, consideration should be given to replacing it with a new chiller that uses an alternative refrigerant. This choice is often cost-effective because significant improvements in chiller efficiency have been made over the past 20 years, and substantial energy savings may be possible.

Retrofits

It may be cost-effective to retrofit a chiller that is less than 20 years old to accept a new and non-CFC refrigerant. This may require replacement of compressor seals, lubricating oil, and refrigerant flow and pressure control devices. The chiller service company or chiller manufacturer should be consulted to determine if a retrofit is practical and what components must be changed. It should be noted that retrofitting may result in a loss in chiller capacity (up to 10%) and a possibly a loss in chiller efficiency (up to 10%).

Low-pressure centrifugal chillers originally designed to use CFC-11 can be retrofit to use HCFC-123. This usually requires replacement of seals, O-rings, and gaskets. Motors must be rewound or replaced on hermetic or semihermetic designs, as HCFC-123 is not compatible with conventional motor winding insulation. In addition, a modified compressor impeller may be needed to minimize losses in efficiency and performance.

Medium-pressure centrifugal chillers originally designed to use CFC-12 can be retrofit to use HFC-134a. The retrofit usually requires replacement of the compressor lubricating oil with an ester-based oil, and installation of a different gear set to minimize losses in capacity and efficiency.

High-pressure centrifugal chillers, screw chillers, and reciprocating chillers that use HCFC-22 cannot be retrofit, as no satisfactory alternative refrigerant is presently available (EPRI 1993f).

Use of Reclaimed CFCs

In many cases, existing chillers with CFCs continue to operate reliably and economically although they have been in service for more than 20 years. Even though CFC production has been phased out, these chillers can still be operated. Supplies of CFCs will continue to be available in the near term as older compressors are retired and their CFC refrigerants are reclaimed. Reclaimed refrigerants are reprocessed to meet new product specifications as set forth in ARI Standard 700. With proper maintenance and improvements in leak detection and repair methods, these chillers can provide additional years of service before retrofit or replacement is required.

5.3.4 COST AND AVAILABILITY

Even with the absence of CFC production, a supply of reclaimed CFC refrigerants will continue to be available. However, the price of CFCs is expected to continue to rise due to decreases in the overall supply and the imposition of a federal excise tax on these refrigerants. The tax is based on the ODP of the CFC. For CFC-11 and CFC-12 with ODP values of 1.0, the excise tax will be $5.80/lb in 1996 and is expected to increase thereafter. It has been predicted that after 1995, the cost of recycled CFCs, including the federal excise tax, will be higher than the cost of the alternative refrigerants.

A number of manufacturers are now producing alternative refrigerants. Table 5-11 presents a list of refrigerant manufacturers that produce HFC-134a (CFC-12 alternative) and HCFC-123 (CFC-11 alternative). Initially, the alternative refrigerants were in scarce supply and

Table 5-11. Manufacturers of Selected CFC Replacement Refrigerants

Manufacturer	*Trade Name*	Refrigerant *HFC-134a*	 *HCFC-123*
Allied-Signal	Genetron	■	■
DuPont	Suva	■	■
Elf Atochem	Forane	■	
ICI Americas	KLEA	■	
LaRoche	—	■	

Source: EPRI (1995f) and EUN (1995)

much more expensive than CFC refrigerants. However, as production has increased, the price of the alternative refrigerants has come into line with CFCs, which are heavily taxed on initial purchase and subsequent storage (EPRI 1995e).

5.4 PHYSICAL CHARACTERISTICS

Physical characteristics must be considered when selecting a chiller both for new installations and retrofit applications. The physical characteristics of the chiller, (i.e., size, weight, noise, and appearance) are important factors that may limit the suitability of particular chiller types at specific sites. In addition, installation costs are highly dependent on the physical characteristics of the chiller.

Size

Equipment room space is usually limited. In a retrofit situation, the equipment room has already been constructed and changes to its size may be difficult or impossible to make. In addition, doors and corridors leading to the equipment room may be limiting factors.

Electric chillers are generally smaller than engine-driven and absorption machines, and are thus generally easier to site in tight mechanical rooms. In addition, electric chillers can often be partially disassembled for installation purposes, and then reassembled in the equipment room. This type of disassembly is often not possible with gas absorption machines. However, if an absorption chiller also provides heating, the boiler may not be required, thus reducing the space requirements.

Table 5-12 compares the floor space and height requirements of several chillers. Footprint and weight comparisons are illustrated in Figures 5-3 and 5-4, respectively.

Weight

The chiller weight can influence the purchase decision. If the chiller is mounted on an upper floor, it may affect the structural needs and subsequent cost of the building. In a retrofit situation, the building may not be structurally sound to accept a heavier chiller. The weight may also affect installation costs, since handling and rigging for heavier equipment is more costly.

Noise

Chiller noise is the result of both airborne noise and vibration. High-frequency airborne noise can be attenuated relatively easily by a low-mass equipment room wall. Low-frequency noise and vibration are less easily attenuated, generally requiring high mass walls, foundations, or isolation equipment.

Table 5-12. Comparison of Chiller Size and Weight

Size (tons)	Chiller Type	Dimensions Length (ft)	Width (ft)	Footprint (ft²)	Height (ft)	Weight (lb)
250	Electric, Screw	9.4	4.5	42	6.7	11,230
	Electric, Centrifugal	14.7	6.4	94	7.8	20,500
	Gas Engine, Screw	15.5	5.5	85	8.2	20,000
	Gas Engine, Centrifugal	—	—	—	—	—
	Absorption, D-F, D-E	17.8	5.3	94	7.3	19,400
500	Electric, Screw	9.8	5.0	49	6.7	14,700
	Electric, Centrifugal	16.1	7.6	122	8.5	29,540
	Gas Engine, Screw	16.8	9.1	153	9.7	27,390
	Gas Engine, Centrifugal	16.0	16.7	267	7.8	46,860
	Absorption, D-F, D-E	18.6	8.9	166	9.1	44,030
1000	Electric, Screw	—	—	—	—	—
	Electric, Centrifugal	15.4	10.8	166	11.1	41,540
	Gas Engine, Screw	23.3	9.6	224	10.0	53,350
	Gas Engine, Centrifugal	18.1	16.9	306	9.2	54,620
	Absorption, D-F, D-E	26.6	12.7	338	11.2	106,280

Note: Values are averaged from two or more manufacturers, and therfore do not apply to a specific model.

Source: Manufacturers' Literature

Both absorption chillers and electric centrifugal chillers have relatively low vibration noise. Electric reciprocating and engine-driven chillers can have both airborne and vibration noise. Exterior noise can also be a problem if it is discernible inside the building or if it disrupts occupants of nearby buildings. In these instances it may be necessary to employ noise-reduction kits or erect sound barriers.

Appearance

Appearance of the interior or exterior of the building may influence where a chiller is located and may also affect the purchase decision of the chiller plant. If outside appearance is important, the chiller might be located inside, leading to the space, weight, and noise concerns. Conversely, if interior space appearance is important the chiller may need to be located outside.

5.5 COST

All chillers, whether gas or electric, have costs associated with their purchase, installation, operation, and maintenance. In addition, the life-cycle cost and expected payback period should be analyzed as part of the chiller selection process.

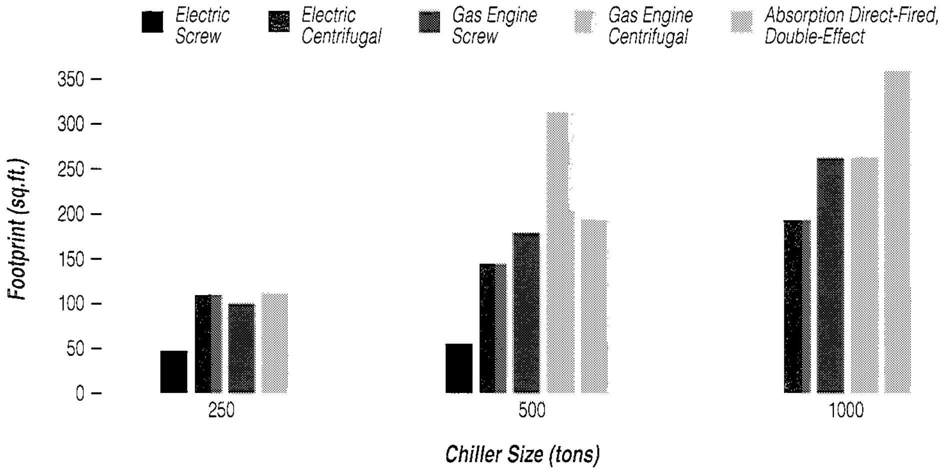


Figure 5-3. Footprint Comparison

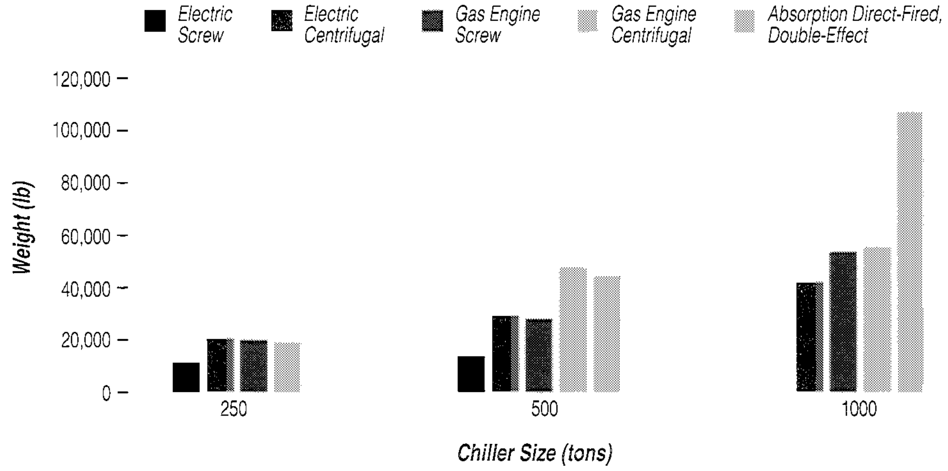


Figure 5-4. Weight Comparison

5.5.1 CHILLER EQUIPMENT COST

For new construction, approximately half of the total installed cost of an electric chiller is due to the cost of the chiller. Quotations from vendors of electric chillers generally include the chiller with electric motor, starter, controls, evaporator, and condenser. For chillers with water-cooled condensers and those with integral air-cooled condensers, the cost of the chiller includes the condenser. For chillers with remotely located air-cooled condensers, the cost of the chiller does not normally include the condenser.

Gas engine-driven chiller equipment costs generally include the chiller, gas engine, controls, evaporator, and condenser. These costs also include the ignition system, starter, muffler, and engine coolant system. The gas engine-driven chiller cost includes the cost of the condenser if equipped with a water-cooled condenser or integral air-cooled condenser. Absorption chiller equipment costs generally include the chiller, with absorber, generator, condenser, evaporator, solution pumps, motor starters, and controls.

Figure 5-5 presents chiller cost data for electric and gas chillers in capacities of 200, 500, and 1000 tons. The data were obtained from a limited survey of chiller manufacturers.

5.5.2 INSTALLED COST

Installed costs include the cost of the chiller plus the ancillary equipment needed for the chilled-water and condenser-water loops. This ancillary equipment includes the chilled-water pump, the condenser-water pump, and cooling tower. Costs for the condenser water piping and installation are typically included. The installed cost for the chilled-water system generally does not include the costs for the piping and installation of the chilled-water loop. Costs associated with the chilled water loop are dependent on building size, chilled-water piping configuration, air distribution system configuration, and air temperature control strategy. Installation costs for electric chillers also include upgrades, if needed, to the electric service panel.

Gas chillers have many of the same installation requirements as electric chillers. Installed costs of gas chillers include the equipment and installation costs for the chiller, condenser pump, piping, and cooling tower. In addition, gas chillers require installation of an adequately sized natural gas line. Adequate ventilation is required to provide combustion air and to eliminate heat radiated from the engine or absorption chiller. In addition, combustion and exhaust gases must be properly vented. Installed costs of gas engine-driven chillers should include enclosures, mufflers, and emissions catalysts, if required.

Figure 5-6 presents installed costs for several types of electric and gas chillers in capacities of 200, 500, and 1000 tons.

5.5.3 OPERATING COST

The primary component of chiller operating costs are the costs of electricity, natural gas, and water. For electric chillers, operating costs include the cost of cooling tower makeup water and the cost of electricity for the electric motor, condenser cooling-water pump, chiller water pump, and controls. Operating costs of gas chillers include the cost of cooling tower makeup water, the cost of natural gas for the gas engine or burner system, and the cost of electricity for pumps, fans, and controls.

Table 5-13 summarizes the information required to calculate the operating costs of electric and gas chillers. Electricity, and natural gas usage depend on the

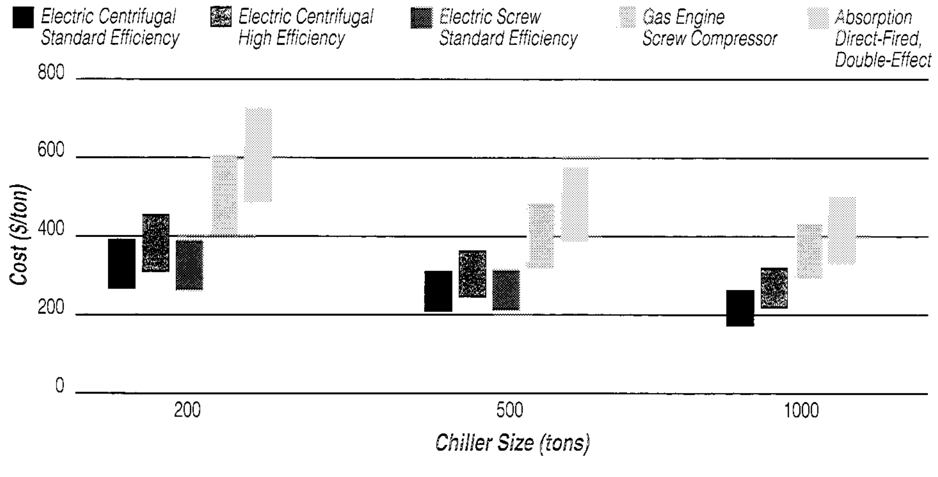


Figure 5-5. Chiller Costs
Source: Manufacturers' Data

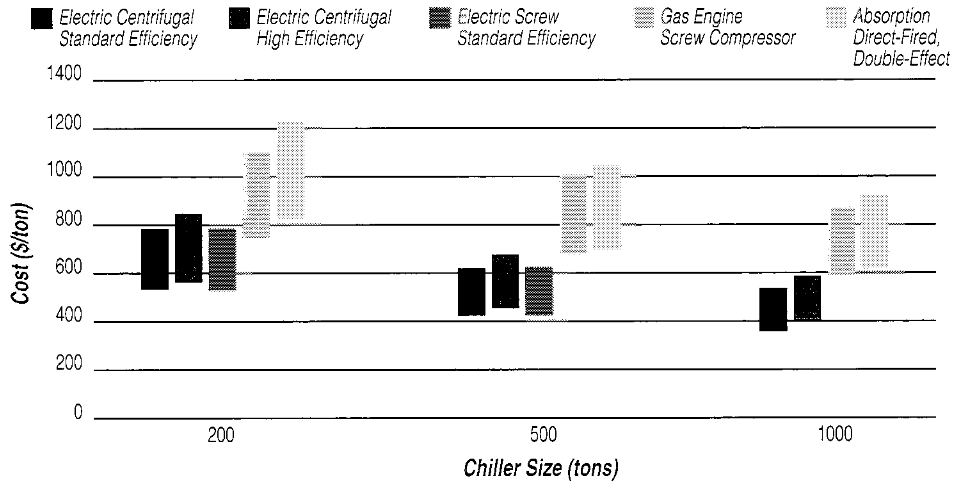


Figure 5-6. Chiller Plus Installation Costs
Source: EPRI (1993c), EPRI (1992a), and Means (1994)

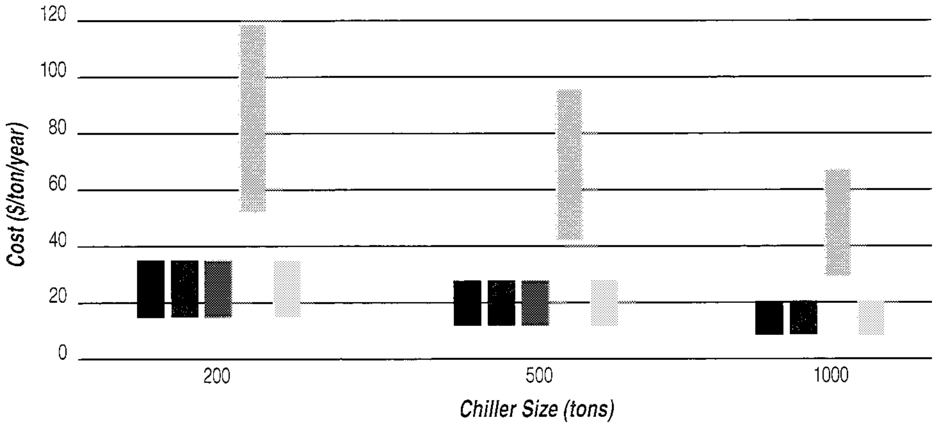


Figure 5-7. Maintenance Costs
Source: EPRI (1993c) and Manufacturers' Data

chiller type, the chiller efficiency at full and part load, the demand profile, and the energy requirements of the ancillary components.

Different types of water-cooled chillers have different water consumption rates that are related to the cooling tower water losses through evaporation and blowdown. For a given cooling capacity, absorption chillers and gas engine-driven chillers have higher water consumption rates due to their larger cooling tower requirements. Table 5-14 presents water consumption rates for gas and electric chillers (estimated from manufacturers' data).

5.5.4 MAINTENANCE COST

Figure 5-7 presents typical maintenance costs for electric and gas chillers. Total maintenance costs of gas engine-driven chillers which include engine overhaul or replacement are approximately three times higher than those of an equivalent capacity electric chiller. Maintenance costs for absorption chillers are comparable to electric chillers.

Table 5-13. Operating Cost Calculation Components

	Electric	Gas Engine-Driven	Gas Absorption Direct-Fired, Double-Effect
Chiller Size (tons)	■	■	■
Efficiency (kW/ton or COP)	■	■	■
Usage (hours at specific load)	■	■	■
Ancillary Electricity (kW/ton)	■	■	■
Water Consumption (gal/h/ton)	■	■	■
Maintenance ($/ton/yr)	■	■	■
Electric Energy Rate ($/kWh)	■	■	■
Electric Demand Charge ($/kW)	■	■	■
Gas Rate ($/therm)		■	■

Electric chiller maintenance costs are due primarily to maintenance of the compressor and not the electric motor. Therefore, gas engine-driven chiller maintenance costs can be calculated by adding the maintenance costs of the gas engine to the maintenance costs of an equivalent electric chiller.

5.5.5 ENERGY AND WATER COSTS

To accurately calculate operating costs, it is important to understand how electricity, natural gas, and water usage are metered and how utility rates are structured.

Electricity

Electricity consumption is metered on both an energy and a demand basis. Energy usage is a reflection of the size of the electric motor and the number of hours of operation. Energy usage is metered in kWh/month, and energy rates are expressed in $/kWh. Demand is a reflection of the size of the electric motor, and is metered in kW/month. The rate structures for both energy and demand charges may change, depending on the season of the year or the time of use during the day. Additional components of the electricity rate structure may include minimum charges, customer charges, taxes, surcharges, and energy cost adjustments.

Energy and demand rate structures are dependent on the utility and vary significantly. For comparison, energy charges may range from $0.03/kWh to $0.12/kWh, while demand charges may range from $3.00/kW to $12.00/kW.

Natural Gas

Natural-gas consumption is metered on a volumetric basis, typically in cubic feet/month. A constant heating value, usually near 1000 Btu/scf (HHV), is assumed. Natural-gas rates are

Table 5-14. Water Consumption

Chiller Type	Water Consumption (gal/h/ton)
Electric (centrifugal)	3.0 [1]
Engine-Driven (screw)	3.3 [2]
Absorption (direct-fired, double-effect)	4.6 [3]

[1] Based on a flowrate of 3.0 gal/min/ton and a consumption (loss) of 1.7%

[2] Based on a flowrate of 3.3 gal/min/ton and a consumption (loss) of 1.7%

[3] Based on a flowrate of 4.6 gal/min/ton and a consumption (loss) of 1.7%

expressed in terms of $/therm, $/million Btu ($/MMBtu), or $/thousand cubic feet ($/Mcf). Natural-gas rate structures may change, depending on the season of the year. In addition, natural gas rate structures may be based on total monthly usage, with the cost in $/therm decreasing as consumption increases. Additional components of natural-gas rate structures may include minimum charges, customers charges, taxes, and surcharges. Natural-gas rates typically range from $0.30/therm to $0.60/therm.

It should be emphasized that the utility's natural-gas rates are based on the Higher Heating Value (HHV) and not the Lower Heating Value (LHV) of the gas. Manufacturers often rate fuel consumption of gas chillers in terms of the LHV. However, for accurate comparisons, calculations should be based on HHV. An approximate conversion between HHV and LHV is shown below:

$$\text{HHV consumption rate (Btu/h)} = \frac{\text{LHV consumption rate (Btu/h)}}{0.9}$$

The formula is accurate if the HHV is 1000 Btu/scf and the LHV is 900 Btu/scf.

Water

Water usage is metered on a volumetric basis in terms of gallons or cubic feet. Water rates are based on $/gallon or $/cubic foot. Typical water rates for commercial customers are $4.00/1000 gallons.

5.5.6 *PAYBACK AND LIFE-CYCLE COSTS*

The installation, fuel, and O&M costs discussed in the preceding sections can be combined to form various cost comparison factors. Two common economic comparison measures are payback and life-cycle cost. Each method is briefly described in this section, followed by an illustration of the calculation approach based on four alternative chillers for a hypothetical installation.

For calculation purposes, the required chiller capacity is assumed to be 500 tons, and the four alternatives examined are

- Electric Centrifugal Chiller, Standard Efficiency
- Electric Centrifugal Chiller, High Efficiency
- Gas Engine Chiller with Screw Compressor
- Gas Absorption Chiller, Double-Effect, Direct-Fired

Assumptions for equipment performance specifications and energy, maintenance, and installation costs are shown in Table 5-15. The cost data in Table 5-15 has been estimated using the graphical information presented earlier in this section.

It is important to note that the economic calculations based on the data in Table 5-15 use average energy rates and equivalent full-load hours (does not account for part-load efficiency). Both assumptions simplify the calculations and allow for quick estimates of payback and life-cycle cost. These quick estimates can be useful for making rough economic viability decisions. However, these estimates should not be used to make chiller selection decisions. A final chiller selection should be based on a more rigorous modeling approach that incorporates actual energy rate schedules and part-load chiller performance (see Section 7 for more rigorous approach).

Payback

One variation of the payback approach is the simple payback analysis. Simple payback is an estimate of the time required to recover the additional capital expense of a chiller alternative. In a simple payback calculation, one or more chiller alternatives is compared to a base-case system. The incremental installed cost of the chiller alternatives is divided by the annual savings for these various alternatives, which yields a payback number in units of time (generally months or years).

Table 5-15. Simplified Cost Calculation Model—Assumptions

		Electric Centrifugal (std eff)	Electric Centrifugal (high eff)	Gas Engine	Absorption (direct-fired, double-effect)
Equipment Specifications and Operation	(tons)	500	500	500	500
	(COP)	—	—	1.70	1.10
	(kW/ton)	0.68	0.57	—	—
	(EFLH/yr)	830	830	830	830
Auxiliary Energy	(kW/ton)	0.13	0.13	0.15	0.22
Water	($/1000 gal)	4.00	4.00	4.00	4.00
	(gph/ton)	3.0	3.0	3.3	4.6
Maintenance	($/ton-yr)	20	20	68	20
Electric Rate	($/kWh)	0.15	0.15	0.15	0.15
Gas Rate	($/therm)	0.40	0.40	0.40	0.40
Installed Cost	($/ton)	520	560	828	867

Figure 5-8 shows the incremental costs and expected annual savings for the four hypothetical chiller systems (based on information in Table 5-15). The variations in cost and savings are calculated relative to a standard-efficiency electric centrifugal chiller, which is assumed to be the base case.

Payback values are plotted in Figure 5-9. As indicated, the high-efficiency electric chiller has a payback of approximately 3 years, and the absorption payback is approximately 11 years. The engine-driven system has an annual maintenance cost nearly equal to the

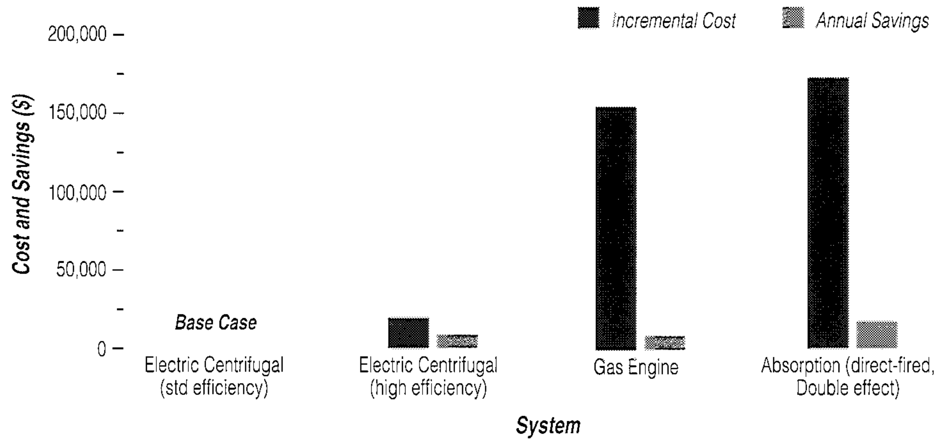


Figure 5-8. Comparison of Costs and Savings

Notes: Based on average energy rates and EFLH. See Table 5-15 for assumptions.

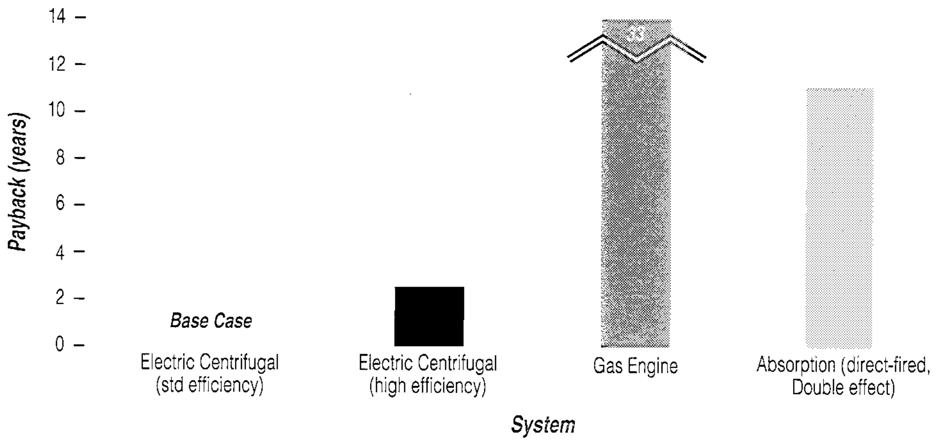


Figure 5-9. Payback Analysis
Notes: Based on average energy rates and EFLH. See Table 5-15 for assumptions.

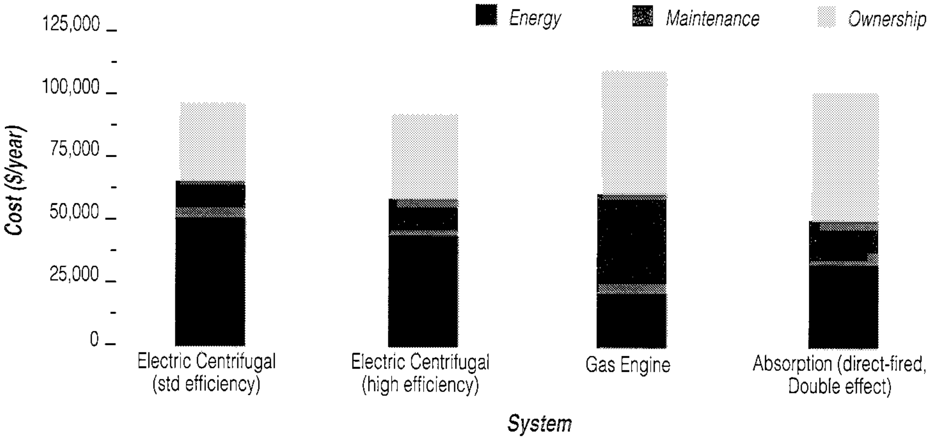


Figure 5-10. Life-Cycle Cost
Notes: Based on average energy rates and EFLH. See Table 5-15 for assumptions.

expected annual savings, and therefore the payback is relatively high (33 years).

Life-Cycle

A life-cycle cost analysis takes into account the equipment life and the cost of money over time, and provides a measure of expected annual costs, including depreciation, over the life of the equipment. An illustration of life-cycle cost calculations is shown in Figure 5-10 (based on data in Table 5-15).

As indicated in Figure 5-10, the life-cycle costs vary from approximately $91,000/year (high-efficiency electric) to $109,000/year (gas engine). The trend in life-cycle costs is consistent with the payback analysis. That is, the high-efficiency electric centrifugal system has the lowest payback and life-cycle cost, followed by the absorption system, and finally the engine-driven chiller.

6

Chilled-Water System Optimization

Optimization is the process of minimizing the cost and energy consumption of the chilled-water system while maintaining the required cooling output. The chilled-water system refers to all components of the condenser-water loop (including cooling tower and condenser pump), the chilled-water loop (including the chilled water pump), and the chiller. Figure 6-1 shows the primary energy consuming components, which include the chiller, the cooling tower, the condenser pump, and the chilled-water pump. Both the cooling tower and chiller are made up of a variety of components, each of which can affect the energy use. Achieving the proper balance among all these components is a complex task.

The previous chapter described many of the factors involved in selecting a chiller. One or more of these factors may dominate the decision process. However, for a given building there are hundreds of options for developing a chilled water system to meet the required demand. This chapter does not attempt to identify an optimum design for a given situation, rather it identifies key options to consider when designing chilled-water systems. In addition, selected case studies are included to illustrate actual chiller installations.

6.1 OPTIMIZATION STRATEGIES

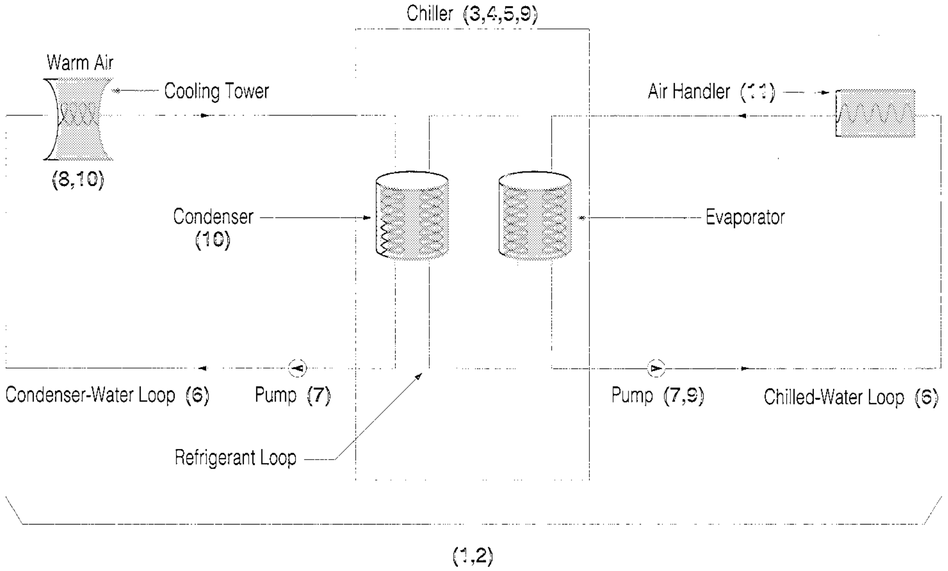
Selecting a chiller to provide cooling for a given building based on peak demand and other selection factors can be straightforward. However, designing the entire chilled-water system for optimum performance requires additional analysis.

Water chiller systems include numerous components that must interact to produce the desired air cooling. These components include the condenser, evaporator, cooling coil, cooling tower, water pumps, piping, valves, and heat exchangers. Optimizing the performance of each component may not result in the optimum system design. For example, by increasing the chilled-water flow rate, the efficiency of the chiller can be improved. However, the increased water flow requires increased pumping power, which may offset the chiller efficiency gain.

Figure 6-1 indicates a number of optimization considerations related to the overall chilled-water system as well as individual components. These considerations can be grouped as follows

- Overall System Analysis and Control
- Chiller Plant
- Individual Components

Each optimization strategy listed in Figure 6-1 is summarized in the following sections.



Overall System Analysis and Control

1. Computer Modeling—Helpful with the design of the entire chilled-water system.
2. Controls—Automated controls are desirable for optimum operation.

Chiller

3. Multiple Chillers—Multiple chillers with proper staging result in higher efficiency.
4. Chiller Sizing—Oversized chillers result in higher first and operating costs.
5. Heat-Recovery Chillers—These systems provide simultaneous heating and cooling.

Individual Components

6. Thermal Lift—Decreased thermal lift (either by increasing the chilled water temperature and/or decreasing the condenser water temperature) helps improve efficiency.
7. Pumps and Piping—High-efficiency pumps and large diameter piping can improve overall performance.
8. Cooling Tower Design—Large-capacity, close-approach towers reduce the condenser water temperature, resulting in higher efficiency.
9. Adjustable Speed Drives—ASDs enable the compressor and pumps to run at lower speed, thus improving part-load performance.
10. Evaporative Condensers—Evaporative condensers can be a cost-effective replacement for cooling towers.
11. Air Distribution System—Variable air volume designs conserve energy.

Figure 6-1. *Selected Chilled-Water Systems Optimization Strategies*

6.1.1 COMPUTER MODELING

An effective first step to optimize a chilled-water system is to utilize a computer modeling program. These programs can model building load and system performance on an hour-by-hour basis and account for climate, building construction, energy costs, building load factors, and HVAC system types.

The HVAC industry has access to a variety of computer building energy and systems analysis programs. Computer modeling programs can be grouped into two categories

- Hourly simulation models
- Modified hourly simulation models

The hourly simulation programs are the most accurate as they compute the energy use and cost for each hour of the year (8760 hours). They utilize detailed building descriptions, energy-use patterns, equipment data, and weather information to calculate the hourly building loads and system energy-use. Detailed utility rate schedules are included to provide hourly, daily, weekly, monthly, and annual cost information. Typical Mean Year (TMY) weather files are used by most major modeling programs.

With hourly simulation programs, it is also possible to use actual site weather data to attempt to match a building's energy usage with actual utility billing information. Energy monitoring of systems, appliances, and other factors can be conducted to help calibrate the model. Once a model is fully calibrated, various scenarios can be quickly and easily modeled. However, this type of analysis can be time consuming and costly.

The modified hourly simulation programs use selected daily energy-use profiles to represent the entire year. One common method is the 48-day format (4 days per month, 12 months per year). The four days represent typical, hot, cold, and nonwork (weekend) days for each month. From this information the energy use can be estimated for a month, and then the entire year. These models are generally less accurate than the hourly models, but may be adequate for an initial screening of options.

The software packages originate from government organizations, universitites, private software vendors, consulting firms, and HVAC equipment manufacturers. Selected software programs are listed in Table 6-1.

Table 6-1. Selected Computer Energy Simulation Tools

Hourly Simulation Models	
• ADM-2	(ADM)
• BLAST	(DOD)
• DOE-2	(DOE)
• ENERCALC	(Texas A&M)
• HAP	(Carrier)
• micro-AXCESS	(EPRI)
Modified Hourly Simulation Models	
• ASEAM	(ACEL)
• COMTECH	(EPRI)
• Market Manager	(SRC)
• System Analyzer	(Trane)
• Trace	(Trane)

The DOE-2 program was developed by the U.S. Department of Energy and has been widely used in the industry for many years. DOE-2 uses an hourly simulation model to estimate the performance and operating cost for buildings and their systems. DOE-2 allows for very detailed building and chilled-water system descriptions to enable modeling of nearly every possible chiller configuration.

PowerDOE, a new building energy simulation program, is currently being developed by EPRI and DOE. PowerDOE is based on DOE-2, but has a graphical user interface and runs under Microsoft® Windows™. The new interface will make DOE-2 easier to use while maintaining its computational power.

COMTECH™ is an example of a modified hourly simulation model. COMTECH results for several chillers are presented in Section 7 of this *Handbook.*

6.1.2 ADVANCED CONTROLS

Controls are an integral part of system operation, and can result in significant energy savings for the chilled-water system. Chiller Automation Packages (CAPs) are available from chiller manufacturers or from independent manufacturers specializing in these systems. Microprocessor-based CAPs automate the operation of chillers, pumps, and fans to optimize the system efficiency. In addition, these systems can monitor equipment and signal when maintenance is required. Many of these systems are equipped with telemetry packages to communicate information to remote-control or service facilities.

6.1.3 MULTIPLE CHILLERS

A single chiller can generally be purchased to supply all of the cooling load for most commercial buildings. However, depending on the application, more than one chiller may be the optimum solution. The following multi-chiller strategies can be used

- Two equally sized chillers
- Multiple unequally sized chillers
- Combination of electric and gas chillers

Two equally sized chillers may meet the backup requirements for a facility. A building that requires 500 tons of peak cooling may be fitted with two 250-ton chillers. At low loads, one chiller can remain off and the other will likely be operating at near peak efficiency. For example, if this same building commonly operates with a 200-ton cooling load, one chiller can be shut down and the other will be operating at 80% capacity, which for electric centrifugal chillers is near maximum efficiency. At this same load with a single 500-ton chiller, the performance begins to drop significantly.

Although equally sized chillers may provide better backup capability, it may be more beneficial to size the chillers unequally. For example, in the previous illustration, the 500-ton building load can be met with a 400-ton and a 100-ton chiller. Unequally sized chillers also allow for staging strategies to enhance

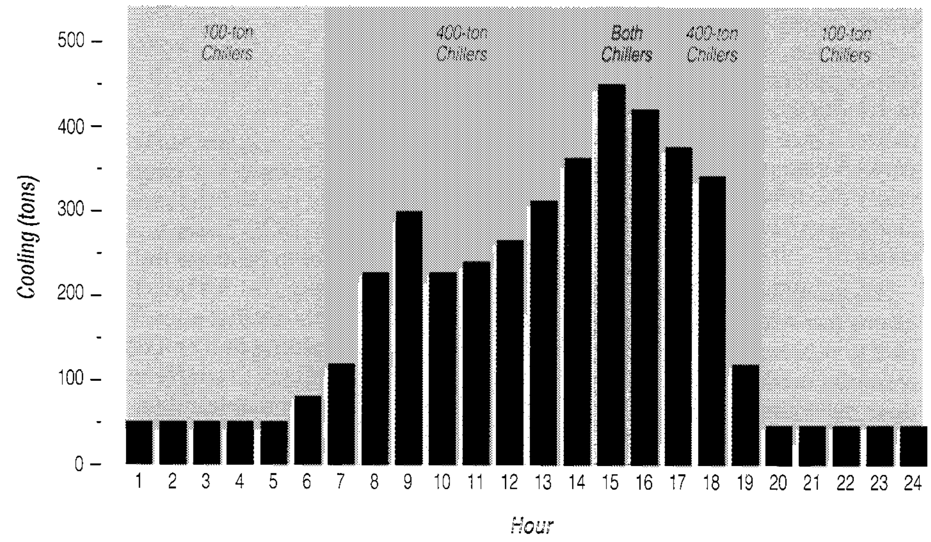


Figure 6-2. Multiple Chiller Strategy Example

performance. For example, a building may have low nighttime requirements and build to its peak load in the afternoon, as illustrated in Figure 6-2. In this hypothetical example, the 100-ton chiller would be used until the building exceeds its capacity at 7:00 a.m. Then the 400-ton chiller can be started (now at 40% load) and the 100-ton unit shut off, thus eliminating the lowest-performance operating range of the larger chiller. The 100-ton chiller would then remain off until the 400-ton capacity is exceeded (at 3:00 p.m.), at which time both chillers would be in operation. In this example, the two chillers operated together only two hours per day. The 100-ton chiller operated 11 of the 24 hours, averaging better than 50% load, and the 400-ton chiller operated the remainder of the time, also at greater than 50% load.

Another optimization strategy in utility service territories with high electric demand charges and low natural-gas rates, is to utilize both an electric and a gas chiller (referred to as a hybrid system). In this scenario, the electric chiller would supply most of the base load, while the gas chiller would be called upon to provide additional cooling during peak periods. With this operating strategy, demand charges may be significantly reduced.

6.1.4 CHILLER SIZING

Proper sizing of a chiller can have a significant impact on cost. Oversizing carries a significant first cost. For example, if a 200-ton chiller costs $600/ton (installed cost) and is oversized by 20 tons, the result is $12,000 of unneeded expenses.

Oversizing can also cause the chiller to run less efficiently. For example, assume a building requires a 500-ton chiller that typically runs between 250 and 350 tons (50% and 70% load). However, if a 700-ton chiller were installed, it would be operating at between 35% and 50% load, which would result in lower efficiencies and higher operating costs. Figure 6-3 illustrates the operating ranges of these two chillers.

One common cause of oversizing occurs when a chiller is replaced without first checking for changes in building load. Building loads can decrease over time (e.g., as a result of more-efficient lighting), and replacing a chiller with one of the same capacity can lead to an oversized system.

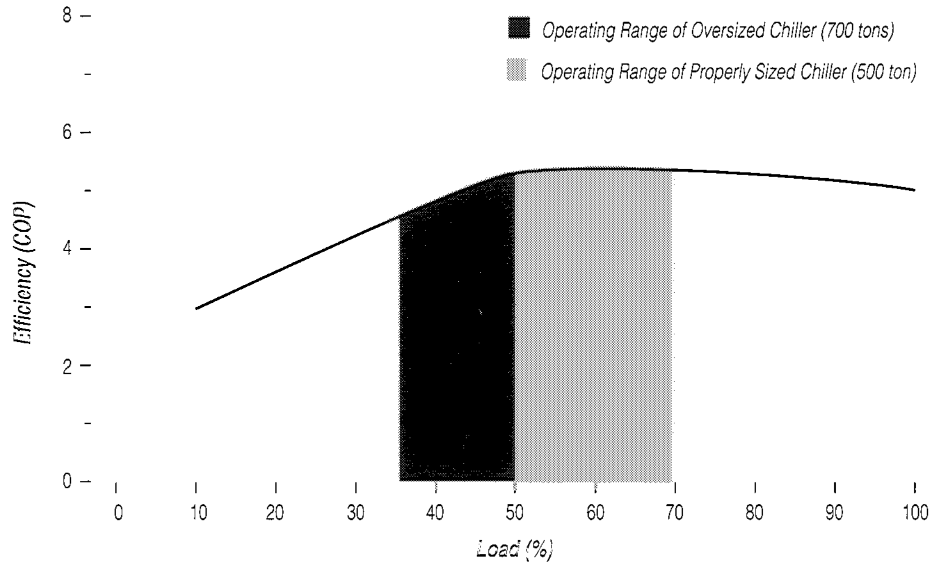


Figure 6-3. Performance Range of Two Chillers (700 ton and 500 ton) Operating in the Range of 250–350 tons

6.1.5 HEAT-RECOVERY CHILLERS

For applications that require simultaneous heating and cooling, a heat-recovery chiller may provide optimum efficiency. The heat-recovery chiller is basically a standard electric chiller with a second condenser. A schematic of the heat recovery chiller is shown in Figure 6-4. When both heating and cooling are considered, a heat-recovery chiller delivers energy at 20% to 40% of the cost of a conventional boiler and chiller, depending on the energy rates and system efficiencies (EPRI 1993a). The cost for the heat-recovery chiller is up to 20% higher than the cost of a similar high-efficiency electric chiller, but in good applications, the increased cost can be recovered in a few years.

Prime building candidates for heat-recovery chillers have the following characteristics

- Low to moderate heating load with coincident cooling load
- High hours of operation and high internal heat gain
- Central HVAC system with a water-cooled chiller
- High domestic hot-water needs

6.1.6 CHILLER THERMAL LIFT

Chiller thermal lift is defined as the difference between a chiller's evaporator temperature and condenser temperature (EPRI 1995a). Chiller energy consumption is generally proportional to chiller thermal lift. Increasing chilled-water temperature, as well as decreasing condenser-water temperature, increases chiller efficiency. The condenser water temperature is a function of cooling tower design (see Section 6.1.8). An increase in the chilled-water temperature may require an increase in the building air supply rate. Therefore, even though reducing chiller lift improves the efficiency, increased fan and pumping power may offset these improvements.

6.1.7 PUMPS AND PIPING

Pumps are used for circulating chilled water and condenser water. The amount of energy consumed by these pumps is a function of pump efficiency and piping design. Most losses in a pump are due to hydraulic friction, which depends on the geometry of the pump and smoothness of pipe surfaces over which the fluid passes. The inlet and outlet piping of the pump are very important to pump per-

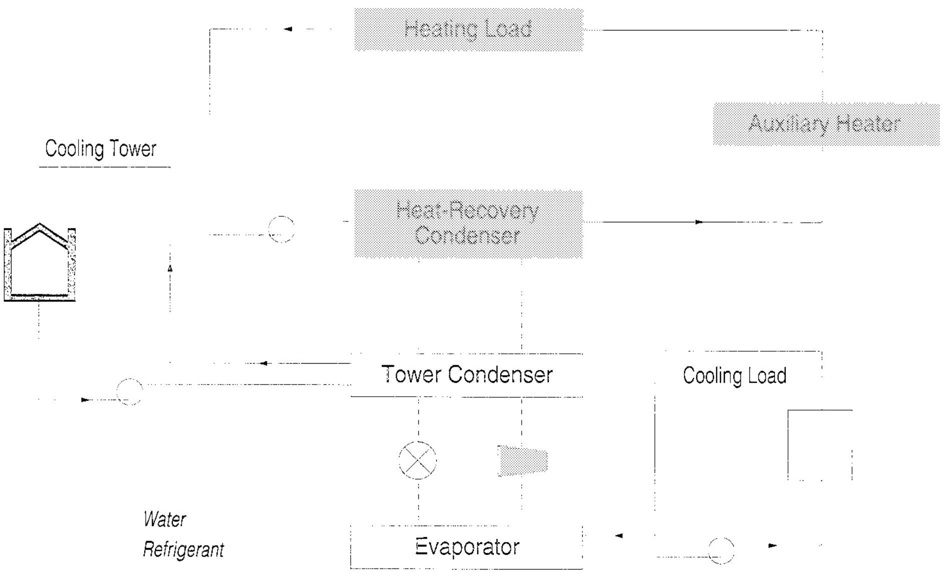


Figure 6-4. *Heat-Recovery Chiller*

formance. Smooth inlet flow conditions must be met in order to achieve the rated pump performance.

The pipe diameter can have a significant impact on the required pumping energy. Pumping energy is a function of pressure drop, and the pressure drop varies with the square of the velocity, and is inversely proportional to the pipe diameter raised to the fifth power. For illustration, if the pipe diameter is doubled, frictional losses in straight pipe runs are reduced by about 97% ($1/32$ of the pressure drop in pipe half the diameter). Therefore, the opposite is also true; reducing the diameter of the pipe in half, increases pressure losses by a factor of 32. In addition to pressure losses in straight pipe, other components such as valves, fittings, and elbows cause additional losses, which may be substantial.

6.1.8 COOLING TOWER DESIGN

The cooling tower is a very important aspect of chiller performance. The chilled-water system rejects heat to the cooling tower. Increasing cooling tower surface area and reducing fan horsepower can substantially reduce chiller operating costs. Using larger cooling towers and operating them to achieve the lowest acceptable leaving-water temperature decreases the chiller condensing temperature, thereby reducing the chiller's operating pressure and improving efficiency. For every degree the tower leaving-water temperature is lowered, the chiller condenser temperature usually drops 1°F, with a corresponding performance improvement of 1–2% (EPRI 1995b).

The range and approach are important factors to consider for cooling tower design (see Figure 6-5). The range refers to the difference in temperature between the water entering and leaving the cooling tower. The approach refers to the difference between the temperature of the water leaving the tower and the wet bulb temperature of the entering air. Closer approach means more-effective heat rejection, thus a more-efficient system.

Cooling towers are typically designed using a 7°F approach and 10°F range at 78°F outdoor wet bulb temperature. However, more aggressive design criteria can offer increased operating savings. Several of these criteria are summarized below:

Large Capacity, Close Approach

The ASHRAE-recommended method for designing cooling towers is to design for a 5°F approach rather than typical design assumption of 7°F approach. By reducing the approach, the size of the cooling tower is increased.

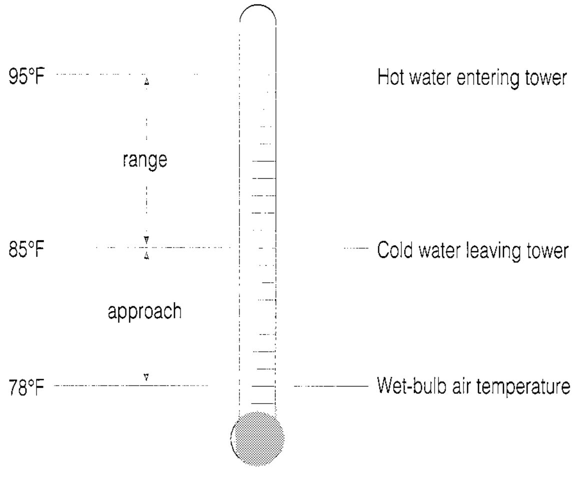


Figure 6-5. Cooling Tower Terminology

It is preferable to design the cooling tower based on the actual heat rejection rate of the chiller, rather than an assumed value. The common assumption of 15,000 Btu/h of cooling tower capacity per ton of chiller capacity is based on a chiller efficiency of 0.88 kW/ton. However, a chiller operating at 0.55 kW/ton rejects only 13,900 Btu/h/ton, and would thus require a smaller cooling tower (EPRI 1995b).

Larger Box

The best way to improve tower capacity is to select a model built with a larger box (increased surface area), rather than a smaller model with increased airflow (requires larger fan motors).

Film Fill

The film fill is the material inside the tower over which water flows. Its purpose is to provide a large surface for exposing water to the airstream, thereby promoting evaporation. Closely spaced sheets of plastic film are recommended.

Induced-Draft

Induced-draft cooling towers are usually more efficient than forced-draft towers, and have significantly lower fan power requirements (0.04–0.07 hp/ton for induced-draft compared with 0.10 hp/ton for forced-draft).

Careful Siting

The tower should be located to prevent recirculation of exhaust air from other towers or heat-producing equipment. Tower exhaust air should not be drawn into fresh-air intakes.

A minor investment in larger, high-efficiency towers can cut chiller energy use by 7–12%. These energy savings, combined with electricity demand savings, usually yield a simple payback of less than two years (EPRI 1995b).

6.1.9 ADJUSTABLE SPEED DRIVES

Possible applications for adjustable speed drives (ASDs) include pump motors (condenser- and chilled-water loops), cooling tower fan motors, and compressor motors. As noted in Section 3.3.3, ASDs are rarely used on condenser pumps. However, they are frequently a good choice for chilled-water pumps (see Section 3.3.1). For cooling tower fans, ASDs generally do not provide an economic advantage. For chiller compressors, ASDs are a good practice if the chiller runs at low load for significant time periods.

6.1.10 EVAPORATIVE CONDENSERS

High-efficiency evaporative condensers may be a cost-effective alternative to cooling towers. Evaporative condensers consist of a coil of metal tubes or pipes inside an evaporation chamber. A fan blows air across the coils as a recirculating water system continuously sprays water over the coils, cooling the air and the coil by evaporation. Evaporative condensers operate more efficiently than a cooling tower with a water-cooled condenser because they do not have an intermediary heat exchanger and a large circulating pump. In addition, they are more compact and therefore take up less physical space (EPRI 1993b).

6.1.11 AIR-HANDLING SYSTEM

Air distribution systems are either constant-air-volume (CAV) or variable-air-volume (VAV) systems. CAV systems deliver supply air at a constant rate, and control the conditioned space temperature by varying the dry bulb temperature of the supply air. CAV systems tend to have relatively high-energy consumption rates as the supply air blowers are constantly run at full load. In addition, reheat or air mixing is required with CAV systems for humidity control, consuming additional energy.

By comparison, VAV systems tend to consume less energy than CAV systems. The dry bulb temperature of the supply air is held constant, and temperature and humidity are controlled by changing the volume of air delivered to the conditioned space. In a VAV system, the airflow is varied by either changing the blower motor speed and/or adjusting the inlet guide vanes on the blower. VAV systems work well for commercial buildings, and offer the advantage of additional energy savings compared to CAV designs (EPRI 1993d).

6.1.12 RECOMMENDATIONS

Each chiller installation is a unique case, and optimization strategies are site specific. However, a few general optimization strategies tend to apply to most chilled-water systems installed in commercial buildings.

- Select a high-efficiency chiller
- Minimize lift (oversize the cooling tower)
- Use unequally sized chillers in multiple chiller applications
- Use variable speed drives on chiller if load fluctuates significantly
- Use VAV for air distribution

Select a High-Efficiency Chiller

The initial cost is higher for high-efficiency chillers, but the incremental cost is generally recovered within a few years due to the energy savings. A few characteristics of high-efficiency chillers include (EPRI 1995a)

- More effective heat exchangers, which allow closer approach and reduced refrigerant-side pressure drop
- High-efficiency compressor motors
- Modulation to allow more efficient operation at part load
- Multistage centrifugal compressors with interstage economizers
- Improved controls for better load matching and temperature control

Minimize Lift

Increasing the chilled-water (evaporator) temperature and decreasing the condenser-water temperature increases chiller efficiency. The primary way to reduce the condenser-water temperature is to improve the performance of the cooling tower.

Use Unequal-Size Chillers in Multiple Chiller Applications

The use of multiple, unequally sized chillers can significantly improve the annual chilled-water system performance. This strategy requires an advanced control system to automatically operate the chillers in their highest performance ranges (usually between 50 and 90% of full load).

Use Variable Speed Drives

Variable, or adjustable speed drives enable the compressor to run at lower speed at part-load conditions, thus improving part-load performance. This strategy is especially beneficial when only one centrifugal chiller supplies the cooling for a building.

Use Variable Air Volume System

VAV systems conserve energy compared to CAV designs. With VAV designs, the volume of air circulated is controlled, thus minimizing blower energy requirements.

6.2 CASE STUDIES

Several case studies, as reported by engineering journals and news magazines, are summarized in Appendix A. The majority of the cases involve the installation of new electric chillers, two cover the combination of both electric and gas systems, and one covers the installation of a new gas system to accompany an older electric system. Two of the studies cover chiller load-reduction strategies; one through installation of a thermal energy storage system and the other through installation of variable speed drives. Many additional chiller load-reduction strategies are used, such as lighting retrofits, advanced building automation systems, or window treatments. Overall, the studies encompass the objectives and optimization strategies from the view points of both the end-user and the utilities.

For end-users, the objectives appeared to be similar throughout the United States, while the optimization strategies appeared to be more regional. The latter was due primarily to differing local utility rates, equipment rebates, state regulations, and climatic conditions. Of the case studies analyzed, several recurring objectives included

- Compliance with the pending CFC phaseout
- Maximum energy savings and minimum project payback time
- Desire to be perceived as an environmentally friendly organization

- Provide backup cooling capacity
- Comply with state mandates

The optimization strategies tended to be more varied and creative. For almost every case study, one of the significant drivers seemed to be the value of the rebate offered by the local utility. The nature of the rebates and the manner in which users qualified for them varied widely. In general, the utilities strongly suggested the use of highly energy-efficient chillers employing non-CFC's. Users generally had to demonstrate, through engineering calculations, a specific overall system efficiency before qualifying for a rebate.

From the standpoint of the utilities, load shifting is a major issue. A variety of rebate programs and other financial incentives are offered to aid in the load-leveling objective. Load shifting serves to reduce the necessity for construction of additional power production capability. Rebate programs are designed to encourage end-users to improve the energy efficiencies of their buildings, and to shift demand to off-peak hours.

Three of the fifteen case studies are outlined in the following pages

- Office Building—Boston, MA
- Hotel—Rancho Mirage, CA
- Department Store—Tucson, AZ

Electric Chillers Replace Steam Absorbers

Summary

By replacing two aging single-effect steam absorption chillers with three non-ozone-depleting high-efficiency electric HFC-134a centrifugal chillers, a Boston office building is projected to save about $130,000/year in energy costs. In addition, the new chiller plant is decreasing emissions of CO_2 and NO_X by an estimated 70%.

Background

In 1992 Rose Associates, Inc., operators of a 32-story office building at 99 High Street in Boston, began investigating options for replacing the building's two 1170-ton, single-effect steam absorption chillers. The units were in reasonably good operating condition, but, at 22 years of age, were nearing the end of their expected lifespan. Further, they provided no backup capacity, given the building's peak load of 1850 tons. Failure of one unit could therefore subject building occupants to high temperatures.

The Rose Associates study focused on three technologies: double-effect steam absorbers, double-effect gas-fired absorbers, and electric chillers. Its goal was to identify the most cost-effective system that could provide backup cooling capacity. The study also considered the following issues:

- The 18th floor chiller plant had little extra space
- The building had no gas service; steam was purchased from a district heating company
- The existing electric service had no capacity for electric chillers
- The "free cooling" system's heat exchangers were inefficient, providing little benefit

Barriers Eliminated Double-Effect Absorbers

A number of size constraints eliminated the double-effect steam absorption chillers as a viable option. Such chillers were unavailable in the required 1200-ton size, and three 800-ton units would not fit in the mechanical room. Further, these chillers could not be "knocked down" to a size small enough to fit through the available structural opening, and, weighing 30% more than the existing single-effect absorbers, posed a structural loading problem.

Double-effect gas-fired absorbers were available in the 1200-ton size. However, because the mechanical room had space for only two units, this configuration would provide no backup capacity. Other concerns were the need to run a 12-inch gas line from the street to the 18th floor and to install a 48-inch chimney from the 18th to the 32nd floor.

High-Efficiency Electric Chillers Prove Best Option

The study identified the best option to be installation of three high-efficiency centrifugal HFC-134a electric chillers totaling 2500 tons. The chillers would offer annual energy use savings over the original equipment, while providing backup capacity. As an added benefit, Boston Edison Company's Energy Efficiency Partnership Program provided nearly $269,000, which covered the extra cost for high-efficiency models.

The energy cost savings stem largely from eliminating chiller steam requirements. HVAC system computer models showed that the electric chiller plant would increase peak electric demand over that of the original equipment from 530 kW to 1380 kW, increase annual energy use from 805,000 kWh to 1.22 million kWh, and decrease steam consumption by 27 million lb. The increases cost about $80,000/year, while eliminating steam saves $210,000, yielding net savings of $130,000/year. These savings help offset the impact of the $400,000 electric service upgrade.

The chiller changeout also provided the building owner an opportunity to upgrade other plant components, which promised an additional $30,000 in annual energy savings, according to computer models. The $282,000 cost for these upgrades—which included modifications to the free cooling system and installation of variable-frequency drives and high-efficiency motors on the condenser water and chilled-water distribution systems—was covered by Boston Edison's Energy Efficiency Partnership Program.

New Plant Exceeds Expectations

The chiller plant changeout was completed in March 1994—on time and within the $2.3 million budget. Construction went smoothly and the plant is "operating beyond expectations," according to Dick Cavanaugh, property manager for Rose Associates. A review of 1994 utility bills shows that the new plant provided significant

Figure 1. *Chiller installation at 99 High Street.*

energy savings, with building steam use down 41% and electricity use up only 8%. These savings came despite higher-than-expected demand resulting from record-high summer temperatures, about 35% higher building occupancy, and a colder winter than the previous year.

Electric Chillers Benefit Environment

Built to run on HFC-134a, the new electric chillers do not contribute to any depletion of the ozone layer. And the chillers are yielding even greater environmental benefits. Because of their higher efficiency, the electric chillers generate an estimated 70% less CO_2 and NO_X emissions than the single-effect absorbers they replaced (see Figures 2 and 3). These emissions estimates include direct emissions—produced from burning natural gas on-site (or nearby) to generate steam—and indirect emissions—produced from burning a mix of oil and natural gas off-site at the electric power plant. As a further environmental bonus, the chillers cut water use by 3 million gallons annually by decreasing steam use in the district steam system, which lacks return lines for water reuse.

Similar Results Expected in Other Applications

Operating five to nine times more efficiently than absorption chillers, electric chillers offer cost, sizing, and environmental benefits in many applications. Most comparisons show that the absorption chiller's single advantage over electric chillers—potential peak-period operating cost savings—will not offset its disadvantages: high installation costs, heat rejection, and auxiliary system energy needs. Each comparison must examine a number of issues, many of which consistently favor electric units:

- Electric and gas/steam rates vary widely. The comparative costs affect the benefits of chiller operation. In this project, electric rates are about \$0.10/kWh in the summer and \$0.08/kWh in the winter (including demand), and steam rates are approximately \$7.80/1000 lb of steam.
- Auxiliary system energy cost. This component costs about \$96,000/year for the original absorption chillers, about 90% more than for the new electric chillers—a typical finding in comparisons of these systems.
- Space and structural concerns. Space and structural constraints may limit the use of absorbtion chillers in many applications, as these units tend to be bigger, heavier, and more difficult to disassemble than electric chillers.
- Heat rejection capacity and water needs. Because absorbers reject about 65-110% more heat than electric chillers, they require more make-up water and larger cooling towers and condenser pumps.
- Emissions. Double-effect absorption chillers produce about 50% less direct CO_2 emissions than the single-effect units in this evaluation. Nevertheless, when indirect emissions associated with absorption chiller auxiliary equipment operation are included in the analysis, absorption chiller systems have higher emissions than electric chillers in almost every comparison of electric generation mix and electric chiller selection.

Reference

This case study was originally published as an EPRI Commercial Cooling Update Case Study (SU-105401).

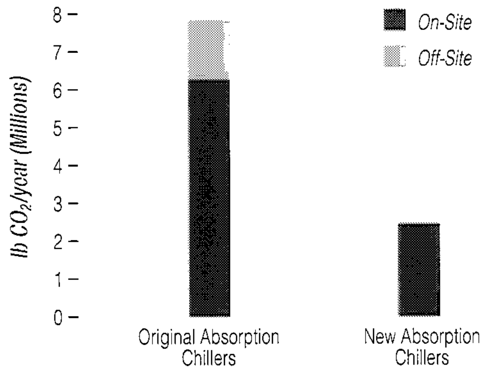


Figure 2.

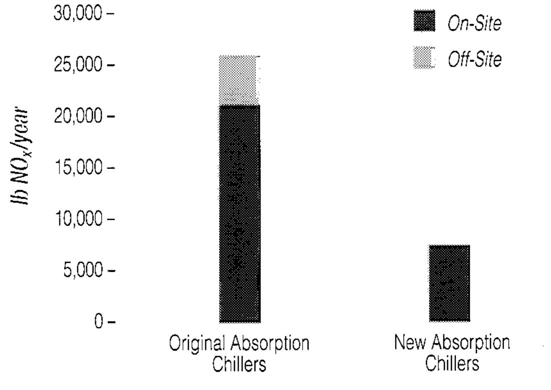


Figure 3.

Assumptions:

- Steam produced with natural gas at 55% efficiency (reference: steam supplier); 9% distribution loss.
- Electricity produced with 50% gas and 50% oil in 25% efficient combustion turbines (conservative; reference: Boston Edison); 10% distribution loss.

New and Rebuilt CFC-Free Chillers Provide Many Benefits

Summary

In side-by-side field tests at a Ritz-Carlton Hotel, Southern California Edison (SCE) is comparing the performance of new and rebuilt centrifugal chillers that use a CFC-free refrigerant. The first phase of testing demonstrated the significant energy savings to be gained by replacing a CFC-11 chiller with a new HCFC-123 unit: cooling system demand dropped 24% and energy use 22%. The second round of performance tests, currently in progress, is comparing the new chiller with an HCFC-123 conversion.

> ***"This project shows that the right environmental decision can also make sound business sense . . . and provide a lot of additional operating benefits."***
>
> *Sam Horlacher, Director of Engineering,*
> *The Ritz-Carlton Hotel, Rancho Mirage, California*

Two-Phase Comparison

The Ritz-Carlton Hotel in Rancho Mirage, California, was operating two CFC-11 chillers to meet its 24-hour, year-round cooling load. The six-year-old centrifugal units were rated at 250 tons each and operated at about 0.8 kW/ton at full load.

SCE selected the hotel as a good site for field-testing new and rebuilt HCFC-123 units. In the first phase of the project, the utility replaced one of the chillers with a new 250-ton centrifugal unit using HCFC-123. SCE monitored the plant for the first year following the replacement, from June 1993 to July 1994. Energy savings were calculated using chiller performance curves derived from measured data for the baseline CFC chiller and the new HCFC-123 unit.

In the second phase of the project, the remaining CFC-11 chiller was converted to HCFC-123 operation. The full-scale reengineering, conducted by the chiller manufacturer, included remachining the compressor impeller to optimize performance for the new refrigerant. The new and rebuilt units were monitored from June through October 1995.

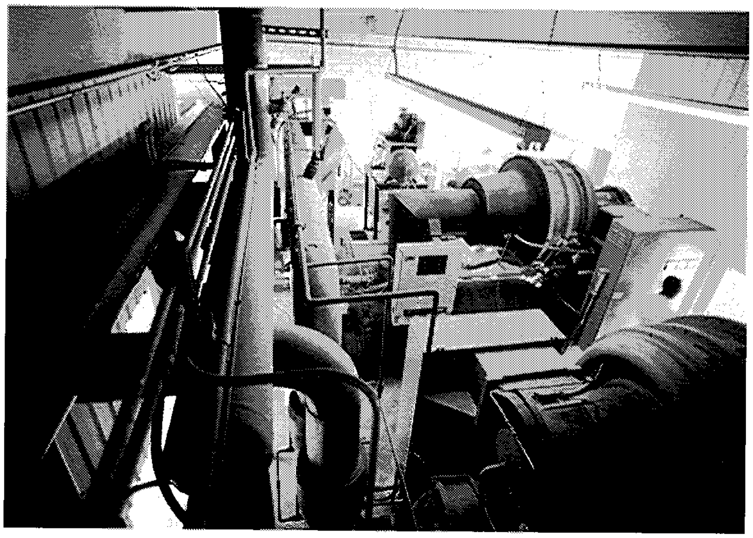
Improved Efficiency

The new chiller, which operates at about 0.6 kW/ton at full load, reduced energy use by 22%, from 1,038,282 kWh/yr to 811,203 kWh/yr. Demand decreased 24%, saving 32 kW during the peak month. Figure 1 compares the performance of the new and baseline chillers. Because the new chiller rejects less heat, it also decreased energy use by the cooling tower fan, saving 3500 kWh/yr. Total energy savings came to $17,842/yr.

Preliminary test results for the rebuild, shown in Figure 2, suggest that under most load conditions its efficiency falls between that of the new chiller and the original CFC-11 configuration. Note, however, that the graph shows only a one-month profile under varying field conditions, and thus no definitive comparison can yet be made.

Additional System Benefits

During extremely hot weather, the original chiller plant had been unable to operate at the desired setpoints because the hotel's 485-ton cooling tower was slightly undersized. The new chiller reduced the cooling tower load about 12%, enabling the plant to better meet building loads. What's more, this load reduction led to annual water savings of 374,000 gallons, worth $573. Corresponding water treatment savings came to $380/yr. Insofar as it outperforms the original CFC-11 configuration, the rebuilt chiller will offer similar benefits.



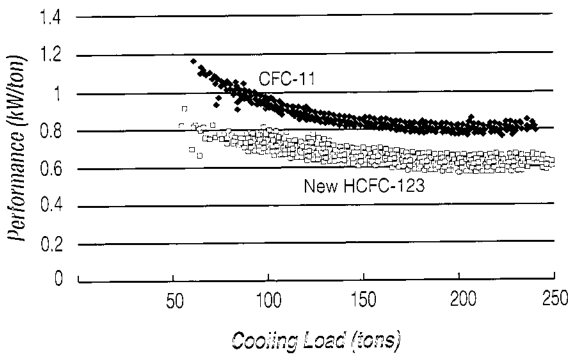


Figure 1. Performance of New vs. Baseline Chiller

Good Payback

The installed cost of the new chiller was $114,300. Annual operating savings—through decreased demand, energy use, and water use—total $18,800, yielding a simple payback of 6.1 years. The $14,000 incremental cost of purchasing this high-efficiency, non-CFC chiller (compared to a standard chiller meeting ASHRAE Standard 90.1i) was paid back in only 9 months.

Modifying the existing chiller to operate on HCFC-123 cost $50,800—less than half the price of replacement. Because all the major components were rebuilt or replaced, the reegineered chiller is expected to achieve nearly the same life as the new unit. Payback on the rebuild will be calculated after monitoring is completed in late 1995.

NO_X = 373 lb/yr
SO_X = 267 lb/yr
CO_2 = 280,000 lb/yr
PM_{10} = 11.5 lb/yr

*Figure 3. Emission Reductions Due to New Chiller**

* From SCE report, *Estimates of Marginal Emission Rates and Factors 1993-2003.* Estimates assume 1.62 lb/MWh NO_X; 1.16 lb/MWh SO_X; 1213 lb/MWh CO_2; 0.05 lb/MWh PM_{10}.

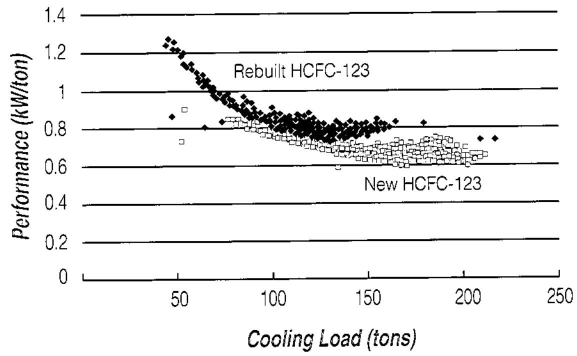


Figure 2. Performance of New vs. Rebuilt Chiller

Reduced Emissions

Both the new and rebuilt chillers benefit the environment, as HCFC-123 has only 2% of the ozone depletion potential of CFC-11. And the increased efficiency results in air pollutant reductions proportional to the energy savings. Expected emissions reductions for the new unit, based on SCE's generation mix, are shown in Figure 3.

To Rebuild or Replace?

This project is providing important insights into whether it is more cost-effective to run, rebuild, or replace a CFC chiller. The final report, due in mid-1996, will compare the original CFC-11 chiller and the new and rebuilt units in terms of kW/ton profiles and total life-cycle costs. Results will be reported in a future Commercial Cooling Update.

Reference

This case study was originally published as an EPRI Commercial Cooling Update Case Study (SU-105401).

New CFC-Free Chillers Offer Two-Year Payback

Summary

By replacing two 300-ton centrifugal chillers with one 290-ton screw non-CFC chiller, the JCPenney Store at El Con Mall in Tuscon is saving about 70,000 kWh—or $3,750–$5,000 each month during the cooling season. At a total installed cost of $94,000, the chiller will pay for itself in less than two years. This upgrade is just one in a series of chiller replacements completed or planned by the JCPenney Company, Inc.

Corporate Chiller Replacements

As part of its environmental commitment, JCPenney is implementing a very aggressive energy management program in some 1,300 stores nationwide. Typical projects include lighting upgrades that cut lighting system energy use almost in half while greatly reducing cooling loads on the chillers. As appropriate, stores have also added adjustable speed drives to pumps and air handlers to modulate motor speed with cooling load; rebuilt cooling towers to deliver colder condenser water to the chiller; and upgraded building controls to reduce energy use.

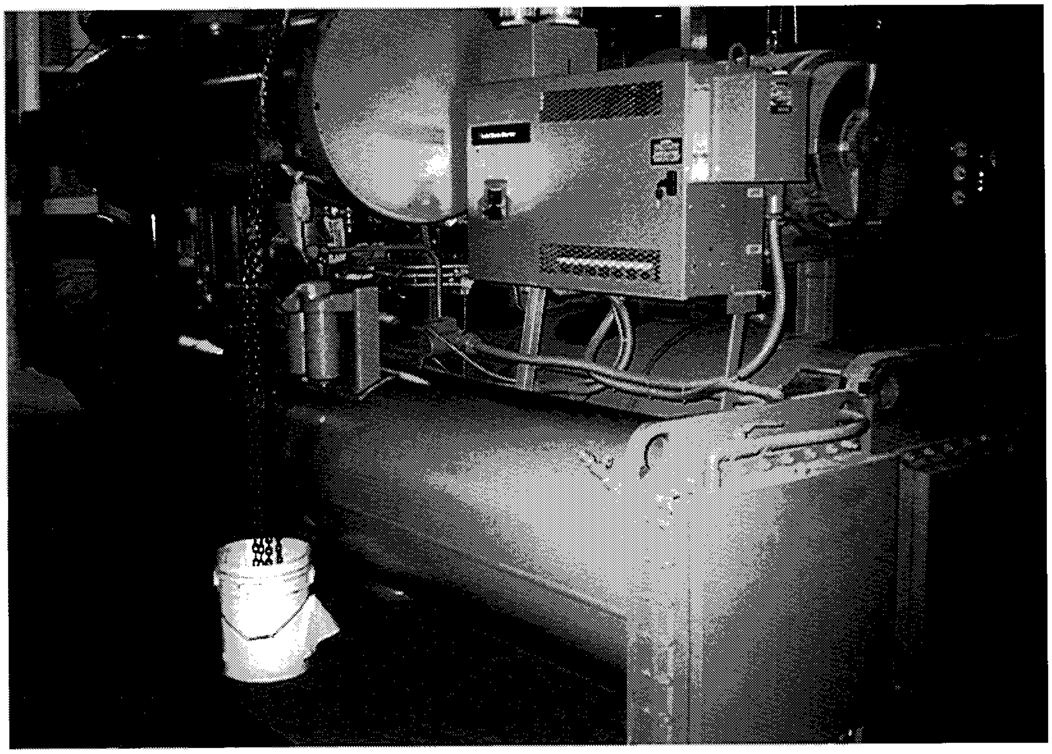
Another significant corporate project is to upgrade chillers to increase efficiency, reduce energy costs, and eliminate CFCs. Most stores today use two 150–300 ton CFC-11 chillers that are more than 20 years old and ready for replacement. Because lighting upgrades have reduced chiller loads, sites are finding that only one new chiller is needed. In the search for non-CFC replacements, two sites installed gas-fired engine-driven chillers. But higher-than-expected maintenance costs forced the company to eliminate gas options from consideration.

Corporate strategy now calls for replacing one chiller at each store with a new HCFC-22 or HFC-134a unit. A number of stores have already completed the upgrade and are reporting simple payback of two years or less. When all sites have installed a new chiller, the second chiller will be upgraded to run on a non-CFC refrigerant and be used for backup service as needed.

El Con Mall Project

The experience of the JCPenney store at El Con Mall in Tuscon is typical of findings from around the country. In

JCPenney store at El Con Mall.



"The new chiller works great. The project started saving money right off the bat, reducing our bills at least $5,000 a month during the cooling season."

David Lempke, Regional Maintenance Manager, JCPenney Company

step with the corporate strategy, this site upgraded the lighting system, saving about 70 kW. In addition, the store replaced a 300-ton 0.95 kW/ton centrifugal CFC-11 chiller that had been installed in 1971 with a new 290-ton 0.638 kW/ton screw chiller that uses HCFC-22. The HCFC chiller itself cost $63,000, and installation and engineering brought the total installed cost to $94,000.

Energy Impacts

Savings resulting from these upgrades have been exceptional. The store has noted total energy savings of about 100,000 kWh/month during the cooling season, equal to $5,000–$7,000/month. Total savings in just the first four months of chiller operation equaled $27,066. The chiller is credited with about three-fourths of the savings, allowing project payback in less than two years. Other advantages of the new chiller include reduced maintenance costs, less refrigerant leakage, and lower refrigerant costs.

Environmental Impacts

Offering higher efficiency, the new chiller also reduces emissions associated with electricity generation. Using data from Tuscon Electric for coal-fired power plants, the new chiller should allow the annual emission reductions shown in Figure 1.

Reference

This case study was originally published as an EPRI Commercial Cooling Update Case Study (SU-105401).

NO_X = 2,900 lb/yr
SO_2 = 3,500 lb/yr
CO_2 = 1,211,500 lb/yr

Figure 1. Emission Reductions Due to New Chiller

7

Chiller Economics

The previous chapters discussed issues involved in selecting and optimizing chillers for commercial buildings. One key step in selecting and optimizing a chiller is to perform an economic analysis. This section provides an example of a chiller screening analysis using the COMTECH™ screening tool. The analysis compares four chiller types:

- Standard-Efficiency Electric
- High-Efficiency Electric
- Direct-Fired, Double-Effect Absorption
- Gas Engine-Driven

The four chiller types are examined in two size ranges: small (120–230 tons) and large (740–900 tons) [1]. The performance of the small chillers was modeled as a function of four building types and

Table 7.1 Building and Chiller Sizes

Building Type	Building Size (ft^2)	Chiller Size (Tons) Los Angeles*	Chicago	Atlanta
Small Buildings				
Office	99,225	180	230	230
Retail	100,000	130	170	170
Health	76,000	140	150	140
Education	99,900	120	210	200
Large Buildings				
Office*	396,900	810	900	880
Health*	475,200	740	710	780
Education*	299,700	780	900	850

*The large building sizes for Los Angles are

Office	496,125
Health	554,400
Education	399,600

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[1] For this report, "small" refers to chillers near 200 tons (120–230 tons actually analyzed) and buildings around 100,000 ft^2 (76,000 - 100,000 ft^2 actually analyzed). "Large" refers to chillers near 800 tons (740-900 tons actually analyzed) and buildings around 400,000 ft^2 (299,700–554,400 ft^2 actually analyzed).

three cities. The large chiller performance was examined as a function of three building types and three cities (see Table 7-1).

7.1 METHODOLOGY

COMTECH is an interactive screening tool for evaluating the cost impacts of a variety of energy technologies in commercial buildings. A few space conditioning technologies include

- Electric Cooling Systems
- Heat-Recovery Cooling
- Gas Cooling
- Cogeneration
- Heat Pumps

COMTECH serves as a first-level screening tool to develop and customize information for specific applications. COMTECH can be used to compare the impact of different chillers in a variety of situations.

The approach for this analysis can be explained by looking at the input requirements for COMTECH as illustrated in Figure 7-1. The input can be divided into four categories:

- Building Energy-Use Patterns
- Energy Rates
- System Performance Parameters
- System Costs

The building energy-use patterns must be developed using a building load modeling program. For the analysis in this chapter, the COMTECH prototype building library was utilized. The end-use load shapes for the buildings in the prototype library were previously generated using EPRI's micro-AXCESS program (version 10.2). The micro-AXCESS results are translated into a 48-day format (4 days per month, 12 months per year). The four days represent typical, hot, cold, and nonwork (weekend) days. For each day, energy requirements for six end-uses (cooling, heating, domestic water heating, lighting, ventilation, and miscellaneous) are recorded. These data are then utilized by COMTECH to model system energy use and cost.

COMTECH offers a flexible and comprehensive energy rate structure framework. This allows the modeling of

- Time-of-use rates
- Fixed block rates
- Load-factor block rates
- Tiered rates with dynamic block range
- Seasonal rates
- Transmission charges
- Cogen discounts
- Ratchets

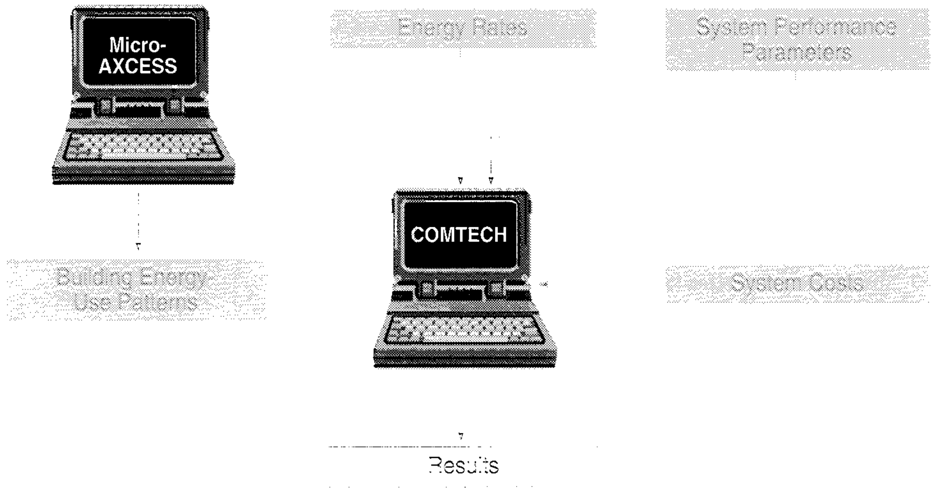

Figure 7-1. COMTECH Input Parameters

The chiller performance parameters include efficiency, cost, and sizing. The full-load efficiencies as well as the part-load performance curves can be specified. Capital and maintenance cost as well as the chiller size can be specified by the user.

The COMTECH approach focuses on chiller parameters and utility rate structures while utilizing predetermined building load data.

7.2 PARAMETERS

The input parameters for this analysis were developed from a variety of printed sources and manufacturer contacts. This section summarizes these parameters and how they were derived, or from which references they were obtained. The goal was to model representative chillers in each of the categories. No attempt was made to optimize each chilled-water system, as many optimization parameters are situation-dependent.

7.2.1 BUILDING ENERGY-USE PATTERNS

As previously mentioned, the buildings modeled in the present analysis were chosen from an available COMTECH default library. Table 7-1 summarizes the building sizes and the selected chiller sizes. These buildings represent a cross-section of commercial building types, each with unique load requirements. Chillers were oversized by 10% and rounded to the nearest 10 tons.

As Table 7-1 indicates, the required chiller size range for the small buildings is 120 to 230 tons. This size range is at the lower end for electric centrifugal chillers analyzed in this study. Gas engine chillers with centrifugal compressors are not widely available in this size range. Therefore, this analysis is based on engine-driven screw machines.

For the large buildings, the chillers range from 740 to 900 tons. The retail

Table 7-2: Chicago Electric Rate
Utility: Commonwealth Edison

Rate 6, General Service, Time of Day
Customer Charge (per month): $39.93

Energy Charge (per kWh)	Summer	Winter
On-Peak	$0.05749	$0.05749
Off-Peak	$0.02491	$0.02491
Demand Charge (per kW)	$14.24	$11.13

Rate 6L, Large General Service, Time of Day
Customer Charge (per month): $246.39

Energy Charge (per kWh)	Summer	Winter
On-Peak	$0.05172	$0.05172
Off-Peak	$0.02273	$0.02273
Demand Charge (per kW)	$16.41	$12.85

Summer: June-September
Winter: October-May
Demand Peak: 9:00 a.m. to 6:00 p.m., M-F, except holidays
Energy Peak: 9:00 a.m. to 10:00 p.m., M-F, except holidays

Table 7-3: Chicago Gas Rate
Utility: Northern Illinois Gas Company

Rate 4, General Service
Customer Charge (per month): $11.50

	Summer	Winter
Gas Supply Cost (per therm)	$0.2277	$0.2841
Distribution Charge (per therm)		
First 150 therms	$0.1297	$0.1297
Next 4850 therms	$0.0721	$0.0721
Over 5000 therms	$0.0464	$0.0464
Total Energy Cost (per therm)		
First 150 therms	$0.3574	$0.4138
Next 4850 therms	$0.2998	$0.3562
Over 5000 therms	$0.2741	$0.3305

Rate 4, General Service with Rider 9
(Gas Engine-Driven and Gas Absorption Air Conditioning)
Customer Charge (per month): $11.50

	Summer	Winter
Gas Supply Cost (per therm) *	$0.2277	$0.2841
Distribution Charge (per therm)		
First 150 therms	$0.1297	$0.1297
Next 4850 therms	$0.0250	$0.0721
Over 5000 therms	$0.0250	$0.0464
Total Energy Cost (per therm)		
First 150 therms	$0.3574	$0.4138
Next 4850 therms	$0.2527	$0.3562
Over 5000 therms	$0.2527	$0.3305

Rider 9 only applies to the gas cooling system energy use and therefore must be metered separately.

Summer: June–November
Winter: December–May

* Gas Supply Cost varies monthly. January 1995 and July 1995 costs used.

facility was not modeled in the large building class because single retail buildings of this size are uncommon, and are usually cooled by multiple chillers. Note that building sizes for Los Angeles were selected to be slightly larger than for the other two cities in order to achieve the desired cooling demand.

All buildings were assumed to be heated by a gas boiler. Hot water was assumed to be supplied by a gas water heater. These system specifications

**Table 7-4. Los Angeles Electric Rate
Utility: Southern California Edison**

Rate TOU-GS, Time of Use, General Service
Customer Charge: $72.05

Energy Charge (per kWh)	Summer	Winter
On-Peak	$0.15383	$0.080520
Mid-Peak	$0.06812	$0.00
Off-Peak	$0.04388	$0.043880
Demand Charge (per kW)		
All, Non-Time Related	$6.30	$6.30
On-Peak	$15.60	$0.00
Mid-Peak	$2.35	$0.00
Off-Peak	$0.00	$0.00

Rate TOU-8, Time of Use
Customer Charge: $387.20

Energy Charge (per kWh)	Summer	Winter
On-Peak	$0.13784	—
Mid-Peak	$0.06503	$0.07719
Off-Peak	$0.04107	$0.04369
Demand Charge (per kW)		
All, Non-Time Related	$3.65	$3.65
On-Peak	$15.80	—
Mid-Peak	$2.50	$0.00
Off-Peak	$0.00	$0.00

Demand Rachet: 50% of maximum yearly demand or actual, whichever is greater

Summer: June–September
Winter: October–May

On-Peak: Noon to 6:00 p.m., summer, weekdays, except holidays
Mid-Peak: 8:00 a.m. to Noon and 6:00 p.m. to 11:00 p.m., summer, weekdays, except holidays
Off-Peak: All other hours

Table 7-5. Los Angeles Gas Rate
Utility: Southern California Gas Company

Rate GN-10, General Service
Cust. Charge (per meter per day): $0.493

Energy Charge (per therm)	Summer	Winter
First 100 therms	$0.8139	—
First 250 therms	—	$0.8139
Over 100 therms	$0.6087	—
Over 250 therms	—	$0.6087

RATE G-AC, Gas Cooling Rate
(Absorption Chillers only)
Customer Charge (per month): $150.00

Energy Charge (per therm)	Summer	Winter
Gas Cooling, all	$0.37299	$0.37299

Summer: December–March
Winter: April–November

remained the same within a given building type. Other end-uses, such as ventilation and lighting, were also specified. More details regarding these parameters are contained in Appendix C (bound separate from this report).

7.2.2 ENERGY RATES

The three locations chosen for conducting the analyses were Chicago, Los Angeles, and Atlanta. Chicago represents a climate with cold winters and hot, humid summers. Los Angeles represents a climate with hot summers and mild winters, but low relative humidity. Atlanta has a climate with mild winters and hot, humid summers. A typical year weather file was utilized by micro-AXCESS to generate the building load information for each city. Weather information is also used by COMTECH to modify equipment performance. The electric and gas utilities in each city were contacted for the current energy rates. All rates were effective as of August 1995.

Chicago, IL

Electric service to the Chicago area is supplied by Commonwealth Edison, while the gas service is provided by Northern Illinois Gas. Table 7-2 summarizes the 1995 rates for Commonwealth Edison. Rate 6 is effective for small buildings, while Rate 6L is the rate for large buildings. Both rate schedules have seasonal variation with a peak period.

The Northern Illinois Gas rates are shown in Table 7-3. Northern Illinois Gas provides special rates for gas cooling clients (Rider 9). This rider applies to both gas absorption and engine-driven chillers. The special rate only applies to the energy used by the gas cooling system, so it must be separately metered. The gas supply cost actually varies by month and year. The value chosen to represent winter is the rate from January 1995, while the value chosen to represent the summer months is the rate from July 1995.

Table 7-6: Atlanta Electric Rate
Utility: Georgia Power

Rate PLM
Customer Charge: $16.75

Energy Charge (per kWh)	*Summer*	*Winter*
First 200 hours of billing demand *	$0.0868	$0.0868
200-400 hours of billing demand	$0.0111	$0.0111
400-600 hours of billing demand	$0.00836	$0.00836
Over 600 hours of billing demand	$0.00732	$0.00732
Demand Charge (per kW)		
All	$8.00	$8.00

Rate PLL
Customer Charge: $16.75

Energy Charge (per kWh)	*Summer*	*Winter*
First 200 hours of billing demand *	$0.086	$0.086
200-400 hours of billing demand	$0.01138	$0.01138
400-600 hours of billing demand	$0.0.009	$0.0.009
Over 600 hours of billing demand	$0.0065	$0.0065
Demand Charge (per kW)		
All	$8.00	$8.00

Summer: June–September
Winter: October–May

* Weighted average value for this block

Los Angeles, CA

Electricity in the Los Angeles area is supplied by Southern California Edison, while gas service is provided by Southern California Gas. Table 7-4 summarizes the electric rates for Southern California Edison. The TOU-GS rate was used for the small buildings, while the TOU-8 was used for the large buildings. The rate schedules have time-of-use rates, demand charges, seasonal differences, and a demand ratchet.

Table 7-5 summarizes the gas rates provided by Southern California Gas. The GN-10 rate is for core small-commercial and industrial customers. Southern California Gas provides a favorable gas rate (schedule G-AC) for customers using absorption chillers only. This rate schedule carries a higher customer charge, but a much lower energy rate.

Atlanta, GA

Electricity in Atlanta is supplied by the Georgia Power Company, while gas is supplied by the Atlanta Gas Light Company. Table 7-6 summarizes the Georgia Power electric rate schedules PLM and PLL. PLM is used for the small building class and PLL is used for large buildings. The billing demand is determined to be the greater of 95% of the largest summer month's demand, or 60%

Table 7-7: Atlanta Gas Rate
Utility: Atlanta Gas Light Company

Rate G-11, General Service
Cust. Charge (per month): $14.80

Energy Charge (per therm)	*Summer*	*Winter*
First 100 therms	$0.536	$0.536
Next 900 therms	$0.497	$0.497
Over 1000 therms	$0.487	$0.487

Rate G-11, Gas Air Conditioning
(Absorption and Engine-Driven Chillers)

Energy Charge (per therm)	*Summer*	*Winter*
First 50 therms	$0.536	—
Over 50 therms	$0.42	—

Summer: May–September
Winter: October–April

Table 7-8: Chillers Selected for Analysis

SMALL CHILLERS (120–230 tons)

Chiller	*Full-Load Efficiency*
Electric Centrifugal (Standard Efficiency)	0.71 kW/ton
Electric Centrifugal (High Efficiency)	0.60 kW/ton
Gas Engine Drive (Screw)	1.5 COP
Absorption (Direct-Fired, Double-Effect)	1.0 COP

LARGE CHILLERS (710–900 tons)

Chiller	*Full-Load Efficiency*
Electric Centrifugal (Standard Efficiency)	0.66 kW/ton
Electric Centrifugal (High Efficiency)	0.58 kW/ton
Gas Engine Drive (Screw)	1.6 COP
Absorption (Direct-Fired, Double-Effect)	1.0 COP

of the largest winter month's demand. The PLM and PLL rates are further divided into blocks according to the hours-of-use of demand. To determine the appropriate rate to be applied, the hours-of-use of billing demand is first calculated using the power (kW) and energy (kWh) data generated by COMTECH. It should be noted that the 0–200 -hour block is further divided into a number of blocks based on energy (kWh) consumption. To accommodate

Table 7-9: Electric Centrifugal Chiller Efficiencies

SMALL CHILLERS (120–230 tons)

Manufacturer	*Model*	*Capacity (tons)*	*Full-Load Efficiency (kW/ton)*	
			Standard	*High*
Carrier	23XL	160-350	0.66	0.61
Carrier	19XL	200-600	0.68	0.60
McQuay	PEH-076/079	280-350	0.70	0.58
McQuay	PFH-048/050	170-280	0.75	0.68
McQuay	PEH-063	170-280	0.70	0.58
Trane	CVHE-320	250	0.81	0.56
York	YS	200-300	0.67	0.62
York	YT	200-800	0.69	0.60
	Average		*0.71*	*0.60*

LARGE CHILLERS (710–900 tons)

Manufacturer	*Model*	*Capacity (tons)*	*Full-Load Efficiency (kW/ton)*	
			Standard	*High*
Carrier	19EF	500-1000	0.64	0.6
Carrier	19EX	800-2300	0.63	0.58
Carrier	17EX	800-2300	0.59	0.54
McQuay	PEH-126	700	0.7	0.59
Trane	CVHF910	800	0.68	0.51
Trane	CVHF910	700	0.67	0.53
York	YT	700	0.68	0.58
York	YT	800	0.68	0.59
York	YK (HFC-134a)	800	0.68	0.61
York	YK (HFC-134a)	700	0.68	0.6
York	YK (HFCF-22)	800	0.68	0.62
York	YK (HCFC-22)	700	0.68	0.63
	Average		*0.66*	*0.58*

COMTECH's input requirements, a weighted average value for the energy rate ($/kWh) was used for this block.

Table 7-7 summarizes the Atlanta Gas Light rates. Rate GS-11 includes a gas cooling rate for absorption and engine-driven chillers. The gas cooling rate applies on consumption greater that 50 therms per month.

7.2.3 SYSTEM PERFORMANCE PARAMETERS

Two electric and two natural-gas-fired chillers of each size (small and large) were selected for this analysis (see Table 7-8). Efficiencies of the chillers were selected based on mid-range equipment in each category. The electric chiller efficiencies for the small buildings were selected based on an average efficiency of eight different chiller models in the 150- to 300-ton range (Table 7-9). The large chiller efficiencies were selected based on an average of 12 chiller models in the 700- to 800-ton range. The conventional electric chillers (0.71 kW/ton, small; 0.66 kW/ton, large) represent standard-efficiency models currently available. These standard-efficiency models were selected as the "conventional" electric chillers against which the others were compared.

Efficiencies of the high-efficiency models range from 0.56 kW/ton to 0.68 kW/ton in the small size range, while the standard-efficiency models range from 0.66 kW/ton to 0.81 kW/ton. The larger chillers are slightly more efficient (see Table 7-9). Based on this information and contacts with manufacturers, 0.60 kW/ton was selected to represent the high-efficiency chiller for the small-sized buildings, while 0.58 kW/ton was selected to represent the high-efficiency chiller for the large buildings.

The gas-fired chiller efficiencies were selected based on mid-range equipment. For example, the Alturdyne WW-150 (engine-driven screw) has a full-load COP of 1.52. Also, GASAIR has larger engine-driven screw chillers available with a full-load COP of 1.6 (see also Table 4-3). A screw compressor was selected for the gas engine chiller because centrifugal compressors are not widely available for the small size range.

Direct-fired, double-effect absorption chillers have full-load COPs in the range of 0.95 to 1.04. For example, the McQuay DC-11U (double-effect absorption) has a COP of 1.0 (AGA 1994, Table 4-3). A full-load COP of 1.0 was used for all absorption chillers.

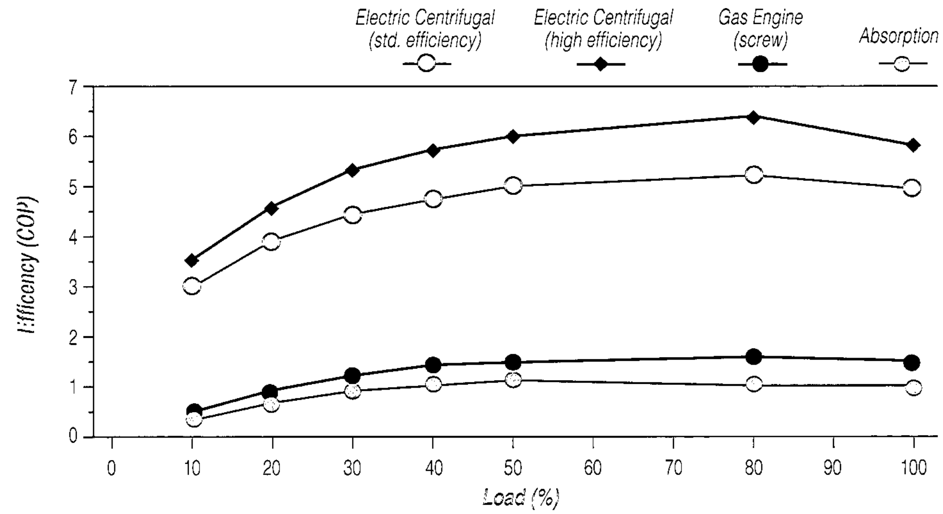

Figure 7-2. Part-Load Performance

Part-Load Performance

The performance of most chillers varies with load. Figure 7-2 shows the part-load performance (COP) of the four small chillers used in this analysis. The part-load curve for the high-efficiency electric chiller was generated based on input from manufacturers as well as printed sources (EPRI 1993c, E-Source 1995, EPRI 1992b). Once the curve shape was determined, it was scaled based on the full-load performance for both the high-efficiency and standard chillers. Therefore, the curves do not directly correspond to a specific chiller, but are intended to be representative of a generic chiller in that size range. The same curve shapes were also used for the large chillers.

The gas engine-driven screw chiller performance curve was derived based on direct input from AGCC and printed sources (AGCC 1995a, AGCC 1994, EI 1994, EPRI 1992b, EPRI 1993). Again, once the curve shape was determined, it was scaled based on the full-load performance (1.5 COP, small; 1.6 COP, large).

The absorption chiller curve was derived from manufacturer's data. The full-load COP is 1.0, and increases to 1.16 at 50% load. Below 50% load, the performance drops below 1.0. This same curve was used to model both the small and large absorption chillers.

COMTECH requires the efficiencies be entered in the units of kW/ton for the electric chillers and MBtu/ton-h (1.0 MBtu=1000 Btu) for the natural-gas chillers. The conversion factors from COP are as follows:

kW/ton = 3.516/COP

MBtu/ton-h = 12/COP

Auxiliary Power Requirements

All chiller systems include a variety of auxiliary items that use electricity. These items consist primarily of pumps and fans. The auxiliaries and their power requirements used for this analysis are shown in Table 7-10. Most of these values were derived from printed sources (AGCC 1994, AGCC 1995a, EPRI 1993c, E-Source 1995).

The chilled-water pump was assumed to operate at 0.04 kW/ton for all cases. The condenser pump and cooling tower fans for the gas equipment utilize more electricity to reject the additional heat. The power requirements for the cooling tower fan and some accessories vary with chiller load.

Table 7-10: Chiller Auxiliary Power Requirements (kW/ton)

	Electric (std eff)	*Electric (high eff)*	*Absorption*	*Engine*
Chilled-Water Pump	0.04	0.04	0.04	0.04
Condenser-Water Pump	0.04	0.04	0.06	0.05
Cooling Tower Fans (var.)	0.05	0.05	0.08	0.06
Accessories*	0.00	0.00	0.04	0.00
Total	0.13	0.13	0.22	0.15
Total Constant	0.08	0.08	0.14	0.09
Total Variable	0.05	0.05	0.08	0.06

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*Accessories include combustion air fan (0.01 kW/ton variable), induced-draft fan, and solution pumps.

7.2.4 CHILLER COSTS

Chiller Installed Cost

Installed costs for the chiller plants were based on quotes from manufacturers and published sources (EPRI 1993c, E-Source 1995, Means 1994, and EI 1994). The small chillers for this analysis range between 120 and 230 tons. The cost ($/ton) for this size range was assumed to increase linearly as the equipment size decreased. The large chiller costs were also assumed to decrease linearly between 740 and 900 tons. Table 7-11 summarizes the installed costs used for this analysis. Refer to Section 5.5 of this *Handbook* for more information.

Installed costs can vary significantly depending on the specific situation. Manufacturers generally offer a variety of options for a given chiller that can significantly affect the cost.

Chiller Maintenance Cost

Maintenance costs used for this analysis were selected based on several references (EPRI 1993c, EI 1994, AGCC 1994, and manufacturers). Maintenance costs can vary significantly by geographic region based on the local labor rates. However, it was assumed that the differences among chiller types and sizes would be the same regardless of location. Table 7-12 shows the per-ton maintenance costs chosen for this analysis.

The maintenance on both of the electric models is the same because the chillers operate in the same manner. Maintenance cost values for absorption chillers vary significantly by source, but fall roughly in the same range as electric chillers, therefore the electric centrifugal and absorption chiller maintenance costs are assumed to be equal.

Table 7-11. Chiller Installed Costs Used for COMTECH Analysis

SMALL CHILLERS (120–230 tons)

Size (tons)	*Electric Centrif. (Standard Eff.) Cost ($/ton)*	*Electric Centrif. (High Eff.) Cost ($/ton)*	*Gas Engine (Screw) Cost ($/ton)*	*Absorption (D-F, Double Eff.) Cost ($/ton)*
130	702	756	1102	994
170	676	728	1061	957
180	670	721	1051	948
190	663	714	1041	938
210	650	700	1020	920
230	637	686	1000	902

LARGE CHILLERS (740–900 tons)

Size (tons)	*Electric Centrif. (Standard Eff.) Cost ($/ton)*	*Electric Centrif. (High Eff.) Cost ($/ton)*	*Gas Engine (Screw) Cost ($/ton)*	*Absorption (D-F, Double Eff.) Cost ($/ton)*
740	482	523	779	819
780	473	512	763	803
810	466	504	752	791
850	456	494	737	775
900	444	481	718	755

Table 7-12. Chiller Maintenance Costs

Chiller	Chiller Maintenance Cost ($/ton/yr)	
	Small (120–230 tons)	Large (740–900 tons)
Electric Centrifugal (Standard Efficiency)	25	18
Electric Centrifugal (High Efficiency)	25	18
Gas Engine (Screw)	85	59
Absorption (Direct-Fired, Double-Effect)	25	18

Maintenance costs for the gas engine chiller were estimated based on maintenance contract quotes from manufacturers and literature sources. In all cases, the gas engine chiller maintenance cost is roughly three times that of the electric chiller. The difference lies in the cost to maintain the engine. Maintenance costs for engines are usually considered in terms of dollars per operating hour. For example, one manufacturer quoted a cost of $4.40 per operating hour for a 200-ton engine-driven chiller. At 4000 hours per year, this results in an annual cost of $17,600, or $88/ton.

The other aspect of maintenance cost is the water use. In all cases, the water cost was assumed to be $4.00/1000 gallons, which is the COMTECH default. The water usage in gallons/hour (gph)/ton was assumed to be 3.0, 3.3, and 4.6 for electric, engine, and absorption, respectively. The increases represent the increased heat dissipation required for the gas-fired equipment. These values were also derived from manufacturer's data and printed sources.

7.3 RESULTS

COMTECH, like other computer energy analysis programs, produces a significant amount of data, ranging from detailed monthly (or even hourly) information to general annual summaries. In this section, general results for all scenarios are first compared, followed by a more-detailed discussion of selected scenarios that highlight the competitive position of electric and gas chillers.

There are several factors the reader should consider when reviewing the results

- All chillers represent mid-range efficiency units for each category (see Table 7-8). No attempt was made to optimize the chilled water systems. Greater savings are anticipated with an optimized arrangement.
- The gas utilities in all cities (Chicago, Los Angeles, and Atlanta) selected for this analysis offer attractive energy rates for gas cooling systems. Energy savings for gas chillers in other locations will vary depending on local utility rates (both electric and gas) and any incentives that may be offered. No installation incentives for gas chillers were included in the analysis.
- Most buildings in this analysis would benefit by having multiple chillers with staging to improve overall energy performance. However, the purpose of this screening analysis was to compare four individual chillers under the same conditions, and multiple chillers were therefore not examined.

General Overview

The results for all scenarios are summarized in Tables 7-13 to 7-18. The tables include selected annual results from the COMTECH runs. The first two columns indicate the building and chiller types. The next two columns show the maximum load and capacity of the chillers (chillers were oversized by approximately 10%). The energy cost ($/year) is the annual cost of both electricity and natural gas for the entire building (including lighting, HVAC systems, hot water heating, and all other loads). The maintenance cost column includes physical maintenance of the energy systems (primarily the chiller) as well as the cost for water. The installed cost is the cost of the chiller including labor, pumps, piping, and the cooling tower. The total savings ($/year) column is the amount of energy savings minus the incremental maintenance cost relative to the conventional electric chiller. The payback column is the simple payback (years) of the chiller compared to the conventional electric chiller.

The results indicate that the high-efficiency electric chillers had the shortest payback in all cases. For the 21 scenarios analyzed, the average high-efficiency chiller payback was 2.8 years. The paybacks varied from 1.4 years (small chiller, Los Angeles, hospital) to 6.0 years (small chiller, Chicago, school). The gas-engine chillers only had a positive payback in 11 of the 21 cases examined. The lowest payback for engine-driven technologies was computed at 7.6 years (large chiller, Atlanta, office and school) and increased to having no payback (additional costs over standard electric chillers) in many cases. The absorption chillers had positive paybacks in 16 of the 21 cases, ranging from lowest value of 9.4 years (large chiller, Atlanta, school) to the highest of

Table 7-13. Small Chiller Results—Chicago

Building Type	Chiller	Peak Load (tons)	Chiller Size (tons)	Energy Cost [1] ($/yr)	Annual Maint.[2] ($/yr)	Installed Cost ($)	Total Energy Savings ($/yr)	Simple Payback[3] (years)
Office	Conv. Electric	210	230	148,946	11,026	164,880	——	——
	High-Eff. Electric	210	230	145,899	11,026	176,150	3,047	3.7
	Gas Engine	210	230	136,499	25,154	225,830	(1,681)	none
	Absorption	210	230	142,317	12,772	248,370	4,883	17.1
Retail	Conv. Electric	150	170	153,094	9,694	130,980	——	——
	High-Eff. Electric	150	170	150,298	9,694	139,820	2,796	3.2
	Gas Engine	150	170	143,615	20,264	178,750	(1,091)	none
	Absorption	150	170	149,741	11,664	196,430	1,383	47.3
Hospital	Conv. Electric	140	150	138,354	8,236	113,250	——	——
	High-Eff. Electric	140	150	136,107	8,236	121,350	2,247	3.6
	Gas Engine	140	150	130,412	17,576	156,225	(1,398)	none
	Absorption	140	150	135,265	10,052	172,125	1,273	46.2
School	Conv. Electric	190	210	174,213	12,383	192,270	——	——
	High-Eff. Electric	190	210	172,470	12,383	202,770	1,743	6.0
	Gas Engine	190	210	165,790	25,088	248,970	(4,282)	none
	Absorption	190	210	168,668	12,943	269,970	4,985	15.6

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1 Annual cost of both electricity and gas for the entire building.

2 Annual maintenance cost includes water use.

3 Equipment incentives not included in payback calculation.

345 years to having no payback in five of the cases studied.

Selected Scenarios—Small Chillers

Each of the four small buildings have unique demand requirements. The office and retail buildings have relatively regular daily schedules throughout the year. The hospital is occupied around the clock and has a much higher demand per unit of floor space for space heating, water heating, and space cooling. Schools have a unique cooling load requirement because their use is typically limited during summer months when cooling demand is typically the highest.

The office building is a common chiller application. Figure 7-3 shows the monthly electric energy use of the small office building in Chicago with the conventional electric chiller. The chiller in this scenario is estimated to operate 4655 hours during the year (1410 EFLH). The chiller is not expected to operate in January or February, thus these months approximate the monthly base electric load (97 - 112 MWh). As expected, the electric use is highest in the summer months when the cooling load is the greatest.

A further breakdown of the annual energy costs for the small office buildings in Chicago, Los Angeles, and Atlanta is shown in Figure 7-4. The energy cost is the total annual cost of electricity and natural gas for the building. Maintenance

Table 7-14. Small Chiller Results—Los Angeles

Building Type	Chiller	Peak Load (tons)	Chiller Size (tons)	Energy Cost [1] ($/yr)	Annual Maint.[2] ($/yr)	Installed Cost ($)	Total Energy Savings ($/yr)	Simple Payback[3] (years)
Office	Conv. Electric	160	180	199,986	9,435	127,640	——	——
	High-Eff. Electric	160	180	195,462	9,435	136,820	4,524	2.0
	Gas Engine	160	180	190,534	20,652	177,680	(1,765)	none
	Absorption	160	180	195,600	11,658	196,220	2,163	31.7
Retail	Conv. Electric	120	130	198,007	8,921	103,910	——	——
	High-Eff. Electric	120	130	194,010	8,921	111,190	3,997	1.8
	Gas Engine	120	130	189,395	17,150	141,870	383	99.1
	Absorption	120	130	193,868	11,209	155,910	1,851	28.1
Hospital	Conv. Electric	130	140	225,405	11,965	103,420	——	——
	High-Eff. Electric	130	140	219,851	11,965	111,120	5,554	1.4
	Gas Engine	130	140	217,304	21,145	143,915	(1,079)	none
	Absorption	130	140	222,613	16,127	158,895	(1,370)	none
School	Conv. Electric	110	120	170,532	7,487	116,910	——	——
	High-Eff. Electric	110	120	168,822	7,487	123,630	1,710	3.9
	Gas Engine	110	120	164,164	14,779	151,950	(924)	none
	Absorption	110	120	167,833	7,979	164,910	2,207	21.7

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1 Annual cost of both electricity and gas for the entire building.

2 Annual maintenance cost includes water use.

3 Equipment incentives not included in payback calculation.

Table 7-15: Small Chiller Results—Atlanta

Building Type	Chiller	Peak Load (tons)	Chiller Size (tons)	Energy Cost [1] ($/yr)	Annual Maint.[2] ($/yr)	Installed Cost ($)	Total Energy Savings ($/yr)	Simple Payback[3] (years)
Office	Conv. Electric	210	230	184,689	13,011	158,060	—	—
	High-Eff. Electric	210	230	178,309	13,011	169,330	6,380	1.8
	Gas Engine	210	230	164,419	27,411	219,010	5,870	10.4
	Absorption	210	230	176,980	16,212	241,550	4,508	18.5
Retail	Conv. Electric	150	170	165,071	10,628	129,880	—	—
	High-Eff. Electric	150	170	160,269	10,628	138,720	4,802	1.8
	Gas Engine	150	170	152,471	21,303	177,650	1,925	24.8
	Absorption	150	170	162,028	13,160	195,330	511	128.1
Hospital	Conv. Electric	130	140	155,657	9,216	106,060	—	—
	High-Eff. Electric	130	140	151,576	9,216	113,760	4,081	1.9
	Gas Engine	130	140	144,652	18,093	146,555	2,128	19.0
	Absorption	130	140	153,606	11,760	161,535	(493)	none
School	Conv. Electric	180	200	200,843	12,657	176,510	—	—
	High-Eff. Electric	180	200	196,331	12,657	186,610	4,512	2.2
	Gas Engine	180	200	184,369	24,929	231,010	4,202	13.0
	Absorption	180	200	192,005	14,110	251,210	7,385	10.1

1 Annual cost of both electricity and gas for the entire building.

2 Annual maintenance cost includes water use.

3 Equipment incentives not included in payback calculation.

includes the physical maintenance[1] of the equipment as well as cooling tower water costs. The ownership cost is the annualized cost of the capital required to purchase the chiller equipment[2].

The energy cost is the most significant portion of the annual cost for each case. The lowest operating costs are realized with the gas engine and absorption chillers. However, the increased maintenance and ownership costs of these machines make the total annual cost higher than that of the high-efficiency electric chiller.

The payback estimates of the high-efficiency electric, gas engine, and absorption chillers in the small office building are shown in Figure 7-5. The high-efficiency electric chiller has the lowest payback of all chillers in all scenarios. For the small office, the payback values range from 1.8 years in Atlanta to 3.7 years in Chicago. The maintenance costs of the gas engine chillers in Chicago and Los Angeles are higher than the energy savings, resulting in no payback. However, in Atlanta, the savings exceeded the maintenance costs resulting in a 10.4-year

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[1] For engine-driven chillers, maintenance is assumed to cover the cost of engine rebuilds.

[2] Annualized at 10% interest and 20 years of equipment life.

Table 7-16. Large Chiller Results—Chicago

Building Type	Chiller	Peak Load (tons)	Chiller Size (tons)	Energy Cost [1] ($/yr)	Annual Maint.[2] ($/yr)	Installed Cost ($)	Total Energy Savings ($/yr)	Simple Payback[3] (years)
Office	Conv. Electric	820	900	626,841	37,405	469,670	—	—
	High-Eff. Electric	820	900	617,592	37,405	502,970	9,249	3.6
	Gas Engine	820	900	577,668	75,662	716,270	10,916	22.6
	Absorption	820	900	603,463	44,638	749,570	16,145	17.3
Hospital	Conv. Electric	780	860	812,808	42,558	449,276	—	—
	High-Eff. Electric	780	860	802,809	42,558	481,784	9,999	3.3
	Gas Engine	780	860	766,187	79,881	689,732	9,298	25.9
	Absorption	780	860	797,168	53,557	722,240	4,641	58.8
School	Conv. Electric	820	900	538,838	38,388	561,410	—	—
	High-Eff. Electric	820	900	532,838	38,388	594,710	6,000	5.6
	Gas Engine	820	900	500,941	75,742	808,010	543	454.1
	Absorption	820	900	514,277	40,808	841,310	22,141	12.6

Table 7-17. Large Chiller Results—Los Angeles

Building Type	Chiller	Peak Load (tons)	Chiller Size (tons)	Energy Cost [1] ($/yr)	Annual Maint.[2] ($/yr)	Installed Cost ($)	Total Energy Savings ($/yr)	Simple Payback[3] (years)
Office	Conv. Electric	740	810	949,072	49,451	411,016	—	—
	High-Eff. Electric	740	810	931,256	49,451	442,444	17,816	1.8
	Gas Engine	740	810	918,027	85,779	643,162	(5,283)	none
	Absorption	740	810	941,536	66,078	674,590	(9,091)	none
Hospital	Conv. Electric	670	740	1,240,937	54,218	402,880	—	—
	High-Eff. Electric	670	740	1,222,875	54,218	433,220	18,062	1.7
	Gas Engine	670	740	1,214,580	88,144	622,660	(7,569)	none
	Absorption	670	740	1,238,949	73,342	652,260	(17,136)	none
School	Conv. Electric	710	780	738,394	39,915	487,410	—	—
	High-Eff. Electric	710	780	728,265	39,915	517,830	10,129	3.0
	Gas Engine	710	780	712,692	73,190	713,610	(7,573)	none
	Absorption	710	780	730,740	46,822	744,810	747	344.6

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1 Annual cost of both electricity and gas for the entire building.

2 Annual maintenance cost includes water use.

3 Equipment incentives not included in payback calculation.

Table 7-18. Large Chiller Results—Atlanta

Building Type	Chiller	Peak Load (tons)	Chiller Size (tons)	Energy Cost [1] ($/yr)	Annual Maint.[2] ($/yr)	Installed Cost ($)	Total Energy Savings ($/yr)	Simple Payback[3] (years)
Office	Conv. Electric	800	880	737,579	44,867	440,044	——	——
	High-Eff. Electric	800	880	718,828	44,867	472,956	18,751	1.8
	Gas Engine	800	880	666,992	83,358	683,628	32,096	7.6
	Absorption	800	880	714,931	57,725	716,540	9,790	28.2
Hospital	Conv. Electric	710	780	965,534	48,220	419,430	——	——
	High-Eff. Electric	710	780	947,903	48,220	449,850	17,631	1.7
	Gas Engine	710	780	909,285	83,067	645,630	21,402	10.6
	Absorption	710	780	960,695	63,512	676,830	(10,453)	none
School	Conv. Electric	770	850	645,294	41,528	509,810	——	——
	High-Eff. Electric	770	850	630,415	41,528	542,110	14,879	2.2
	Gas Engine	770	850	577,739	77,668	748,660	31,415	7.6
	Absorption	770	850	609,458	48,406	780,960	28,958	9.4

1 Annual cost of both electricity and gas for the entire building.

2 Annual maintenance cost includes water use.

3 Equipment incentives not included in payback calculation.

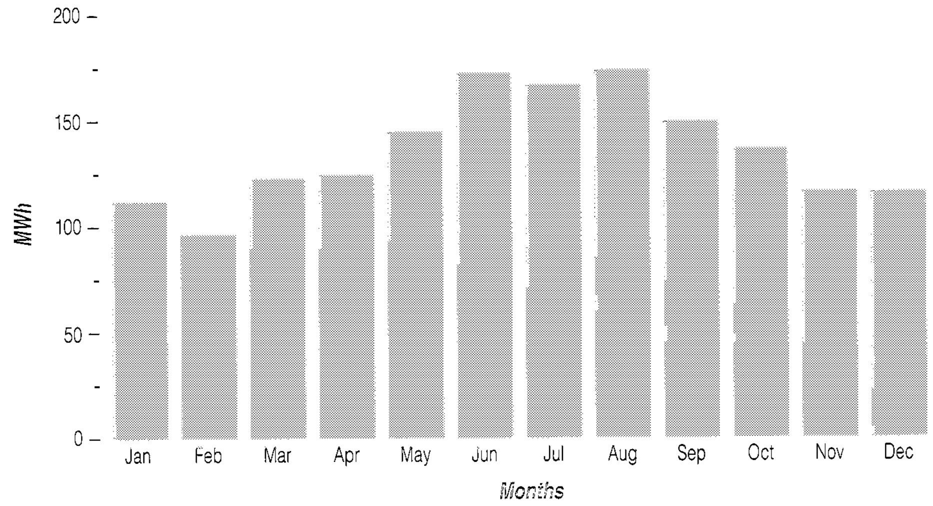

Figure 7-3. Monthly Electric Energy Use—Small Office Building in Chicago

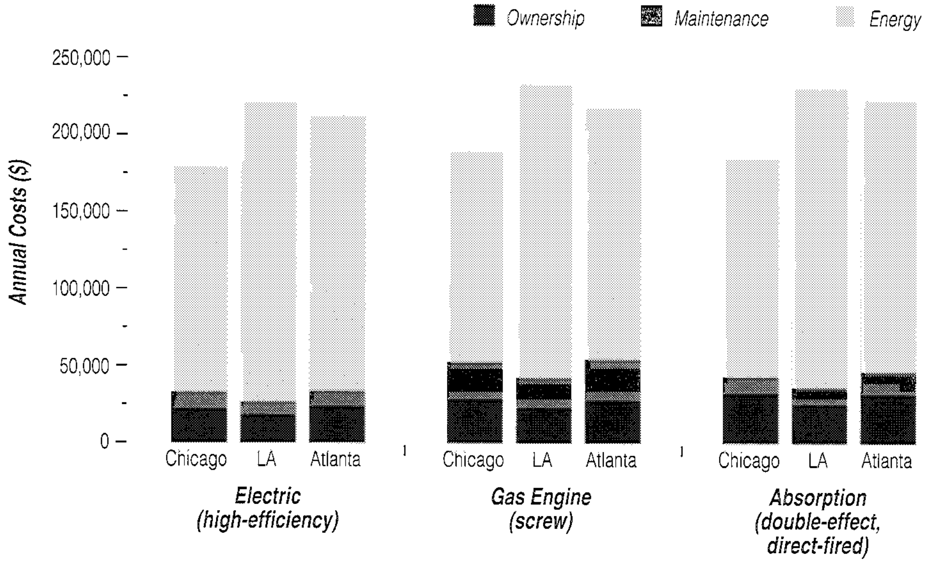

Figure 7-4. Chiller Annual Costs—Small Office Buildings

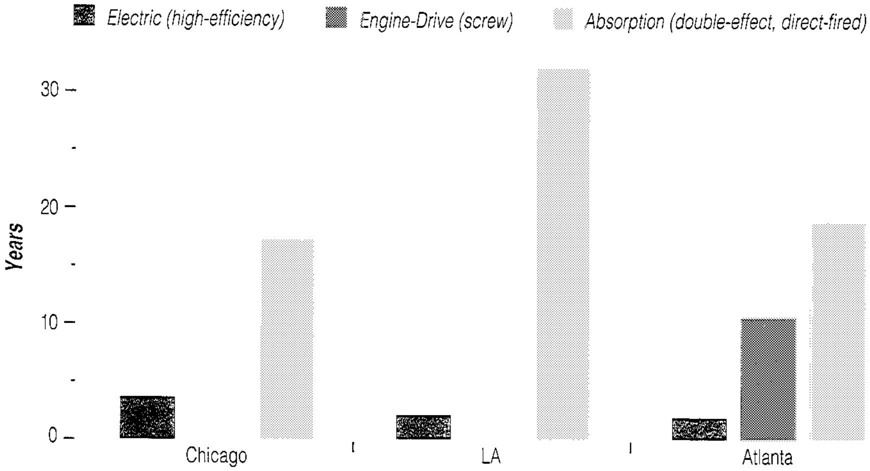

Figure 7-5. Chiller Payback—Small Office Buildings

payback. The absorption chiller payback is the lowest in Chicago (17.1 years) and the highest in Los Angeles (31.7 years).

A breakdown of the payback components of the three chillers in the Atlanta small office building is shown in Figure 7-6. The high incremental installed cost and lower annual savings of the gas chillers results in higher payback periods. It should be noted that if the absorption chiller is utilized for space heating and hot water heating (referred to as a chiller/heater), the cost of the boiler ($9900) and water heater ($1650) could be eliminated. In this situation, the payback for the absorption chiller is reduced to 16.0 years. Even in this situation, the high-efficiency electric chiller produces the lowest payback (1.8 years).

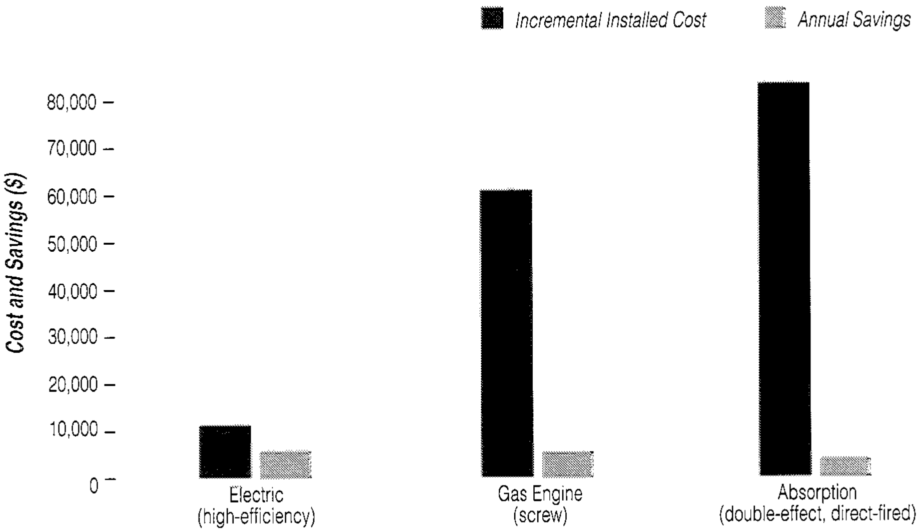

Figure 7-6. Chiller Payback Components—Small Office Building in Atlanta

Selected Scenarios—Large Chillers

Results for the large chillers are summarized in Tables 7-16 to 7-18. In many scenarios, the comparison trends are similar to those of the small chillers. As in the small buildings, the high efficiency electric chiller produced the lowest payback in each scenario. The gas engine chillers generally had lower paybacks in large buildings compared to small buildings. No consistent trends were observed for the payback of the absorption chillers between the two building sizes. One observation is that the paybacks for the large absorption chillers in the office and school in Los Angeles are noticeably higher (actually negative for the office) compared to the small buildings.

A closer look at the monthly energy costs for the Los Angeles large office building reveals some insight as to why the absorption chiller performance was reduced. Figure 7-7 shows the monthly energy cost savings for this scenario. The summer months (June through September) show a clear and significant energy cost savings for the absorption chiller over the conventional electric chiller. However, the other months reveal a cost penalty for using the absorption chiller. In this case, year-round cooling is required. During winter months, cooling is required at a low level, and the chillers provide that cooling at low efficiency. For example, in January the electricity cost savings is $4452 with the absorption chiller, but the gas cost increase is $5928, resulting in a $1476 deficit.

The energy rates also play a significant role in this case. The Southern California Edison electric rate structure includes high summer demand charges, but minimal winter demand charges. This is the primary reason for the significant summer savings by using the absorption chiller.

The high efficiency electric chiller is clearly the best choice for large hospitals. For Chicago the gas engine and absorption chillers show high paybacks of 25.9 and 58.8 years. In Los Angeles, the annual operating costs of the gas-fired chillers are higher than for the conventional electric chiller, so no payback is possible. The Atlanta service territory is more favorable for the gas engine chiller, but still produces no payback for the absorption chiller.

7.4 APPLICATION GUIDELINES

The results in Section 7.3 indicate that high efficiency electric chillers are the

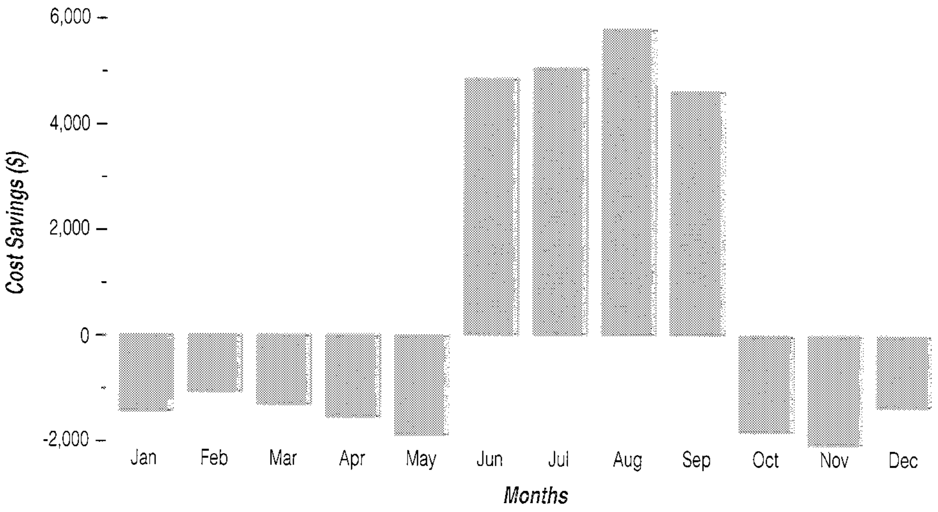

Figure 7-7. Absorption Chiller Energy Cost Savings (Cost Increase)—Large Office Building in Los Angeles

most economical choice for the scenarios examined (includes the Chicago, Los Angeles, and Atlanta service territories). For the scenarios analyzed, the gas chillers are less cost-effective (i.e., longer simple payback) compared to high-efficiency electric chillers. The following observations may be helpful when choosing electric chillers for a specific application

- High-efficiency electric chillers produced the lowest payback in all scenarios. The lowest payback (1.4 years) occurred for the hospital in Los Angeles (Table 7-14).
- High-efficiency electric chillers performed well in both large (around 700 tons) and small (around 200 tons) buildings.
- In all Atlanta scenarios, the payback for the high-efficiency electric chiller was 2.2 years or less.
- Gas engine chillers produced the greatest annual energy savings, but these energy savings were accompanied by high maintenance costs, resulting in lengthy or non-existent paybacks.
- Gas engine chillers generally performed better in the large buildings.
- The payback for absorption chillers was more dependent on service territory and building type than building size.

While this analysis indicates that high-efficiency electric chillers have the lowest payback for the 21 scenarios examined, there are a number of factors that can influence these results and shift conclusions. A few of these factors are listed below:

- Installation incentives may be provided by local gas utilities or manufacturers that were not factored into this analysis. An incentive of $100/ton can significantly improve the economic position of a gas chiller. Favorable natural gas rates are often provided by utilities to customers of absorption or engine-driven chillers. These utilities may also provide significant installation incentives ($20 - $100/ton) for gas-fired chillers. These incentives would significantly reduce the incremental cost and thus the payback would be improved.
- Electric and gas energy costs vary widely across the country and have the greatest impact on chiller operating costs.
- Maintenance costs for engine chillers are significantly higher than the others. However, manufacturers may offer discounted maintenance contracts with the sale of the gas engine chiller which could substantially reduce the paybacks presented here. This study assumes camparable electric and

absorption maintenance costs.

- Heat recovery from gas and electric chillers was not factored into this analysis, and may help reduce costs for both chiller types.
- Absorption chillers are available as absorption chiller/heaters, which can potentially provide both space heating and cooling. In this situation, the capital cost of a gas boiler and water heater would be eliminated, thereby reducing the overall capital cost.
- Hybrid chiller configurations (i.e., a combination of electric and gas chillers in one facility) offer opportunities to further reduce energy costs. High-efficiency electric chillers can be used for base load cooling, while gas chillers can be used to trim peak electrical energy consumption and thus reduce demand charges.
- Thermal energy storage offers peak reduction potential and associated cost savings, particularly for electric chillers.
- High-efficiency condensing systems using oversized cooling towers and evaporative condensors are often cost-effective electric chiller system alternatives.
- Modeling programs other than COMTECH may produce different results than those presented in this study. The selection of the program and the modeling approach can impact the results of any performance comparison.

To illustrate the potential influence of gas system incentives, consider the small office building in Chicago (see Table 7-13). The incremental cost of the 230-ton absorption chiller is $83,490. If a $100/ton incentive is provided, the incremental cost is reduced to $60,490. In addition, if a gas boiler and water heater can be eliminated with a chiller/heater arrangement, the capital cost may be further reduced by perhaps $18,370 (incremental capital now at $42,120). With the same annual savings of $6,629, the payback would be 6.4 years. This value is now more competitive with the high-efficiency electric chiller (3.7 years).

A similar scenario could be made for the gas engine chiller in Atlanta (see Table 7-18). Here the chiller size is 880 tons, and the incremental cost over the conventional electric chiller is $235,584. If a $75/ton incentive is provided, the incremental cost is reduced by $66,000 to $177,584. Also, if the manufacturer provided a service contract costing 40% less than the estimate, the annual savings is increased by $33,343 to $65,439. This results in a 2.7-year payback, which is more competitive with the high-efficiency electric chiller (1.8 years).

7.5 SUMMARY

Electric chillers have historically dominated the space cooling market for commercial buildings. In recent years, a significant issue related to the use of electric chillers has been the availability of refrigerants. The production of chlorofluorocarbon (CFC) refrigerants was banned effective December 31, 1995, and phaseout of hydrochlorofluorocarbon (HCFC) refrigerants will occur in coming years.

Refrigerant and chiller manufacturers have responded quickly to refrigerant curtailments, and non-CFC chillers are presently available. In addition to developing non-CFC technologies, manufacturers have continued to improve the features and efficiency of electric chillers.

In this study, we specifically analyzed high-efficiency electric chillers compared to gas engine and absorption systems. The performance of these chillers was modeled for three cities (Los Angeles, Chicago, and Atlanta), four building types, and two building sizes (small buildings, near 200 tons of load – large buildings, near 700 tons of load). A total of 21 scenarios were examined with these parameters.

High-efficiency chillers had significantly lower simple payback values in all 21 scenarios compared to the gas engine and absorption technologies. The results of the analysis indicate that electric centrifugal chillers are the most economical to own and operate and will make electric chillers the continuing choice for space cooling in commercial buildings.

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Appendix A
Case Studies

CASE STUDY 1

Location:	Washington, DC
Application:	Shiloh Baptist Church Family Life Center.
Approach:	Replace three existing 14-year-old 55-ton air-cooled reciprocating chillers.
Goal:	To reduce annual electric bills through HVAC, lighting, building envelope, and motor system retrofit.
Constraints:	Mandatory participation in lighting retrofit program in order to be eligible for PEPCO's rebate under its Chiller Early Retirement Program.
New Chillers:	Two 45-ton and one 55-ton HCFC-22, air-cooled, reciprocating chillers, rated at 1.1 kW/ton.
Decision Factors:	$118,619 rebate from PEPCO's Custom Rebate Program Projected 16 tons of cooling load reduction due to lighting retrofit. Projected 15 tons of cooling load reduction due to reduction in airflow rate, and precooling strategy employing ambient air under 55°F.
Cost Summary:	No up-front costs for $201,641 project (before rebate). $83,022 of project cost financed with a 10% loan from PEPCO's Commercial Loan Program. 438,939 kWh of consumption trimmed from annual electric bill, as well as a reduction of 89 kW from peak demand. $28,824 trimmed from annual electric bills. 4-year payback period.
Other:	PEPCO's Custom Rebate Program expanded to include the Chiller Early Retirement Program. PEPCO's rebate and loan programs available to all commercial, government, and single-metered multifamily facilities.
Reference:	"Esco Arranges Utility Rebate, Loan to Fund Church's Retrofits," EUN Vol. 19, No. 6, June 1994.

CASE STUDY 2

Location:	Atlanta, GA
Application:	400,000 ft^2, 30-story office building.
Approach:	Rebuild an existing CFC chiller.
Goal:	Rebuild poorly maintained 25-year-old chiller to avoid shutdown, and replace CFC refrigerant.
Constraints:	Chiller plant inconveniently located in penthouse mechanical equipment room.
	Components used in refurbishment had to fit in building's freight elevator.
	Expense too high to install a new system, and a simple overhaul insufficient.
	Critical to ensure no disruptions to building operations during refurbishment.
New Chillers:	Two Trane 750-ton model LX "CentraVac" chillers retrofitted with HCFC-123 compatible compressors, rated at full-load efficiencies of 0.73 kW/ton.
Decision Factors:	Replace existing compressors, rated full-load efficiencies of 0.90 kW/ton, with new compressors rated at 0.73 kW/ton.
	Full-load energy efficiency of system improved by 19%; part-load efficiencies improved as well.
	Control panels installed for optimal chiller plant management; panels tied in to manager's computer.
	Improvements projected to reduce peak demand.
Cost Summary:	Project cost of $650,000.
Other:	Compressor motor panels added for smooth, dependable startup.
Reference:	"Replacement Compressors, Other Changes Solve Problems of Building's Aging Chillers," The Air Conditioning, Heating and Refrigeration News, June 20, 1994.

CASE STUDY 3

Location: San Jose, CA

Application: San Jose Mercury News Building.

Aproach: Replace two 430-ton, CFC-11 centrifugal chillers.

Goal: Install a chiller plant that demonstrated the organization's commitment to environmental and energy savings issues, and establish a leadership position in these arenas.

Constraints: 90-day (Jan–Mar) installation window had to be met in order to qualify for a rebate from PG&E.

Significant expense and complicated logistics associated with asbestos removal.

Significant expense associated with old equipment removal, as well as the demolition and reconstruction of equipment room walls.

New Chillers: Two York International "CodePak" low-energy, HCFC-22, 630-ton electric chillers.

Decision Factors: $93,500 rebate from PG&E.

Cooling system optimized from 0.8 kW/ton to 0.4 kW/ton.

Intallation of system to fully automate operation of chiller plant.

Cost Summary: $598,000 project cost before rebate.

18-month simple payback.

Other: Consumption reduction from 0.8 kW/ton to 0.4 kW/ton had to be met in order to earn rebate from PG&E.

Reference: "California Newspaper Renovates Facility With HCFC-22 Chillers," The Air Conditioning, Heating and Refrigeration News, August 1, 1994.

CASE STUDY 4

Location: San Francisco, CA

Application: 54-story, 2-million ft^2 Bank of America World Headquarters Building, 2000 tons peak, as well as 160,000 ft^2 adjacent building.

Approach: Add a third chiller to an existing system consisting of two York International Turbomaster 1750-ton CFC-12 electric chillers.

Goal: Prevent chiller shutdown during low-load periods due to chiller over capacity.

Constraints: Limited space made removal and replacement of old primary chiller prohibitively expensive.

Could not locate a chiller that exactly matched the desired cooling capacity and the building's voltage capacity.

New Chillers: One York International 1035-ton single-stage HFC-134a electric chiller.

Decision Factors: $86,063 rebate from PG&E. Replace old compressor and driveline and install a variable speed drive that was responsible for 33% of the total energy savings.

Chiller demand optimized from 0.85 kW/ton to 0.63 kW/ton, at full load.

Installation of a control panel to independently optimize chiller operation.

Cost Summary: $349,200 project cost.

Energy consumption cut by 1,306,254 kWh, and peak demand reduced by 415 kW.

$147,187 trimmed annually from utility bills.

1.79-year payback after rebate.

Other: Rebate offered as part of PG&E's Retrofit Customized Rebate Program.

Compressor retrofit performed as part of York's "Codekit" service package.

Overall system complexity significantly reduced by removing intercooling and thermocycling components.

Reference: "Bank's Chiller Conversion and VSD Retrofit Realize 22-Month Payback," EUN Vol. 19, No. 1, January 1994.

CASE STUDY 5

Location:	Naperville, IL
Application:	1.2-million ft^2 AT&T Bell Labs Building.
Approach:	Replace five existing 900-ton electric chillers.
Goal:	To correct a cooling imbalance for existing chiller load and to add new as well as backup capacity.
Constraints:	HFC-134a ruled out due to high cost. HCFC-123 ruled out due to its toxicity.
New Chillers:	Two York International 1000-ton gas-fired lithium bromide absorption chillers. One York International 1000-ton HCFC-22 electric centrifugal chiller rated at 0.69 kW/ton.
Decision Factors:	$200,000 rebate from Northern Illinois Gas. Two field panels added to complex's 17,000-point Metasys building automation system to accommodate upgrade. Free cooling strategy (incorporating plate-and-frame heat exchangers) to account for 94% reduction in utility bill for existing service.
Cost Summary:	$400,000 project cost before rebate. Projected reduction of 2,459,600 kWh in annual electricity consumption. $174,000 trimmed from annual utility bill. 1.1-year payback. Gas-fired absorption chiller $40,000/year cheaper to operate than equivalent electric chiller.
Reference:	"AT&T Lab Heat Exchangers, Absorption Chillers Net 1.1 Year Payback," EUN Vol. 19, No. 5, May 1994.

CASE STUDY 6

Location:	Fort Meyers, FL
Application:	10-Building Edgewood Elementary School Complex.
Approach:	Add thermal storage to existing system comprised of two Trane 141-ton HCFC-22 air-cooled electric chillers.
Goal:	To simultaneously comply with Florida's uniform building code and realize substantial savings in annual electric bills by switching to time-of-use rates.
Constraints:	Florida's uniform building code mandated use of thermal energy storage. Needs of occupants had to be met first and foremost.
New Chillers:	none
Decision Factors:	$59,000 FP&L rebate. Projected 88% reduction in annual electricity bill savings by using thermal energy storage and switching to time-of-use rates. Annual fees of $25,170 avoided by shifting demand to off-peak hours. Thermal energy storage allowed the achievement of colder chilled water supply temperatures, better humidity control, and overall improved comfort. Lower water temperatures allowed specification of smaller piping and ductwork.
Cost Summary:	$87,060 project cost after rebate. 3-year project payback.
Other:	3000-ton-h thermal energy storage addition. Thermal energy storage cost $146,060 more than alternative air-cooled electric chiller plant. Rebate offered under FP&L's Thermal Energy Storage Program. $2500 offered by FP&L for initial thermal energy storage feasibility studies.
Reference:	"School's Thermal Storage, Time-of-Use Service Nets Nearly $30,000/yr Savings," EUN Vol. 19, No. 8, August 1994.

CASE STUDY 7

Location: Detroit, MI

Application: 5.5-million ft^2, 5-building complex.

Approach: Automate chiller plant comprised of one 1200-ton and three 4000-ton electric centrifugal chillers.

Goal: To realize significant energy savings by upgrading building automation system.

Constraints: Upgrade had to be achieved in a manner that would allow the integration of 20-year-old and state-of-the-art equipment.

Had to improve on the $500,000 yearly savings achieved through manual optimization.

Adopted load-shedding strategies subject to tenant comfort.

New Chillers: none

Decision Factors: $38,516 rebate from Detroit Edison's Custom Equipment Incentive Program.

Five load-shedding strategies programmed into controls to occasionally shut down equipment in noncritical areas.

Chiller performance optimized through the use of daily printouts of graphs of chiller performance.

Cost Summary: $236,000 project cost before rebate.

Electricity consumption trimmed by 3.8 million kWh in the first two months of the year's cooling season.

1500 tons shed from cooling load by optimizing chilled water flow rate.

$298,000 of savings achieved in first two months of cooling season after upgrade.

2-month payback achieved versus initially projected 2-year payback.

Other: Upgraded building controls are easy to program (user-friendly).

Upgraded building controls allow easy integration of 20-year-old technology with the state-of-the-art.

Reference: "Cooling System Optimization Saves 5-Building Complex $298K," EUN Vol. 19, No. 12, December 1994.

CASE STUDY 8

Location: Newport Beach, CA

Application: 17-story, 249,000 ft^2 660 Tower (Newport Center) office building.

Approach: Replace existing chiller and hot water boiler.

Goal: Create a "fuel blind" energy savings program and reduce the cost of energy for the building owners.

Constraints: Upgrade chillers based upon a "fuel blind" philosophy.

Energy savings program mandated to take aggressive steps towards conservation, demand-side management, and integrated resource planning.

New Chillers: One 400-ton York International HCFC-123 electric chiller.

One 400-ton York International gas-fired chiller.

Decision Factors: Existing chiller controls modified by incorporating demand-based optimization logic.

Cost Summary: $1.5 million HVAC and lighting retrofit at no up-front cost to building owner.

Projected annual consumption to decrease by 2.5 million kWh.

$228,000 projected reduction in annual utility bills.

60% of up-front project cost paid by Southern California Edison (SoCalEd), and 40% paid by Southern California Gas (SoCalGas).

Total annual energy savings amount to $228,000: 80% of savings paid directly to prinicipal and interest of loan, 10% goes to building owner, 6% to SoCalEd, 4% to SoCalGas.

Other: Retrofit funded by the "Irvine Initiative", a joint-effort between SoCalEd and SoCalGas, created to develop long-term energy-efficiency programs without regulatory mandates, and without up-front investments by end-users.

Utility-customer collaboration endorsed by state regulators.

Reference: "Gas, Electric Utilities Unite to Aid User," EUN Vol. 20, NO. 1, January 1995.

CASE STUDY 9

Location: Plymouth, MA

Application: Jordan Hospital.

Approach: Add a previously owned 100-ton Trane single-effect absorption chiller to an existing plant comprised of two 100-ton reciprocating electric chillers.

Goal: To optimize the use of excess cogenerated steam, and to reduce the amount of purchased power during summer peak demand.

Constraints: Upgrade had to fit with existing cogeneration loop to utilize excess steam.

New Chillers: One newly installed previously owned Trane 100-ton single-stage absorption chiller.

Decision Factors: Add to existing chiller plant to make use of otherwise vented steam.

Water treatment and makeup water feed costs reduced.

Lower utility costs due to upgrade.

Cost Summary: $125,000 project cost.

Projected 489,000 kWh reduction in consumption, as well as 170 kW in demand.

Projected $60,000 to be trimmed annually from electric bill.

Projected $11,000 to be trimmed annually from water and water treatment bill.

1.8- to 2.5-year payback.

Reference: "Hospital Optimizes Cogen Plant With Absorption Chiller," EUN Vol. 20, No. 8, August 1995.

CASE STUDY 10

Location: Boston, MA

Application: 32-story office building, 99 High Street.

Approach: Replace two existing steam-driven absorption chillers.

Goal: Replace two aging single-effect absorption chillers and add backup capacity.

Constraints: Mechanical room size.

New Chillers: Three high-efficiency centrifugal HFC-134a chillers with a total capacity of 2500 tons.

Decision Factors: Additional backup capacity desired.

Mechanical room size constraints eliminated direct-fired and steam-driven absorption chillers.

Boston Edison Company's Energy Efficiency Partnership Program provided $269,000 to cover the incremental cost for the three high-efficiency chillers.

In addition to assistance provided to purchase the chillers, Boston Edison Company's Energy Efficiency Partnership Program provided $282,000 to cover various chiller system upgrades (e.g., installation of variable-frequency drive, high-efficiency motors, and other cooling system modifications).

Cost Summary: Peak electric consumption estimated to increase from 530 kW to 1380 kW.

Electric energy consumption estimated to increase from 805,000 kWh/yr to 1.22 million kWh/yr.

Steam reduction of 27 million lb/yr.

Net savings were $130,000/yr ($210,000 steam savings minus $80,000 of added electric demand charges and energy expenses).

Other: The new electric HFC-134a chillers (3 units with a total capacity of 2500 tons) are estimated to reduce CO_2 and NO_X emissions by 70% compared to the previous single-effect steam absorption chillers (2 units with a total capacity of 2340 tons).

Reference: EPRI (1995i)

CASE STUDY 11

Location: Coral Gables, FL

Application: 4.5 million ft^2 of University of Miami campus buildings.

Approach: Replace five independently operated CFC-11 chilled-water plants with a campuswide chilled-water system.

Goal: Install a chilled-water-loop system that makes the University of Miami the most energy-efficient university in the nation.

Constraints: Chilled-water-loop system had to be designed to facilitate easy upgrade to cooling capacity as the campus expands in phases.

New Chillers: One Trane centrifugal chiller rated at 0.55 kW/ton and two ultra-high-efficiency "EarthWise CenTraVac" centrifugal chillers rated at 0.51 kW/ton for Phase I addition to the loop.

One existing CFC-11 centrifugal chiller retrofitted with DuPont Suva 123 refrigerant for Phase I addition to the loop.

Decision Factors: Trane "EarthWise CenTraVac" chillers have the highest energy efficiencies ever recorded for commercial refrigeration equipment.

DuPont Suva has the highest thermodynamic cycle efficiency of available CFC alternatives.

Cost Summary: University of Miami qualified for 50% matching costs for construction under Phase I from Florida's Energy Office and FP&L due to projected energy efficiency.

University of Miami now paying 5.8 cents/kW versus previous 7.5 cents/kW for power since qualifying for Florida Power and Light's CILC rate.

Reduce maintenance costs by retiring 600 tons of stand-alone direct-expansion equipment.

Other: Trane "EarthWise CenTraVac" centrifugal chillers utilizing DuPont Suva 123 are designed for "near-zero" emissions, and lose less than 0.5% of their refrigerant charge per year.

Matching funds provided under Florida Energy Office's Institutional Conservation Program grant.

Reference: "Florida Campus Cuts CFC Use, As Well As Energy Consumption," The Air Conditioning, Heating and Refrigeration News, July 10, 1995.

CASE STUDY 12

Location: Washington, DC

Application: EPA's headquarters building.

Approach: Replace two 875-ton Trane electric chillers rated at 0.77 kW/ton.

Goal: Achieve energy efficiency in EPA's headquarters by employing a total systems approach.

Constraints: Upgrade in a manner that satisfied EPA's total systems approach. Design an upgrade that resulted in significant utility-generated emissions.

New Chillers: Two Trane 670-ton electric chillers, utilizing DuPont Suva 123, and rated at 0.52 kW/ton.

Decision Factors: New chillers draw about half the power, 348 versus 674 kW, of the old chillers on a peak-load day.

Cost Summary: Energy savings of 35% realized by upgrade to EPA's headquarters; savings projected at 4 million kWh/year, or $300,000/year at typical energy rates of 7.5 cents/kWh.

Internal rate of return of 15 to 60% projected for building owners through implementation of EPA's "Energy Star Buildings Program".

Other: EPA's total systems' approach to upgrading the efficiency of its building included a variable-flow water pumping system, a variable frequency drive, new induced-draft cooling towers, lighting retrofits, new window treatments, and smaller, more-efficient chillers.

EPA's energy savings projected to reduce utility-generated emissions by 6,000,000 lb of CO_2, 72,000 lb of SO_2, and 22,000 lb of NO_X.

Trane's "EarthWise CenTraVac" chiller's low-pressure compressor designed so that in the event of a leak, air leaks into the machine rather than refrigerant leaking out.

Reference: "Trane Helps EPA Set Good Example for CFC-Free Energy Efficiency," The Air Conditioning, Heating and Refrigeration News, June 5, 1995.

CASE STUDY 13

Location: Washington, DC

Application: Washington Adventist Hospital.

Approach: Replace three 20-year-old CFC electric chillers.

Goal: To replace the old chillers with new chillers that exemplified the hospital's commitment to be an environmentally conscious and cost-efficient organization.

Constraints: Too expensive to convert old chillers.

Old chillers' poor energy efficiency and high refrigerant loss record disqualified them from retrofitting.

New high-efficiency chillers had to be installed for hospital to qualify for local utility's (PEPCO) financial inventives and technical expertise.

New Chillers: Two Trane 740-ton "EarthWise CenTraVac" electric centrifugal chillers rated at 0.49 kW/ton and based on DuPont Suva 123 HCFC.

Decision Factors: Rebate from PEPCO through its chiller replacement program.

Replace three 20-year-old CFC electric chillers.

Cost Summary: Projected 4.5-year payback.

Projected annual savings on electric bills through the use of high-efficiency units.

Reference: "Washington Hospital Selects New Chillers, With New Refrigerant," The Air Conditioning, Heating and Refrigeration News, April 3, 1995.

CASE STUDY 14

Location: Rancho Mirage, CA

Application: Ritz-Carlton Hotel.

Approach: The previous chiller plant was comprised of two 250 ton CFC-11 chillers with full-load efficiencies near 0.8 kW/ton. The approach was to replace one of these chillers with a HCFC-123 unit, and rebuild the other chiller to operate with HCFC-123.

Goal: Field test new and rebuilt centrifugal chillers that use non-CFC refrigerants (e.g., HCFC-123).

Constraints: No significant constraints.

New Chillers: 250-ton centrifugal HCFC-123 unit with a full-load efficiency near 0.6 kW/ton.

Decision Factors: Southern California Edison was interested in having field-test data to quantitatively compare the performance and cost of new versus rebuilt non-CFC electric chillers.

As a first step, one of the 250-ton CFC-11 chillers was replaced with a HCF-123 chiller. This work was completed in 1993, and monitoring was conducted from June 1993 to July 1994.

The second step involved rebuilding the remaining CFC-11 chiller.

Analysis of the rebuilt chiller performance was scheduled for completion by late 1995.

Cost Summary: The new chiller reduced energy consumption from 1,038,282 kWh/yr to 811,203 kWh/yr (22%). Electric demand was reduced by 32 kW (24%) during the peak month. The higher efficiency new chiller reduced cooling tower fan energy consumption by 3500 kWh/yr, and also reduced water consumption.

The total annual savings for the new chiller were $18,800, compared to an installed cost of $114,300. The resulting payback is 6.1 years.

Other: Data for the rebuilt chiller will be available in 1996.

Reference: EPRI (1995j)

CASE STUDY 15

Location:	Tucson, AZ
Application:	JCPenney Store in the El Con Mall.
Approach:	The previous chiller system consisted of two 300-ton CFC-11 centrifugal chillers with full-load efficiencies near 0.95 kW/ton. These chillers were installed in 1971. The approach was to replace one of these chillers with a new HCFC-22 unit.
Goal:	Increase efficiency, reduce energy costs, and eliminate CFCs.
Constraints:	No significant constraints.
New Chillers:	One 290-ton HCFC-22 screw chiller with a full-load efficiency near 0.64 kW/ton.
Decision Factors:	Aging CFC-11 chiller in need of replacement with a non-CFC unit. Chiller replaced as part of an overall energy management program. Other improvements included more-efficient lighting.
Cost Summary:	Energy savings due to chiller are about 70,000 kWh/month, which translates to monthly savings of $3750 to $5000. Installed cost of chiller was $94,000 ($63,000 for purchase of new chiller). Projected payback is approximately 2 years.
Other:	As a result of the energy management program, total energy savings for the store during the cooling season are estimated at 100,000 kWh/month. About 75% of these savings are credited to the new, more-efficient chiller.
Reference:	EPRI (1995k)

Appendix B
Vendor Contact Information

Electric Chillers

Carrier Corporation
P. O. Box 4808
Syracuse, NY 13221
315-432-6000

Dunham-Bush
101 Burgess Road
Harrisonburg, VA 22801
540-434-0711

McQuay International
13600 Industrial Park Blvd.
Minneapolis, MN 55441
612-553-5330

The Trane Corporation
3600 Pammel Creek Road
La Crosse, WI 54601
608-787-2000

York International Corporation
P.O. Box 1592
York, PA 17405
717-771-7890

Gas Engine-Driven Chillers

Alturdyne Energy Systems
8050 Armour Street
San Diego, CA 92111
619-565-2131

GASAIR
P.O. Box 5348
Kingwood, TX 77325
713-360-0893

Hercules Energy Products
2896 Telegraph Road
Fillmore, CA 93015
805-524-5880

Sierra Power
6101 West Courtyard Drive
Building II, Suite 225
Austin, TX 78730
512-343-9591

Tecogen
45 First Avenue
P.O. Box 8995
Waltham, MA 02254
617-622-1400

York International Corporation
P.O. Box 1592
York, PA 17405
717-771-7890

Direct-Fired Absorption Chillers

American Yazaki Corporation
13740 Omega Road
Dallas, TX 75224
214-385-8725

Carrier Corporation
P. O. Box 4808
Syracuse, NY 13221
315-432-6000

McQuay International
13600 Industrial Park Blvd.
Minneapolis, MN 55441
612-553-5330

The Trane Corporation
3600 Pammel Creek Road
La Crosse, WI 54601
608-787-2000

York International Corporation
P.O. Box 1592
York, PA 17405
717-771-7890

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

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