DISTRICT COOLING BEST PRACTICE GUIDE

FIRST EDITION

Published to inform, connect and advance the global district cooling industry

INTERNATIONAL DISTRICT ENERGY ASSOCIATION

Westborough, Massachusetts, USA

Dedicated to the growth and utilization of district cooling as a means to enhance energy efficiency, provide more sustainable and reliable energy infrastructure, and contribute to improving the global environment.

IDEA invites comments, criticisms and suggestions regarding the subject matter in this publication, including notice of errors or omissions.

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Preface

When the National District Heating Association (NDHA) was founded in the United States in 1909, its mission was to be a collegial and vibrant resource of practical engineering and operational information, to connect people with technical resources and real-world solutions, and to advance the district energy industry through education and advocacy on the economic and environmental benefits of district heating systems. The cornerstone of the association was the open exchange of information on design, construction and safe operation of district heating systems.

NDHA published the first edition *Handbook of the National District Heating Association* in 1921, with subsequent revisions of the district heating handbook in 1932, 1951 and 1983. Over time, the association would evolve to encompass district cooling, combined heat and power and the world beyond North America, resulting in a name change from the National District Heating Association (NDHA) to the International District Heating Association (IDHA) in 1968 to the International District Heating and Cooling Association (IDHCA) in 1984 to the current International District Energy Association (IDEA) in 1994. Throughout the first 100 years, IDEA has remained true to its original mission by drawing from the collective experience of all membership segments – personnel from the operations, engineering and distribution arenas as well as consultants and manufacturers.

In 2004, Dany Safi, founder and chief executive officer of Tabreed, suggested IDEA develop an industry guidebook to help transfer the deep technical and engineering experience resident within IDEA to support the nascent district cooling industry across the Middle East. Now, as IDEA begins its second century in 2009, there is massive investment in new district cooling systems in the Middle East, where the harsh climate and pace of real estate development demand a wide range of technical resources. It is this unique market segment that is the principal focus of this first edition of the *District Cooling Best Practice Guide*.

The *Best Practice Guide* is a compilation of practical solutions and lessons learned by industry practitioners. It is not a compendium of standards, reference documents and design drawings and is not intended to displace long-standing reference sources for codes and ratings. The *Best Practice Guide* is intended to support engineers, business developers, managers and service providers in the business of district cooling. This first edition may not incorporate every detail of the industry, but any omissions or oversights are unintentional. IDEA welcomes suggestions and comments to support improvements in future editions.

On behalf of the many contributors to this *Best Practice Guide* and the IDEA Board of Directors, thank you for your interest in district cooling and for selecting the IDEA as your industry resource.

Acknowledgements

It may not be possible to properly acknowledge all of the contributors to IDEA's *District Cooling Best Practice Guide*. By its very nature, a best practice guide reflects the collective experience of industry participants, openly sharing case studies, experiences and practical solutions to the complex business of designing, constructing, operating and optimizing district cooling systems. Since IDEA's inception in 1909, generations of IDEA members have made successive contributions to future colleagues. It is our sincere hope that publishing this *District Cooling Best Practice Guide* will continue and extend the IDEA tradition of providing guidance to future industry participants in developing reliable, efficient and environmentally beneficial district energy systems. The world demands our best efforts in this arena.

The principal vision for IDEA's *District Cooling Best Practice Guide* began with Dany Safi, CEO of Tabreed. In 2004, at the start of his first term on the IDEA Board of Directors, Safi proposed that IDEA assemble a guide book to help transfer the collective technical and business experience on district cooling that he had encountered over many years of attending IDEA conferences. The principal founder of the burgeoning district cooling industry in the Middle East, Safi foresaw the value and importance of technical guidance and experience exchange to ensure that newly developed systems are properly designed, constructed and operated for highest efficiency and reliability to preserve the positive reputation of the industry. Safi contributed personally, professionally and financially to this guide and deserves special recognition for his singular and sustaining commitment to a robust and environmentally progressive global district energy industry.

The principal authors of this guide are Mark Spurr and colleagues Bryan Kleist, Robert Miller and Eric Moe of FVB Energy Inc., with Mark Fisher of Thermo Systems LLC authoring the chapter on Controls, Instrumentation and Metering. These gentlemen have dedicated hundreds of hours in organizing, writing, researching and editing this *Best Practice Guide*, drawing from decades of personal, professional experience in the design and engineering of numerous district cooling systems around the globe. Important contributions were also made by Bjorn Andersson, Peter Beckett, John Chin, Ehsan Dehbashi, Leif Eriksson, Leif Israelson, Ryan Johnson, Todd Sivertsson, Sleiman Shakkour and Bard Skagestad of FVB Energy; Trevor Blank, Stanislaus Hilton and Sai Lo of Thermo Systems LLC; and Peter Tracey of CoolTech Gulf. Completing the guide demanded the focused personal commitment of these fine industry professionals who have made a lasting and substantial professional contribution to IDEA and the entire global industry community.

From the outset and over the extended development process, the IDEA Board of Directors remained committed to the project with continuous support and leadership from Robert Smith, Juan Ontiveros, Tom Guglielmi and Dennis Fotinos. In addition, a core support team of IDEA leaders and volunteers chaired by Laxmi Rao and comprised of Cliff Braddock, Kevin Kuretich, Jamie Dillard and Steve Tredinnick contributed substantially by providing regular technical input and insight and participating in project updates and review meetings.

Hundreds of pages of technical content were reviewed chapter by chapter by industry peers. These individuals volunteered to support IDEA's *Best Practice Guide* by reading, verifying and editing chapters in their areas of specialty to ensure editorial balance and the technical integrity of the final product. IDEA is indebted to peer reviewers John Andrepont, George Berbari, Bharat Bhola, Joseph Brillhart, Cliff Braddock, Jamie Dillard, Steve Harmon, Jean Laganiere, Bob Maffei, Gary Rugel, Ghassan Sahli, Sam Stone, Craig Thomas, Steve Tredinnick and Fouad Younan. We also appreciate the assistance of the operation and maintenance team at Tabreed, led by James Kassim, who contributed insights from their experience in operating a wide variety of district cooling systems.

Important financial support for the *Best Practice Guide* was provided via an award under the Market Development Cooperator Grant Program from the United States

Department of Commerce. IDEA acknowledges the important support of Department of Commerce staff including Brad Hess, Frank Caliva, Mark Wells, Sarah Lopp and Patricia Gershanik for their multi-year support of IDEA.

Tabreed provided substantial financial support during the early stage of the project, and Dany Safi, CEO of Tabreed, made a substantial personal financial contribution to sponsor the completion of the *Best Practice Guide*. IDEA thanks and gratefully acknowledges the leadership and unparalleled commitment demonstrated by Dany Safi and Tabreed, global leaders in the district cooling industry.

Monica Westerlund, executive editor of *District Energy* magazine, provided timely editing of the guide and worked closely with Dick Garrison who designed the final layout of the book. This was a challenging task achieved under a tight timetable. Laxmi Rao provided management and stewardship throughout the project, and the printing and binding of the book was ably managed by Len Phillips. IDEA staff Dina Gadon and Tanya Kozel make regular contributions to the IDEA community and therefore directly and indirectly contributed to this effort. The sum of our IDEA parts is a much larger whole.

The IDEA community has grown with the recent addition of hundreds of members from the recently formed Middle East Chapter. The chapter would not be in place without the commitment and resourcefulness of Joel Greene, IDEA legal counsel from Jennings, Strouss & Salmon. As former chair of IDEA, Joel has been committed to IDEA's growth in the Middle East region. Additionally, Rita Chahoud of Tabreed, the executive director of the IDEA Middle East Chapter, is a dedicated and energetic resource for the industry. Without her contributions and stewardship, the IDEA Middle East Chapter would not be where it is today.

Finally, the IDEA membership community is comprised of dedicated, committed and talented individuals who have made countless contributions to the success and growth of the district energy industry. As we celebrate IDEA's centennial and begin our second century, I wish to acknowledge the collective energy of our members in advancing the best practices of our chosen field of endeavor.

Robert P. Thornton
President, International District Energy Association
Westborough, Massachusetts, USA

September 2008

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1. Introduction

1.1. Purpose

The purpose of the International District Energy Association's *District Cooling Best Practice Guide* is to facilitate the design of district cooling businesses and systems that are reliable, efficient and profitable. The guide is focused on a key district cooling growth market – the Middle East – that has some specific challenges due to climate, the nature of the loads and the pace of development.

The guide is not a set of standards, nor is it an encyclopedia covering every detail of district cooling systems or a detailed design and specification guide. Rather, it is intended to share insights into key design issues and "lessons learned" from the recent development and operation of district cooling systems, particularly in the Middle East.

It is important to emphasize that "best practices" will vary depending on a wide variety of case-specific conditions, including

- seasonal and daily load characteristics;
- type of cooling load and any special reliability requirements (e.g., hospitals, computer servers, etc.);
- size of plant site and any conditions or constraints relating to the site (height restriction, air emissions, noise sensitivities of neighbors, etc.);
- availability and prices of electricity, water and natural gas;
- local codes and regulations;
- underground conditions affecting pipe installation;
- organizational resources; and
- financial criteria and strategic goals of the district cooling company.

The intention of the *District Cooling Best Practice Guide* is to address the advantages and disadvantages of design options, discuss the circumstances under which a given option may be the best approach and suggest approaches to determining the optimal approach once key factors affecting a specific case are known.

The International District Energy Association envisions this guide will be updated periodically as technologies and the district cooling industry evolve.

1.2. Overview and Structure of the Guide

The next chapter, Chapter 2 – Why District Cooling?, is a review of the rationale for district cooling, including its benefits for customers, governments and the environment. It is useful to review the drivers behind the establishment of district cooling systems so that discussion of business and technology best practices relate to the key reasons such systems are developed.

Chapter 3 – Business Development presents key topics on the business side of district cooling, including the fundamental importance of approaching district cooling as a utility business. This viewpoint has implications for designing all aspects – technology, business and operating structure – of the district cooling company. Other critical business considerations, including marketing and communications, risk management and rate structures are also covered.

Chapter 4 – Design Process and Key Issues covers essential pre-design tasks with enormous cost and risk implications, such as load estimation and the fundamental design parameters that have significant technical and cost implications for all elements of a district cooling system, such as design supply and return temperatures. It also suggests approaches to master planning complex district cooling systems and the critical and often-difficult topic of obtaining permits to develop the district cooling system. The challenges and opportunities of integrating district cooling system planning and design with other infrastructure are discussed. This chapter closes with an emphasis on the importance of designing with long-term operation and maintenance in mind, consistent with the philosophy that successful district cooling systems must be approached as a utility business.

Chapter 5 focuses on building cooling system design and energy transfer stations or ETS (interface between the distribution system and the building).

Chapters 6 and 7 address district cooling distribution systems and plants.

Although these discussions may appear to be presented out of order, this structure was deliberately chosen for several reasons. First, satisfaction of comfort requirements is the ultimate business and technical purpose of district cooling systems, so success is not possible without good design on this end. Second, the economic performance of district cooling systems is dependent on sound performance of building systems, particularly delta T (temperature difference between supply and return). The economic implications of delta T are large and pervasive.

Chapter 8 – Controls, Instrumentation and Metering ties the ETS, distribution and plant systems together.

The guide concludes in Chapters 9 and 10 with discussions of options for project procurement, delivery and commissioning.

A summary of abbreviations and definitions and a list of conversion factors are provided as appendices. A variety of units are used in this document, consistent with practices in the Middle East.

2. Why District Cooling?

District cooling is being implemented worldwide by many different kinds of organizations, including investor-owned power utilities, government-owned utilities, privately owned district energy companies, universities, airports and military bases. District cooling systems serve a wide variety of types of buildings, including commercial offices, residential, hotels, sports arenas, retail stores, schools and hospitals.

District cooling is growing rapidly for many reasons, including

- increasing demand for comfort cooling, due to construction of many new buildings that are "tighter" than older buildings and contain more heat-generating equipment such as computers;
- a growing trend toward "outsourcing" certain operations to specialist companies that can provide these services more efficiently;
- reductions in peak electricity demand provided by district cooling;
- environmental policies to reduce emissions of air pollution, greenhouse gases and ozone-depleting refrigerants; and
- most important, the customer value provided by district cooling service in comparison with conventional approaches to building cooling.

When properly designed and operated, district cooling systems cost-effectively deliver a variety of benefits to customers, including superior comfort, convenience, flexibility and reliability.

2.1 Customer Benefits

When properly designed and operated, district cooling systems cost-effectively deliver a variety of benefits to customers, including superior comfort, convenience, flexibility and reliability.

2.1.1 Comfort

Comfort is the ultimate purpose of air conditioning. District cooling systems can help keep people more comfortable because industrial-grade equipment is used to provide a consistent and high-quality source of cooling. In addition, specialist attention is focused on optimal operation and maintenance of cooling systems – providing better temperature and humidity control than packaged cooling equipment and, therefore, a healthier indoor environment. Buildings are quieter because there is no heavy equipment generating vibration and noise, making tenants happier and allowing them to be more productive.

2.1.2 Convenience

District cooling is a far more convenient way to cool a building than the conventional approach to air conditioning because cooling is always available in the pipeline, thus avoiding the need to start and stop building cooling units. From the building manager's standpoint, it is attractive to be able to provide reliable comfort without worrying about managing the equipment, labor and materials required for operating and maintaining chiller and cooling tower systems. This allows the manager to focus resources on more critical bottom-line tasks, such as attracting and retaining tenants.

2.1.3 Flexibility

The pattern and timing of cooling requirements in a building vary depending on building use and weather. With building chiller systems, meeting air-conditioning requirements at night or on weekends can be difficult and costly, particularly when the load is small. With district cooling, these needs can be met easily and cost-effectively whenever they occur. Each building can use as much or as little cooling as needed, whenever needed, without worrying about chiller size or capacity.

2.1.4 Reliability

The building manager has a critical interest in reliability because he or she wants to keep the occupants happy and to avoid dealing with problems relating to maintaining comfort. District cooling is more reliable than the conventional approach to cooling because district cooling systems use highly reliable industrial equipment and can cost-effectively provide equipment redundancy. Staffed with professional operators around-the-clock, district cooling companies are specialists with expert operations and preventive maintenance programs. A survey conducted by the International District Energy Association (IDEA) shows that district cooling systems have a documented reliability exceeding 99.94%, which is significantly more reliable than individual building cooling systems.

District cooling has fundamental cost advantages, including load diversity, optimized operations, advanced technologies and better staff economies.

2.1.5 Cost-effectiveness

Fundamental cost advantages

District cooling has numerous fundamental cost advantages:

Load diversity

Not all buildings have their peak demand at the same time. This "load diversity" means that when cooling loads are combined in the district cooling system, more buildings can be reliably served at lower cost.

Optimized operations

With district cooling, equipment can be operated at the most efficient levels, whereas with building cooling equipment, the units operate for most hours each year at less-than-optimal levels.

Advanced technologies
District cooling also offers economies of scale to implement more efficient and advanced technologies, such as

- thermal energy storage (TES), which can further reduce peak power demand, save energy, enhance reliability and reduce capital expenses for both the utility and its customers;
- natural gas-driven chillers;
- integration with wastewater treatment infrastructure through use of treated sewage effluent (TSE) for condenser cooling; and
- use of seawater for condenser cooling, either for makeup water in cooling towers or for direct condenser cooling.

Better staff economies
District cooling cost-effectively provides around-the-clock specialized expertise to operate and maintain the equipment required to reliably deliver building comfort.

Customer risk management

For the real estate developer, district cooling systems reduce capital risk because no capital is tied up in the building for cooling equipment. Operating risks associated with operation and maintenance of building cooling equipment are eliminated, with more predictable costs. In a competitive real estate market, buildings that consistently provide superior comfort will attract and keep tenants and maintain a higher market value. Poor indoor comfort is a primary reason for tenants to leave a building or not renew a lease. District cooling provides technical benefits that mitigate loss of tenants.

The costs of the conventional approach to cooling involve far more than the cost of electricity.

Cost comparison
The costs of the conventional approach to cooling involve far more than the cost of electricity, as described below.

Capital costs
By choosing district cooling service, a building avoids a large capital investment for the total installed capital costs of a building chiller system, including

- construction cost of space for equipment;
- chiller and condenser cooling equipment;
- pumps and controls;
- power utility connection fees and/or substation construction, as required;
- transformers and cables;
- engineering services; and
- replacement capital costs.

Capital costs for a building to connect to a district cooling system are generally very low, encompassing piping, valves, controls and, in many cases, a heat exchanger. Some district cooling utilities require the customer to pay for the cost of extending pipe from the nearest pipe main to the building, while other utilities cover this cost so that the customer pays only for the piping, valves and ancillary equipment inside the building wall.

With district cooling systems that distribute water at a lower-than-normal temperature (such as is possible with ice thermal energy storage or freeze-point depressant chemicals), it is possible to further reduce building costs. This is because such systems enable reductions in the size of fans and ducts due to the reduced temperature of air produced in air-handling systems.

Annual costs
District cooling service allows the building manager to eliminate the annual costs of operating and maintaining a building chiller system, including

- electricity,
- scheduled annual maintenance,
- periodic major maintenance,
- unscheduled repairs,
- refrigerant management,
- spare parts,
- labor and
- management oversight.

It is also appropriate to account for the opportunity cost of the income or amenity value of the building area or rooftop used for equipment. For example, if building chillers would be located within the building, this space might otherwise be rentable (even for storage space), thereby generating revenue. Space used for roof-mounted chillers or cooling towers could instead be used for tenant amenities such as a swimming pool. Chillers located on the ground take up space that could be used for parking.

Further discussion and guidance regarding presentation of cost comparisons is provided in Chapter 3.

2.2 Infrastructure Benefits

2.2.1 Peak power demand reduction
The benefits that district cooling offers relative to power demand and annual energy are key advantages of the technology. Chiller equipment in the Middle East is typically subject to a difficult operating environment, including extreme heat, windborne sand and saline humidity. Equipment performance will degrade as the system ages, particularly if there is not an aggressive maintenance program. Over time, the performance, efficiency and reliability of this equipment suffers, leading to high electricity demand, maintenance costs and, ultimately, to the need for equipment replacement.

District cooling reduces power demand in new development by 50% to 87% depending on the type of district cooling technology used.

Figure 2-1 summarizes representative peak electric demand efficiencies of several major types of district cooling systems and compares them with representative peak demand of conventional air-cooled systems. District cooling reduces power demand in new development by 50% to 87% depending on the type of district cooling technology used.

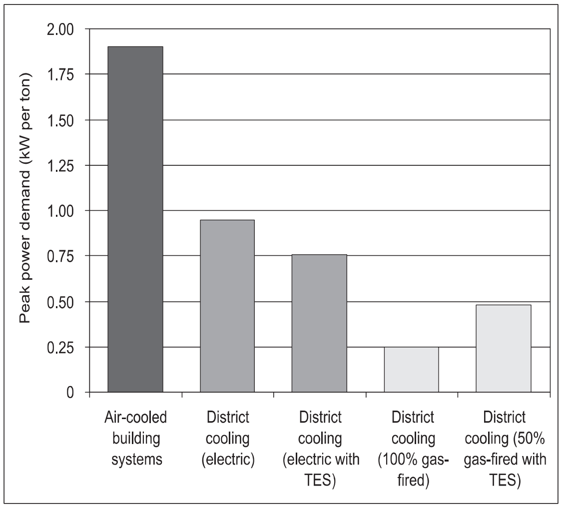

Figure 2-1. Peak power demand reductions with district cooling.

A straight centrifugal chiller plant will cut peak demand (compared with the conventional air-cooled approach) by about 50%. The impact of thermal energy storage (TES) depends on the peak day load profile of the aggregate customer base. The graph illustrates a representative situation in a mixed-use development in the Middle East, in which TES reduced the peak power demand of the district system by about 20%. Natural gas district cooling can provide even more dramatic reductions in power demand. As discussed in Chapter 7, engine-driven chillers are the most cost-effective gas-driven approach. Figure 2.1 shows the peak power demand of two gas-driven options: 100% gas-driven without TES and a hybrid in which 50% of the capacity is gas-driven, 40% is electric-driven and 10% is TES.

2.2.2 Reduction in government power sector costs

District cooling reduces the capital investment required for additional power generation, transmission and distribution infrastructure. District cooling also reduces power sector operating costs. Because power costs are typically subsidized in the Middle East, district cooling saves governments substantially both in capital investment and in operating subsidies. In the long run, a proper accounting of the total cost of power must include not only fuel and other operating costs, but also the cost of amortizing the capital to build power plants and deliver the power to customers.

District cooling reduces the capital investment required for additional power generation, transmission and distribution infrastructure.

Capital costs of power capacity

New power generation capacity in the Middle East is typically large [more than 250 megawatts (MW)] combustion turbine combined-cycle plants that use byproduct steam for desalination. Capital costs for power plants have increased dramatically since 2005 for a variety of reasons, including significant increases in materials costs and a very tight international market for qualified contractors. Through 2009, the estimated unit cost of power generation capacity is US$1,067 per kilowatt (kW). In addition, substantial investment must be made in transmission and distribution (T&D) facilities including substations. The estimated average costs of T&D infrastructure is US$296/kW, for a total generation and T&D cost of US$1,363/kW.

Power sector operating costs

Table 2-1 summarizes operating cost factors for a new combined-cycle power plant. New combined-cycle power plants can reach maximum operating efficiencies of more than 55% under ISO conditions (16 C or 60 F) outdoor air, 60% relative humidity and 1 atmosphere barometric pressure (14.7 psi). However, combustion turbine power output drops significantly as the ambient air temperature increases. For Middle East conditions, combined-cycle generation efficiency is projected to be 48.4% [heat rate 7050 Btu/kilowatt-hour (kWh)]. With estimated T&D losses of 7.0%, the net (delivered) efficiency is 45.0%.

With variable operation and maintenance (O&M) costs of US$2.13/megawatt-hour (MWh), fixed O&M costs of US$12.93/kW and a capacity factor of 0.60, the average non-fuel O&M cost is US$4.59/MWh.

Power plant heat rate	7050 Btu/kWh
Generation efficiency	48.4%
Transmission/distribution losses	7.0%
Net efficiency	45.0%
Variable O&M	2.13 US$/MWh
Fixed O&M	12.93 US$/kW
Capacity factor	0.60
Average non-fuel O&M cost	4.59 US$/MWh

Table 2-1. Combined-cycle power plant operation cost factors.

Although a state-owned power utility may buy fuel very cheaply from a state-owned company, it is worthwhile to reflect on the opportunity cost of using that fuel to produce power to run inefficient chillers.

Fuel for power generation may be natural gas or oil depending on available resources. Although a state-owned power utility may buy fuel very cheaply from a state-owned company, it is worthwhile to reflect on the opportunity cost of using that fuel to produce power to run inefficient chillers. Certainly, oil could instead be sold at the increasingly high international price. (See Figure 2-2.) Figure 2-3 illustrates the conversion of oil prices from U.S. dollars per barrel to U.S. dollars per million Btu. The same data is shown in tabular form in Table 2-2.

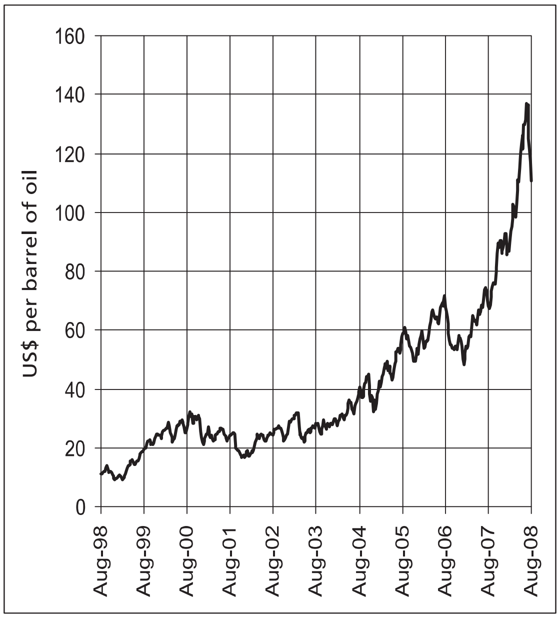

Figure 2-2. World oil prices during the past 10 years.

The value of power plant fuel should be based on a realistic assessment of long-term energy prices.

If natural gas is the power generation fuel, it also has an international market value to an increasing extent. Natural gas demand is growing worldwide, driven by rapidly growing energy requirements in China, India and other developing nations, continued growth in industrialized countries and declining domestic reserves in the U.S. The natural gas market is becoming a competitive, market-driven sector with a trend toward liquefaction and export. These trends mean that the market price for natural gas will trend upward as it becomes an increasingly tradable commodity as liquefied natural gas (LNG) in international markets.

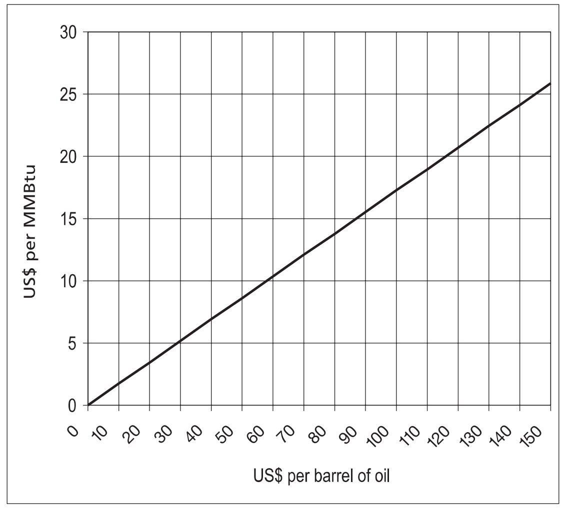

Figure 2-3. Oil prices in US$ per MMBtu.

US$ per barrel of oil equivalent (BOE)	US$ per million Btu (MMBtu)
0	0
10	1.72
20	3.45
30	5.17
40	6.90
50	8.62
60	10.34
70	12.07
80	13.79
90	15.52
100	17.24
110	18.97
120	20.69
130	22.41
140	24.14
150	25.86

Table 2-2. Conversion of fuel prices in US$ per barrel oil equivalent (BOE) to US$ per MMBtu.

Long-term infrastructure choices made by Middle Eastern governments should be made based on the recognition that, although power generation fuel can be "priced" internally at a low level, the value of that energy will be significantly higher. In other words, there will be an increasing "opportunity cost" associated with using available natural gas for power generation instead of using it for higher value uses or exporting it as LNG.

Natural gas or LNG prices are frequently tied to oil prices. Figure 2-4 shows the projected impact of changes in oil prices on the price of delivered LNG, based on extrapolation from analysis of historical price data.[1]

As illustrated in Figure 2-2, oil prices jumped substantially between early 2007 and mid-2008. As this report goes to print, world oil prices have pulled back from the highs set in July 2008. However, in the mid-term (2010-2015), the price floor is likely to exceed US$140/barrel. Based on Figure 2-4, delivered LNG prices can be expected to seek a mid-term level of US$9/MMBtu to US$18/MMBtu, with an average value of US$13.50/MMBtu.

Excluding the costs of liquefaction, transportation and regasification, the estimated average "opportunity cost" of natural gas in the mid-term is US$9/MMBtu, equivalent to about US$50/barrel of oil equivalent (BOE). In other words, this is the lost revenue if gas in hand is burned instead of sold into the LNG market and is an appropriate basis for long-term valuation of fuel used in Middle Eastern power plants.

In discussion of fuel prices, prices are referred to in terms of dollars per BOE, or the cost of the energy in one barrel of oil. Conversion of fuel prices between U.S. dollars per BOE, U.S. dollars per MMBtu and BOE per MMBtu is summarized in Table 2-2 shown earlier.

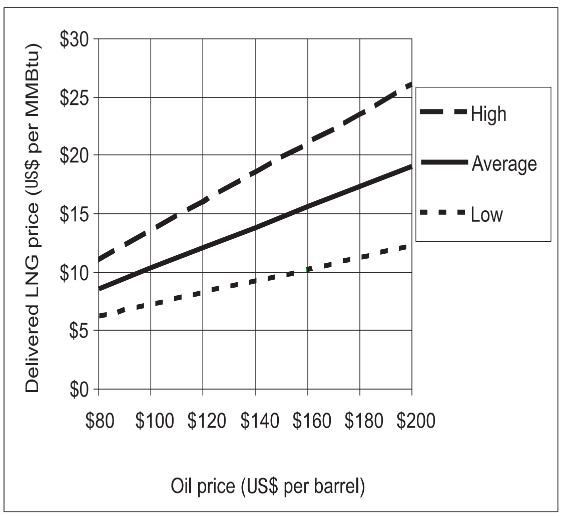

Figure 2-4. Projected impact of oil price on price of delivered liquefied natural gas.

Total costs of electricity

Governments cannot make good decisions about allocating capital and natural resources unless all of the long-run marginal costs of generating and delivering power are considered, including amortized capital and the market value of fuels in the context of long-term world energy prices.

Figure 2-5 shows the long-run marginal costs for electricity in the Middle East under a range of fuel cost assumptions. "Long-run marginal costs" are the total costs of providing an additional kilowatt-hour of energy output over and above any energy currently being produced, and they include all capital and operating costs. These calculations reflect the total costs of building and operating highly efficient new combined-cycle power plants and power transmission and distribution infrastructure, based on the capital and operating costs discussed above. A capacity

> Governments cannot make good decisions about allocating capital and natural resources unless all of the long-run marginal costs of generating and delivering power are considered.

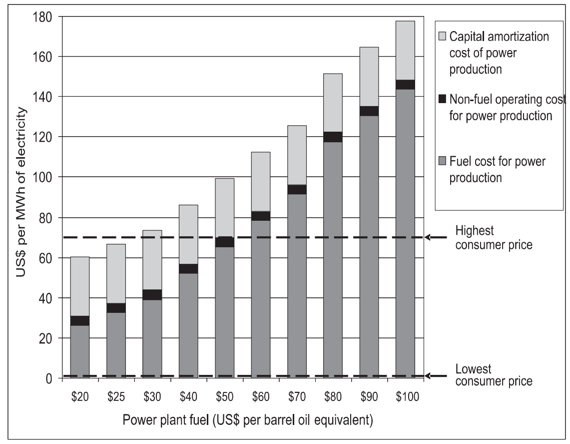

Figure 2-5. Long-run marginal costs of delivered electricity from new combined-cycle plant at a range of fuel prices.

factor of 60% was assumed. Capital costs were amortized assuming a weighted average cost of capital of 8.7% over a 20-year term, based on 70/30 debt/equity ratio, 6.0% debt interest rate and 15.0% return on equity.

Power utility recognition of district cooling benefits

Governments throughout the Middle East are grappling with the challenge of meeting rapidly growing power demands. While district cooling is viewed as beneficial in this regard, there is generally no recognition of its benefits in the structure and levels of power tariffs. Most power rates continue to be subsidized and generally do not incorporate incentives to reduce peak power demand.

> Power utilities in North America, Europe and other regions often encourage peak power demand reduction through the rate structure or with special incentives.

Power utilities in North America, Europe and other regions often encourage peak power demand reduction through the rate structure or with special incentives. Examples of this include the following:

- A portion of the cost of service, particularly for large users, may be paid in a demand charge (or capacity charge).
- Rates during the high-load summer season are often set above the rates for other parts of the year.
- Rates during high-load times of day are higher than low-load periods (time-of-day rates).
- Utilities sometimes provide a capital incentive to install technologies such as thermal energy storage, which is tied to the number of kilowatts of peak demand reduced.

Use of demand charges, seasonal and time-of-day rates and demand reduction incentives better reflects the actual cost of service and gives appropriate "price signals" to users, leading to optimal use of capital and fuel resources.

In a competitive electricity market, costs of power production can vary significantly from day to night, and this is reflected in market-based power rates. For example, prices from the New England Hourly Electricity Price Index are shown as bars in Figure 2-6, measured against the scale on the right (in US$/kWh). Not surprisingly, the highest prices occur in the period of highest demand (as indicated by the curved shaded area).

The bottom line is that there are sound economic reasons to structure power rates to better reflect actual costs, and that doing so will increase the value of district cooling generally and TES in particular.

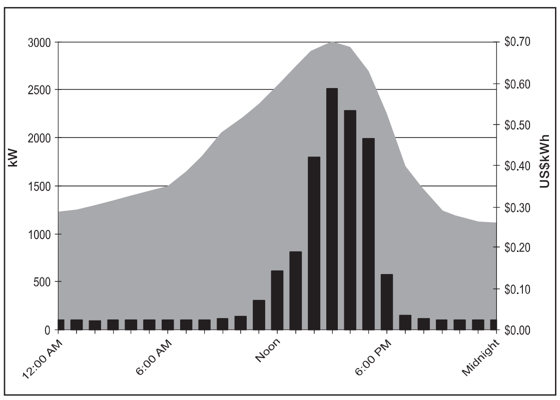

Figure 2-6. Example of time-of-day power rates compared with power demand, per New England Hourly Electricity Price Index.

2.3 Environmental Benefits

District cooling can help the environment by increasing energy efficiency and reducing environmental emissions, including air pollution, the greenhouse gas carbon dioxide (CO_2) and ozone-destroying refrigerants.

District cooling can help the environment by increasing energy efficiency and reducing environmental emissions.

2.3.1 Energy efficiency

Figure 2-7 summarizes representative annual electric energy efficiencies of several major types of district cooling systems and compares them with a representative annual efficiency of conventional air-cooled systems. District cooling reduces annual electricity consumption in new development by 45% to 86% depending on the type of technology used. Note that although gas-driven district cooling drastically reduces electricity consumption, these systems require the consumption of natural gas at the plant.

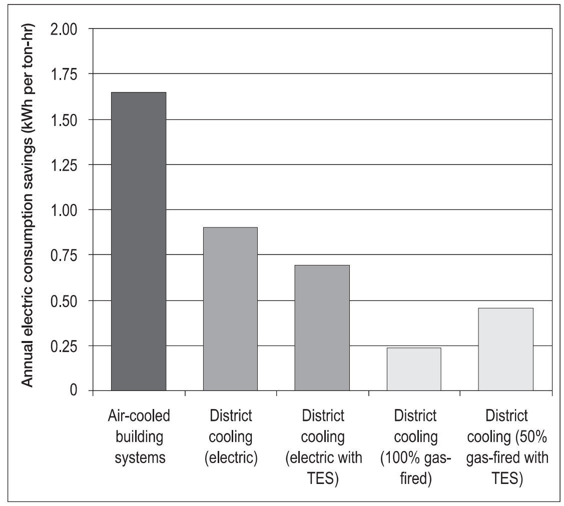

Figure 2-7. Annual electric energy consumption savings with district cooling.

A substantial portion of energy savings results from the fact that almost all district cooling systems use water to cool the chiller condensers, an inherently more efficient process than air cooling. District cooling systems are increasingly being designed so that no water is required from the municipal water system. Instead, these systems employ a variety of technologies, such as

- using seawater to cool the condensers directly (the water actually runs through the chillers),
- using seawater for cooling tower makeup,
- conditioning water by reverse osmosis desalination for use in cooling towers and
- using treated sewage effluent (TSE) for cooling tower makeup.

District cooling's superior energy efficiency results in reduced fuel consumption, with corresponding reductions in emissions of air pollution and CO_2 (the greenhouse gas that causes global warming).

2.3.2 Climate change

Most Middle East countries are parties to the United Nations Framework Convention on Climate Change. With growing international interest in strong action on climate change, and with generally high emissions per capita in the Middle East, climate change will become an increasingly important issue for the Middle East governments.

The Kyoto Protocol, an international agreement to control greenhouse gas emissions, is expected to be replaced by a more aggressive treaty with broader participation. It is widely expected that future international agreements will lead to worldwide greenhouse gas emissions trading, potentially providing economic incentives for energy-efficient technologies such as district cooling. The ultimate cost of allowances will depend on many factors, including the level of greenhouse gas reduction commitments and the specific rules of the "cap-and-trade" programs. A number of corporations are using "shadow prices" (an assumption of CO_2 emissions cost for the purpose of comparing options) of at least US$9/metric ton. Prices in the European Union emissions trading system, still in the beginning stages of implementation, averaged US$25/metric ton of CO_2 equivalent in 2006, spiked to almost US$40 in early 2006, then tumbled to US$12 later in 2006. Some studies conclude that an emissions value of US$100/metric ton will be required to bring greenhouse gas emissions down to a safe level.[2]

It is widely expected that future international agreements will lead to worldwide greenhouse gas emissions trading, potentially providing economic incentives for energy-efficient technologies such as district cooling.

2.3.3 Ozone depletion

Chlorofluorocarbon (CFC) refrigerants used in chillers destroy the stratospheric ozone layer. The ozone layer's destruction is of serious international concern because this layer protects the earth from harmful ultraviolet radiation which can cause human health and environmental damage, including increased incidence of skin cancer, cataracts, immune system suppression, damage to crops and other impacts. CFCs and some other refrigerants also act as greenhouse gases.

International agreements phased out the production of CFCs as of January 1996 and have scheduled the phaseout of hydrochlorofluorocarbon (HCFC) refrigerants. Hydrofluorocarbons (HFCs) and ammonia, which are also used as refrigerants, are not restricted by international protocols.

District cooling can be a key strategy for accomplishing an economical and environmentally wise phaseout of harmful refrigerants. Through their better staffing and operational practices for monitoring and control, district cooling systems are better able to control emissions of whatever refrigerant is used.

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[1] "A Formula for LNG Pricing," Gary Eng, December 2006.
[2] "Stern Review on the Economics of Climate Change," Nicolas Stern, Oct. 30, 2006.

3. Business Development

3.1 District Cooling as a Utility Business

It is critically important to emphasize that the design, development and operation of a successful district cooling system must be approached as a long-term utility service business. If it is approached primarily as a contracting job, with a focus on lowest first costs and without sufficient consideration of life-cycle costs and customer satisfaction, the actual return on investment for the district cooling company will fall short of expectations. Best practices therefore involve not only good engineering design, but also good organizational design. Note also that, relative to engineering, business and organizational design, it is imperative that district cooling utilities work with customers (technically and contractually) to optimize their designs and operations for compatibility with district cooling service.

It is critically important to emphasize that the design, development and operation of a successful district cooling system must be approached as a long-term utility service business.

3.1.1 Engineering design

A focus on district cooling as a long-term utility service affects the design process and design criteria in a number of ways. For example:

- The foundation of the design should be the customer requirements, and the design process should then proceed "upstream" to the piping and plant systems, rather than the other way around. The entire design, including controls, should focus on ensuring achievement of the ultimate goal: consistent, reliable comfort in customer buildings.
- Building the plant and distribution systems is only the first step, and operational costs and reliability ultimately become critical considerations. Operation and maintenance (O&M) issues should be considered from the beginning of the design process, and O&M staff should be involved in the design process.
- Design options must be evaluated based on life-cycle costs and high reliability.
- Focus on long-term reliability affects design relative to equipment redundancy, ease of maintenance and speed of response in the event of equipment failure.

A focus on district cooling as a long-term utility service affects the design process and design criteria in a number of ways.

These engineering design considerations are addressed in upcoming chapters on design of building connections, piping systems, plants and controls.

3.1.2 Organizational design

A good engineering design does not ensure success unless the organization is designed and is operated to achieve customer satisfaction. A basic issue is the degree to which the corporate culture of the district cooling company is truly customer-focused. Success will require a different culture than might have existed within a company that traditionally simply constructed facilities or sold a commodity.

A good engineering design does not ensure success unless the organization is designed and is operated to achieve customer satisfaction.

All staff should consider customer satisfaction part of their job description. This orientation should extend beyond the marketing team to everyone in the district cooling company, particularly those who have direct contact with customers, such as accounting people, meter technicians, etc. Ongoing training is recommended to ensure that all staff view themselves as being in the customer satisfaction business – and that they send the message to the customer that they are eager to understand and solve customer problems. Strong leadership, expert assistance and staff development can be key elements in strengthening the corporate culture.

The responsiveness of the district cooling company to customer needs or problems is critical to the company's success. The prospective customer must be confident that the company will do what it takes to ensure the delivery of cooling to the building. Then, once that customer is connected to the system, the company must justify the customer's confidence by providing excellent service. Increasingly, district cooling companies are also offering customer service past the building boundary – helping the customer implement and operate improvements to the building system so that cooling that is reliably delivered to the building and is also efficiently distributed within the building. Optimization of the building HVAC system can improve both delta T and occupant comfort.

3.2 Marketing and Communications

Successful district cooling business development requires focused and effective communication with potential customers and other key stakeholders, such as the government. It is essential to appropriately position district cooling service and clearly communicate the value proposition to customers, to government and to society as a whole.

3.2.1 Positioning

Successful marketing of district cooling service requires educating prospective customers regarding the full value of the technology. An essential first step is to

District cooling makes it easy.
- Increased comfort
  - even temperature
  - better humidity control
  - healthier building
- Quieter building, less vibration
- Convenient service – always available
- Flexibility to increase or decrease capacity
- Free up time to focus on primary business

District cooling reduces risks.
- Less capital tied up in building
- More predictable costs
- Less price risk as power sector is restructured
- No concerns regarding refrigerant costs and management
- Increased building value

District cooling enhances reliability.
- Highly reliable industrial units
- Sophisticated controls
- Professional operators round-the-clock
- Preventive maintenance
- Equipment redundancy

District cooling has cost advantages.
- Diversity in building loads reduces costs
- Better equipment loading = better efficiency
- Economies of scale to implement advanced technologies
- Better staff economies
- Diversity of equipment can minimize price risk

Costs of owning and operating building chiller systems far exceed the costs of electricity.
- Initial capital costs
- Opportunity cost of income or amenity value of the building area or rooftop used for equipment
- Scheduled annual maintenance
- Periodic major maintenance
- Unscheduled repairs
- Spare parts
- Equipment replacement
- Labor
- Management oversight
- Electricity
- Water and wastewater fees
- Refrigerant management

Table 3-1. Summary of customer value proposition.

position district cooling as the option that delivers a unique combination of benefits and most cost-effectively provides the greatest total value. In other words, in all communications – verbal, marketing materials, advertising, presentations, etc. – the emphasis should be on value and performance before price.

This is not to say that price is unimportant. A critical element in marketing and selling district cooling is presentation of the total value of district cooling and comparison with the costs of other options. This comparison should not be framed as a question of "Which option costs less?" Instead, the question should be, "Which option delivers the greatest total value most cost-effectively?"

3.2.2 Customer value proposition

Value proposition summary

A bulleted summary of the customer value proposition is presented in Table 3-1. Customer benefits are described more fully in Chapter 2.

> Manufacturer data for brand new equipment operating under ideal conditions is not an appropriate basis for estimating the efficiency of building chiller equipment.

Building chiller system efficiency

Estimation of building chiller system electricity peak demand and annual electricity energy consumption in the cost comparison deserves note. Consistent with the discussion in section 2.2.1 regarding power requirements of building chillers, the peak power demand for building chiller systems should be calculated based on peak ambient temperature conditions and should be adjusted for performance degradation over time. Annual electric energy consumption should be based on weighted average temperature conditions and should also be adjusted for performance degradation due to the difficult operating environment in the Middle East. Manufacturer data for brand-new equipment operating under ideal conditions is not an appropriate basis for estimating the efficiency of building chiller equipment since the specified operating situation seldom occurs in real life.

Structuring the cost comparison

The costs of district cooling can be compared with building chiller system costs in a number of ways. The simplest approach is to compare the total annual costs based on current operating cost factors and district cooling rates. In such a comparison, the capital costs must be converted into an annual amortization cost. It is important in choosing the amortization factor to make it consistent with the developer's actual weighted average cost of capital (WACC) and with a term consistent with the realistic life of the building chiller equipment. The WACC can be calculated as follows:

DR = Ratio of debt to total capital
ER = Ratio of equity to total capital
DIR = Debt interest rate
ROE = Targeted return on equity

WACC = (DR x DIR) + (ER x ROE)

So, for example, if the DR is 0.70, DIR is 7.5% and ROE is 15%, the WACC is 9.75%.

The term used for the amortization factor applied to building chiller system capital costs should be consistent with the realistic expected life of the equipment. With the harsh operating conditions in the Middle East (high heat, dust and saline humidity), equipment lives are shorter than indicated by the *2005 ASHRAE Handbook - Fundamentals*.

The disadvantage of a simplified annual cost comparison is that it does not account for potential variations in escalation of operating cost factors for building chiller systems or for district cooling. This can be addressed with a multi-year net present value (NPV) analysis in which cost factors are escalated based on projections or contract escalation allowances. If a multi-year analysis is undertaken for a period longer than the expected life of the building chiller equipment, it is essential to include not only the initial capital costs of the chiller system but also the costs of equipment replacement over time.

Communicating with prospective customers

In educating prospective customers about district cooling, it is useful to help them understand the essence of district cooling as a business as well as a technology. To this end, it can be helpful to communicate district cooling's similarities to the real estate business. Both real estate development and district cooling typically require pre-subscription to support financing and benefit from long-term customer contracts. The district cooling service contract is like a real estate lease – demand charges are like base rent and energy charges are like operating costs. Both are capital-intensive, with capital costs front-loaded. Targeted returns are achieved when the building (or district cooling system) is fully subscribed.

In educating prospective customers about district cooling, it is useful to help them understand the essence of district cooling as a business as well as a technology.

To further reinforce the real estate analogy, it is helpful to communicate using real estate terms, including expression of costs in terms of cost per square meter or square foot of building space.

3.3 Risk Management

3.3.1 Nature of district cooling company

Any business involves risk, and the district cooling business is no different. Of course, the risks vary depending on the nature of the district cooling company and its customers. For example, a development company may establish a district cooling company to serve its projects, and this parent corporation may assume some key financial risks. On the other hand, a merchant district cooling company, serving multiple customers with different ownership, must pay especially careful attention to risk management.

Ultimately, each district cooling company must determine what risks it is willing and able to accept based on its strategic goals, financial objectives and financial resources.

3.3.2 Capital-intensiveness

Development of a district cooling system is a relatively capital-intensive undertaking. Further, capital costs are "front-loaded" because of the high costs of installing basic plant infrastructure and pipe mains in the early years – in contrast to adding customers in later years with relatively short, small-diameter pipe additions and the installation of additional chillers in the plant. Given these characteristics, a fundamental risk in development of a merchant district cooling system is lower-than-projected customer load. This may be due to a low level of success in marketing to targeted customers, or as a result of slower-than-projected buildout of development by customers and/or master developer.

3.3.3 Will visions be realized?

Throughout the Gulf region, very ambitious development projects are announced on a seemingly daily basis. The prefix "mega" is frequently used. Many projects envision a buildout of a massive mixed-use development over a number of years, starting with an often highly aggressive schedule for the first phase. Yet development projects very frequently experience delays in getting the initial phase completed. This problem has increased due to the large number of "mega" projects in the region and the resulting competition for materials, equipment and contractors. Thus, in the short term, schedule creep is almost a certainty. In the long term, the reality is that there is a limited ability for the marketplace to absorb new space on a sustainable basis, and master developers cannot be sure that their long-term visions will be realized.

In negotiating service agreements, the district cooling company should agree to no more risk than the developer is accepting so that, in the event the building is not fully sold out, the district cooling company is not then holding "stranded" investments that can't be paid in the absence of building occupants.

> There is a limited ability for the marketplace to absorb new space on a sustainable basis, and master developers cannot be sure that their long-term visions will be realized.

3.3.4 District cooling company risks

Stranded capital

Despite the lack of certainty regarding realization of long-term real estate development plans, district cooling companies are expected to design and install infrastructure to meet both the short- and long-term requirements. Avoiding district cooling revenue shortfalls if the master developer's buildout dreams are not realized requires careful attention to ensuring that contracts with master developers and customers mitigate the district cooling company's risks that infrastructure capital will be stranded by a delay in buildout or a reduction in the development's ultimate size. One way to accomplish this is to ensure that fixed-capacity charges are consistent with actual district cooling investment costs as the system is built out, rather than the long-term capacity costs per ton applied to the relatively low-ton load in the near term.

Temporary chillers

All too frequently, some customers require cooling service before a permanent district cooling plant can be built. Temporary chillers are expensive to operate, particularly if, as is often the case, there is no power available so that power generation with engines must also be provided to run the temporary chillers. If completion of the permanent plant and related distribution piping is delayed, the district cooling company must operate this expensive capacity for a longer period. This possibility highlights the importance of being conservative in projecting the time required to complete the permanent facilities and eliminating, or at least limiting, the district cooling company's liability to absorb high operating costs for temporary chiller plants.

Construction risks

Underground congestion
Since underground construction is a key element in developing district cooling systems, a significant risk is higher-than-anticipated costs due to unforeseen congestion in underground services already in the street. Underground obstacles should be considered early in the planning process. To the extent that good data on underground service locations is lacking, safety margins should be incorporated into the construction budget. In addition to congestion, underground soil conditions can present surprises for the pipe installer. Excessive sand will require additional and unplanned support, while rocks could slow the installation process. Soil samples in advance of the installation help to mitigate surprises.

Community relations
Construction of the district cooling distribution system often results in disruptions that can pose public relations risks. The inconvenience of restricted traffic and real or imagined harm to downtown businesses can lead to negative feelings among the public, downtown businesses and the city government. Going the extra mile to proactively address potential concerns will pay many dividends. Best practices include these proactive steps:

- Communicate early and often with the potentially affected parties (building and business managers, city government and the general public).
- Include affected parties in planning to the extent possible.
- Be accessible, responsible and accountable.
- Be aware of upcoming street repairs and closures.

General construction issues
As with any other facility construction project, there are risks associated with unforeseen conditions, accidents or contractor performance, which can lead to higher costs, delayed completion or quality control problems. Addressing these risks is fundamentally no different than other facility construction-related risks. For example, best practices include

- using reputable contractors and vendors under strong contracts;
- implementing a thorough procedure of pre-operational equipment and system checks, integrated with the construction process;
- being sure to identify who is responsible for risk issues as well as delays and addressing unforeseen events;
- establishing a reliable and effective communications plan and documentation system; and
- addressing passivation of piping systems that transport the district cooling water, up to and including heat exchangers.

Following best practices is especially critical for distribution system construction because this is a more specialized area and the cost of rectifying problems is high.

Revenue generation risks

Inadequate chilled-water delivery
Poor comfort control is a revenue generation risk because a hot customer is not paying for all the cooling that it needs. It is important for district cooling utilities to understand that good control of supply-water temperature

inside customer buildings is the key to this. From a business standpoint, it is critical to provide customers with water cold enough on the building side of the energy transfer station (ETS) to provide all of the required cooling.

Poor comfort control is a revenue generation risk because a hot customer is not paying for all the cooling that it needs.

Delays in connecting buildings

Initiation of district cooling service requires timely action not only by the district cooling company, but also by customers, who must connect their building system for interface with the district loop. As a result, there are risks of reduced revenues due to delays in connecting buildings. These risks can be reduced through ongoing customer communication and technical assistance during the building conversion process, as well as through contract provisions requiring initiation of payments at a certain date.

Metering

Appropriate billing of district cooling customers requires accurate metering. Risks related to inaccurate metering include low revenues, resulting in diminished profits, and potential customer relations problems due to overbillling.

These risks can be minimized through procurement of high-quality meters and a strong program for maintaining them.

The extent of revenue risk associated with low occupancy depends on the district cooling rate structure.

Reduced building occupancy

Many residential properties with district cooling service are being sold in the Middle East as an investment opportunity, with little expectation of ongoing occupancy at least in the near term. The extent of revenue risk associated with low occupancy depends on the district cooling rate structure. As discussed below, a single rate (price per ton-hour) exposes the district cooling company to a variety of risks, including revenue reduction resulting from low occupancy rates or energy conservation measures. A two-part rate structure reduces or eliminates these risks, depending on the specific rate structure and its relationship to costs.

3.4 Rate Structures

District cooling rates may be structured in a variety of ways. Most district cooling rates include capacity rates (sometimes called demand rates) and consumption rates (sometimes called energy rates). Connection charges may also apply, depending on the application and economic requirements of the utility and its customer.

The district cooling company may own part or all of the ETS equipment. The ETS is the contractual energy transfer point and physical boundary between the provider and customer's equipment.

3.4.1 Capacity, consumption and connection rates

Capacity rates

Capacity rates are charged to recover some or all of the district cooling provider's fixed costs (i.e., debt service, depreciation, labor, administration). Fixed costs generally do not vary in the short run with increases or decreases in the amount of energy provided. Capacity rates are linked to the contracted capacity and are usually escalated at a rate lower than general inflation.

Consumption rates

Consumption rates are charged to recover at least the variable costs, which vary in the short run with increases or decreases in the amount of energy (i.e., fuel, electricity, water and chemicals). Consumption charges are typically designed to recover the variable costs and may also help recover some fixed costs.

Connection charges

Some district cooling utilities also require a connection charge. This is a one-time fee to connect to the system. In some instances this is a negotiated tradeoff between initial capital costs and operating costs based on the building developer's financial preferences. Other district cooling companies establish a fixed charge per ton of peak demand. Others base the connection charge for a particular customer on the additional revenue required for the utility to meet its return on investment (ROI) criterion. The amount depends on how much it will cost for the utility to install pipes and other equipment to connect the customer to the system.

Some district cooling utilities provide the heat exchanger (which transfers cooling energy from the district cooling system to the building air-conditioning system) and the district cooling meter, thereby offsetting costs that the customer would otherwise incur to obtain district cooling service.

Regional rate examples

Examples of 2007 district cooling rates from the Gulf Region are illustrated in Figure 3-1, showing the breakdown of capacity, commodity and connection charges. Note that not all of the rate examples can be directly

A capacity and consumption rate structure is recommended, and almost all district cooling utilities use such a rate structure.

compared because of differences in electricity and water costs, which directly affect commodity charges.

3.4.2 Rate structure recommendations

Capacity rates

A capacity and consumption rate structure is recommended, and almost all district cooling utilities use such a rate structure. If the rate structure is limited to a single rate per ton-hour, there will be a poor match of monthly cash flow to monthly costs. There will also be the risk of inadequate revenues if annual cooling energy requirements are lower than projected due to projection error or cooler-than-normal temperatures. This is especially critical in serving real estate developments with many absentee owners with low annual occupancy rates, as is the case with many current developments in the Gulf Region.

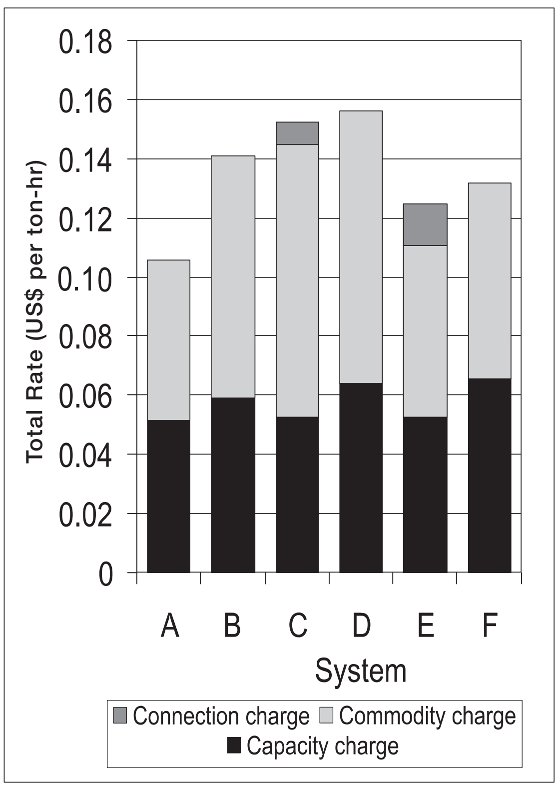


Figure 3-1. Examples of Middle East district cooling rates.

Capacity and energy charges also provide a basis for tying prices to related costs, and if contract demand is updated based on metered demand, this approach provides a useful price signal to the customer. For example, customers will be motivated to reduce peak demand, which frees the district cooling utility to sell this capacity to others.

A capacity and consumption rate structure can present marketing challenges if it is too strongly weighted to the capacity charge. Customers may find it difficult to understand why they must pay a significant part of their annual cooling costs in a fixed monthly charge, even in winter. This should be addressed through a specific and well-designed communications effort in marketing and ongoing customer relations.

Connection charges

From the district cooling company's standpoint, connection charges can help mitigate near-term capital requirements, covering service line and ETS-related costs, and sometimes defray distribution system extension costs. On the other hand, mandatory connection charges can present a marketing challenge in that they counter a key element in the district cooling value proposition – eliminating or drastically reducing the building developer's capital costs associated with cooling. It is often advantageous to provide a range of options for balancing connection charges and capacity charges, thereby increasing the district cooling company's ability to adapt to a range of customer circumstances and attitudes regarding tradeoffs between capital and operating costs.

Initial contract demand

It is important to establish the initial contract demand as accurately as possible because (1) if the demand is too high, it increases the marketing challenge; and (2) if the demand is too low, the district cooling company will not recover its costs, and there may be inadequate capacity to meet the actual peak demand.

Although reducing the contract demand is tempting as a strategy for getting customer contracts signed, this approach should be carefully and infrequently used only if truly necessary to "jumpstart" a customer base. A technique that has worked for other startup district cooling companies is to offer "curtailable" demand at a reduced cost. This curtailable capacity reservation would be subject to reduction during peak times if the district cooling company supplier needed the firm capacity to serve other customers. This option could introduce customer satisfaction issues and therefore should only be considered as a negotiating tool to close a deal that needs a small price incentive.

One of the biggest challenges in the district cooling industry is encouraging building design choices and operational practices that will help optimize total system performance.

Rate design to encourage optimal building design and operation

One of the biggest challenges in the district cooling industry is encouraging building design choices and operational practices that will help optimize total system performance. Good rate-structure design can help the customer make the best choices with the greatest total cost optimization benefit.

To this end, it may be worthwhile considering some variations in capacity, consumption and connection rates based on the compatibility of the building system design and operation with optimal district cooling service parameters. The district cooling company incurs additional costs for extra infrastructure, operating and energy costs if the building system isn't designed and operated to be optimally compatible. It is important to manage these elements with a contract that provides an economic incentive for the building owner to do the right thing for his or her building and the district cooling utility.

Some district cooling utilities address poor delta T performance through the consumption charge. For example, there may be an "excess flow" penalty charge based on the extent of the difference between actual delta T and the target delta T. However, such mechanisms generally don't address the full economic impact of low delta T, which affects not only variable costs but also fixed costs, particularly capital costs.

Another incentive mechanism is revising customer contract capacity after an initial period of operation (e.g., two years), based on actual metered peak demand. This allows contracts to be brought in line with actual (instead of estimated) demand. It also supplies an incentive for buildings to operate the building system in ways that reduce peak demand on the district cooling system, thereby freeing up capacity for the system to serve other customers. Incorporating a contract capacity reset may or may not be advisable for a given district cooling business, depending on the maturity of the system, the prospects for growth and technical constraints on growing the customer base.

3.5 Performance Metrics

Early consideration should be given to metrics that define the successful development and operation of a new district cooling system. Such performance metrics must be established and systems put in place to measure the key parameters.

Examples of performance metrics might include the following:

Customer service
- number of customer outage hours
- number of customer complaint calls

System operations
- total variable operating cost (US$/ton-hr)
- peak electrical demand (kW/ton)
- average electric energy efficiency (kWh/delivered ton-hr)
- water consumption (l/ton-hr or gal/ton-hr)
- system delta T performance at peak (temperature difference between supply and return)

Financial performance
- capital cost to engineer, procure and construct (US$/ton)
- internal rate of return on total invested capital (%)
- return on equity (%)

Environment
- estimated emissions impact (CO_2 emission reduction/ton-hr)
- estimated demand reduction on the electrical grid (kW/ton)

> Early consideration should be given to metrics that define the successful development and operation of a new district cooling system.

4. Design Process and Key Issues

4.1 Load Estimation

Defining the cooling load is the foundation for designing a district cooling system. Properly estimating cooling loads affects the design, operation and cost-effectiveness of the district cooling system in many ways, including

- ensuring sufficient but not excessive plant and distribution capacity,
- providing the ability to cost-effectively meet the daily and seasonal range of loads and
- providing a basis for accurate revenue projections.

Properly estimating cooling loads affects the design, operation and cost-effectiveness of the district cooling system in many ways.

District cooling systems typically provide cooling to a variety of building types, including commercial offices; retail shopping centers; hotels; and educational, medical and residential buildings. Although weather is a key driver of cooling loads, occupancy, lighting, computers and other equipment also create load independent of weather. Depending on building use and many case-specific factors, these loads can be quite significant. Operational practices and controls also have a significant impact on total cooling energy requirements (e.g., reducing fresh-air intake at night would substantially reduce dehumidification and cooling requirements).

For most district cooling systems, particularly in the Middle East, customer loads consist primarily of new buildings. Consequently, in most situations, cooling loads must be projected without the aid of historical data for the specific buildings. It is possible, however, to use historical data from similar buildings in the same climate to help estimate reasonable loads. This type of data should be used to provide a "reality check" on the load estimates provided by consulting engineers for developers and building owners and managers. These estimates, based on HVAC rules of thumb or building modeling programs, tend to overstate loads.

Computerized building simulation programs are available to determine building peak design cooling loads and to predict monthly, daily, and hourly cooling loads that must be satisfied. Load estimation modeling typically addresses these key variables:

- weather
- building envelope, particularly windows
- lighting and computers
- number of people in occupied areas
- outside air for ventilation
- occupancy schedule

Load estimates based on HVAC rules of thumb or building modeling programs tend to overstate loads.

The international experience of the district cooling industry over the past 30 years is clear: Conventional methodologies and software tend to overstate peak loads. This is understandable, given the consequences of underestimating loads for the purposes for which these methods are used. The last thing a consulting engineer wants is to be blamed for inadequate capacity. Consequently, typical load estimation methodologies tend to result in unrealistically high load estimates. Design practices that contribute to high load estimates include

- using higher than the ASHRAE design temperatures for wet bulb and dry bulb,
- assuming the peak dry-bulb and wet-bulb temperatures are coincident,
- compounding of multiple safety factors and
- inadequate recognition of load diversity within the building.

Overestimation of load can be painful for a district cooling company in many ways.

Overestimation of load may be appropriate for a building HVAC consulting engineer who wants to make absolutely sure that the customer has sufficient capacity. But for a district cooling company, these conservative methodologies, or rules of thumb that are similarly conservative, can be painful in many ways. They can lead to

- overinvestment in district cooling infrastructure,
- overprojection of revenues,
- disagreements with prospective customers' engineers regarding contract loads (excessively high contract demands can sink the economics of district cooling) and
- poor efficiencies in meeting low loads in the early years of district cooling system growth.

District cooling system load estimates are often overstated because the buildings are not brought online according to the predicted schedule and the load does not materialize until later. This results in problems for the district cooling plant at low-flow conditions (e.g., control valve sizing).

There are three major aspects of customer load projections:

- peak demand
- peak-day hourly load profile
- annual cooling load profile

4.1.1 Peak demand

Peak-temperature conditions for cooling design are very high in the Middle East. Figure 4-1 summarizes the 0.4% dry-bulb and mean-coincident wet-bulb temperatures (temperatures exceeded only 0.4% of the time) per the *2005 ASHRAE Handbook – Fundamentals*. Design dry-bulb temperatures range from 35 C to 47 C (95 F to 117 F), with mean coincident wet-bulb temperatures ranging from 18 C to 25 C (64 F to 77 F).

Figure 4-2 summarizes the 0.4% wet-bulb and mean-coincident dry-bulb temperatures. Design wet-bulb temperatures range from 21 C to 31 C (70 F to 87 F), with mean-coincident dry-bulb temperatures ranging from 28 C to 40 C (83 F to 104 F).

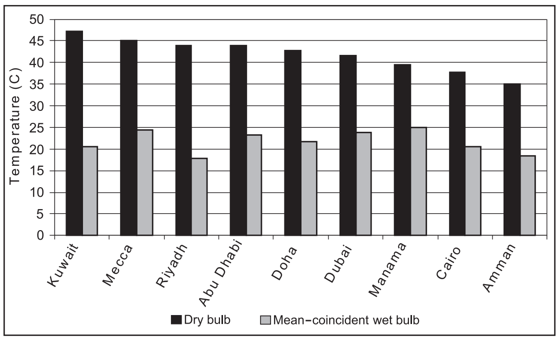


Figure 4-1. Design dry-bulb and mean-coincident wet-bulb temperatures for selected Middle East cities (ASHRAE 0.4% design point).

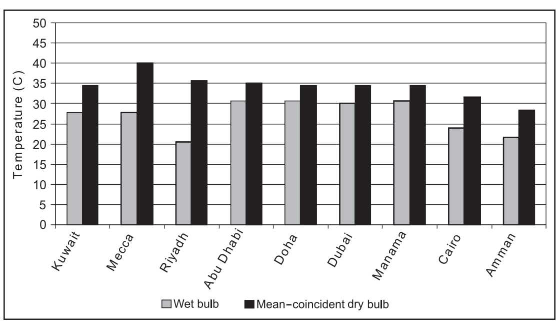


Figure 4-2. Design wet-bulb and mean-coincident dry-bulb temperatures for selected Middle East cities (ASHRAE 0.4% design point).

"Diversity factors," also called "coincidence factors," are extremely important elements in peak load estimation. These factors are used to account for the fact that not all loads have their peak at the same time. This occurs within a building, between buildings and between building usage types (e.g., offices compared to residential). In addition, particularly with recreational investment properties, diversity factors must also account for variations in occupancy.

Actual peak demands for district cooling customers in the Middle East range from 20 to 52 square meters per ton (sq m/ton) (215 to 560 sq ft/ton), with a representative value of 35 sq m/ton (377 sq ft/ton) for systems serving a mix of customer types. With the recent new regulations regarding building efficiency and the drive for green buildings in the Gulf Cooperation Council, the peak cooling demand in new buildings is expected to decrease, with values reaching 45 sq m/ton (484 sq ft/ton) or more expected in the near future.

The ultimate level of system load diversity (coincident district cooling system peak demand compared to the sum of individual peak demands) depends on the mix of building types, building operating practices and the system's maturity. A district cooling system at the early stages, with relatively few buildings served and/or relatively little diversity in building types, will have a very small system load diversity. On the other hand, a large system serving many types of buildings may have a diversity of 0.85 or lower (coincident peak district cooling system load is below 85% of the sum of individual annual building peak demands).

4.1.2 Peak-day hourly load profile

The peak-day load profile should be modeled based on building use, occupancy schedule, weather, HVAC system characteristics and other case-specific variables. Load profiles vary significantly with building use. Examples of profiles from the Middle East are shown in Figure 4-3. While offices, hotels and residential buildings tend to peak in the late afternoon, retail buildings typically peak in the evening.

If customer buildings operate with night setback in the off-peak months or reduce cooling use during the weekend, there can be very high peak loads coincident with the initial call for cooling the next morning. This should be addressed by using controls to limit any excessive rise in building chilled-water temperature or space temperature and humidity.

Particularly relative to office buildings, an important variable is whether or not the building operators shut

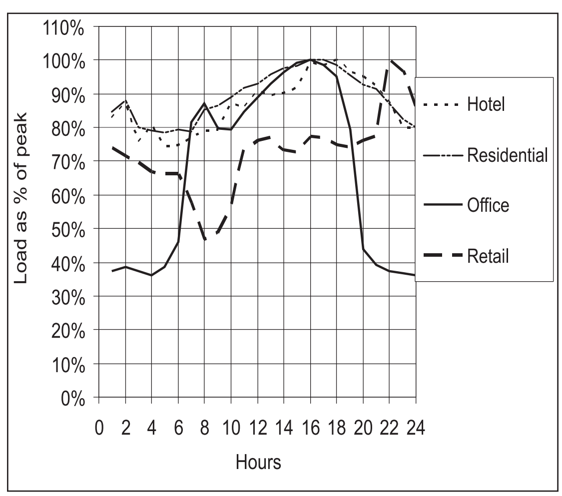


Figure 4-3. Example peak-day load profiles for various building types.

down fresh-air intake at night. Decreasing fresh-air intake at night would cut down dehumidification requirements and load.

Figure 4-4 shows an illustrative district cooling system peak-day load profile for a sample mix of buildings (40% office, 16% retail, 27% residential and 17% hotel). In this example, average peak-day load is 78% of the hourly peak, providing a potential opportunity for thermal energy storage to be used as part of the district cooling system.

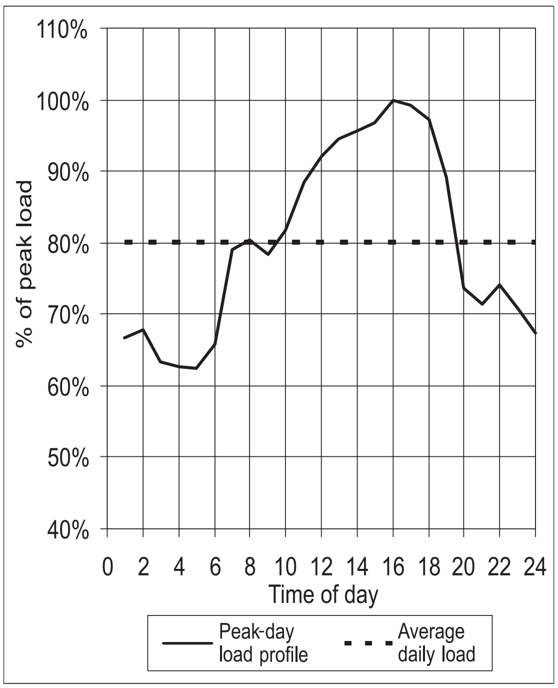


Figure 4-4. Illustrative peak-day load profile for district cooling serving mixed building types.

4.1.3 Annual cooling load profile

Estimating annual cooling energy is essential for proper evaluation of plant alternatives and revenue projections. Modeling of hourly loads throughout the year enables the development of an annual load duration curve. See the example annual load duration curve for a mixed-use district cooling system in the Middle East shown in Figure 4-5.

The load-duration curve is useful for evaluating plant options because it provides information on how many operating hours a given element in the dispatch order can be used. The annual load profile also enables calculation of the total annual energy, and thus the annual equivalent full-load hours (EFLH) for the system, which is critical for rate structure development and revenue projections.

> The load-duration curve is useful for evaluating plant options because it provides information on how many operating hours a given element in the dispatch order can be used.

EFLH is the ratio of annual cooling energy to the peak demand and can be calculated with the following equation:

$$\text{EFLH} = \frac{\text{Annual Cooling Energy Consumption (ton-hr)}}{\text{Peak Hourly Consumption (tons)}}$$

For Middle East countries, the full-load hours are normally in the range of 3000 to 4600. In the case graphed in Figure 4-5, there are 3978 EFLH.

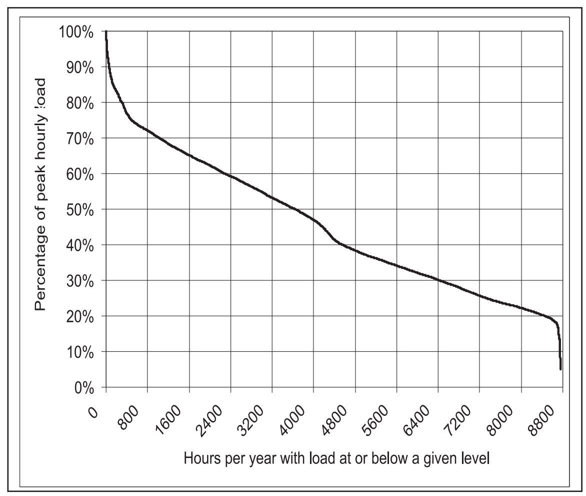


Figure 4-5. Illustrative district cooling annual load-duration curve.

4.2 Design Temperatures and Delta T

4.2.1 Delta T is a key parameter

Delta T is a key parameter in the design and operation of district cooling systems and is an excellent measure of total system performance at any load condition. It is the difference between supply and return temperatures measured across the chillers, plant, distribution, energy transfer stations and customer buildings. Flow is inversely proportional to delta T. With high delta T, less flow, pump energy and equipment capacity are required to satisfy cooling requirements.

District cooling customers expect to receive efficient, reliable and cost-effective cooling. While it is very important to achieve high delta T in the distribution system and in the plant(s), it should not come at the expense of customer comfort or control. High delta T (and high chilled-water return temperature) should be achieved, but not directly controlled.

Low delta T results in wasted energy, limited available capacity, added complexity and loss of comfort control.

With a comprehensive strategy to design *and* operate the system to achieve high delta T at all load conditions, it is possible to reduce unnecessary capital, operating and energy costs and significantly improve the performance and economics for both a district cooling company and its customers.

This is not a task that should be taken lightly. In the Middle East and in the broader district cooling industry, low delta T remains one of the most common, troublesome and unresolved problems. Low delta T results in wasted energy, limited available capacity, added complexity and loss of comfort control.

For a district cooling system to be successful, it is essential that all elements of the system are integrated and operate together without compromising performance. This includes

- building HVAC systems,
- energy transfer stations,
- chilled-water distribution system and
- district cooling plant(s).

Achieving high delta T requires a savvy technical and business approach that goes beyond typical industry practice. Tariffs in contracts should enable customers to make sound economic decisions in their buildings that enhance delta T performance. District cooling companies should prepare technical guidelines and work with their customers to achieve success.

The goal is to design the plant and distribution system for as large a delta T as practically possible and to provide the design, operations and business guidelines to ensure it will be achieved with each customer in operation. This means the lowest-possible supply chilled-water temperature and the highest-possible return temperature.

Supply-water temperature is limited by the district cooling plant and distribution system performance. Return-water temperature is typically limited by cooling coil performance in customer buildings. These factors are also interrelated. With proper control, cold supply-water temperature to cooling coils enables them to produce a higher return temperature.

With low delta T in the distribution system, the district cooling provider is forced to process the “excess” chilled water. For example, there are 315 liters per second (l/s) (5,000 gpm) excess flow at 10,000 tons of load if the system is operating at 6.7 C vs. 8.9 C (12 F vs. 16 F) design delta T. There are three choices to process the excess flow:

- Overflow chillers in operation.
- Turn on additional chillers or expend TES sooner.
- Blend return water with supply water.

None of these options is ideal for energy, capacity or control.

Life-cycle costs should be analyzed for the entire system (building HVAC, ETS, distribution, plant) to optimize total economic performance.

For district cooling systems serving new construction (as is the case with most systems in the Middle East), life-cycle costs should be analyzed for the entire system (building HVAC, ETS, distribution, plant) to optimize total economic performance. For example, lowering the supply-water temperature from the plant (with colder chiller leaving-water temperatures, ice storage, or low temperature fluid) may significantly reduce the cost of pumps, piping, valves, fittings and heat exchangers for the district cooling company. This can also reduce the cost of customer pumps, fans and ductwork if lower supply-water and supply-air temperatures are used. However, lowering the supply-water temperature has certain operational and efficiency drawbacks, as discussed below.

Furthermore, high return-water temperatures can be achieved with smart investments in building systems (control valves, air handlers, cooling coils) and a sound delta T strategy. Individual system components may have marginally higher costs (e.g., more cooling coil rows or more coils in series), but the total system capital and/or energy costs may be significantly reduced.

4.2.2 Limitations on lower chilled-water supply temperature

Chiller efficiency

Centrifugal chiller power requirements depend mainly on how much refrigerant flow the compressor has to pump and what pressure differential the compressor must overcome.

The first is dependent on the system cooling load requirements, which are a given. The second is determined by the difference between the condensing and evaporating temperatures or what is referred to as the “lift.” Entering condenser water temperature is limited by the ambient wet-bulb temperature as well as the number and capacity of cooling towers in operation. Leaving chilled water can be increased or decreased, also changing the lift. The lower the supply chilled-water temperature, the higher the lift, and hence the more power the compressor has to overcome to help produce the same refrigeration effect. The added power may be offset by a reduction in pumping power achieved with higher delta T.

Evaporator freezeup

The other limitation to how low the chilled-water temperature can go is its freezing point. If chilled water is going to freeze, it will start to do so at its lowest temperature location: somewhere inside the evaporator tubes. The effects are catastrophic, damaging the evaporator. Evaporator tubes may corrode and thin, adding to the problem.

For safety reasons, the minimum design chilled-water temperature is usually determined to be around 3 C (5 F to 6 F) above its freezing point. Minimum velocities are set to prevent a sudden drop in heat transfer because of laminar flow. Enhanced chiller tubes or turbulators may be selected to help strip away laminar boundary layer flow. Where even lower chilled-water temperatures are desired, an anti-freeze agent may be added to the chilled-water media to prevent freezing. A supply-to-return-water bypass may be added to ensure minimum flow.

Thermal energy storage

The majority of thermal storage systems in the Middle East are based on chilled-water storage technology. As discussed in Chapter 7, a variety of ice storage systems are also available.

Most chilled-water thermal storage systems are based on designs that exploit the tendency of warm and cold water to stratify. That is, cold water can be added to or drawn from the bottom of the tank, while warm water is returned to or drawn from the top. A boundary layer or thermocline, which can be from one to a few feet in height, is established between these zones. Specially engineered diffusers ensure laminar flow within the tank. This laminar flow is necessary to promote stratification since the respective densities of the return water and supply water are in fact almost identical because of the relatively small differential temperature of the supply and return.

Therefore, thermal stratification of the chilled water inside the tank has to be maintained at all times. While maximizing the delta T helps maintain the stratification, this is constrained by the fact that the minimum supply temperature is the temperature at which the water density is at its maximum (at 4 C or 39 F). If supply chilled-water temperature gets below this point, the less-dense colder water will start moving up in the storage tank, upsetting the carefully maintained thermocline and causing mixing.

Thermal storage generally designed for peak shaving or load leveling can substantially offset part of the chiller capacity in the plants and contribute to reduction of peak electric load.

4.2.3 Limitations on higher chilled-water return temperature

Dehumidification and coil performances

Higher delta T or "low-flow" designs provide required cooling capacity by using less water at colder temperatures. How does reduced water flow affect the performance of the cooling coil? An understanding of thermodynamics and the heat-transfer equation, Q = U × A × LMTD, tells us that less water flow through the coil tubes reduces heat-transfer coefficient U (waterside resistance to heat transfer increases). But as Figure 4-6 illustrates, the log-mean temperature difference (LMTD) increases because the entering-water temperature is *colder*.

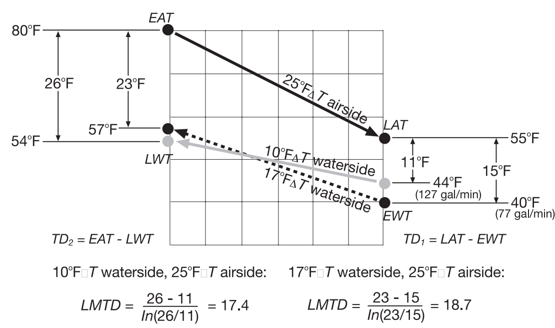


Figure 4-6. Effect of increased delta T on LMTD of cooling coils.

Source: Trane Engineers Newsletter 31 Vol. 1.

Lower supply temperature tends to increase the LMTD and this helps offset the reduced heat-transfer coefficient; however, a higher return-temperature value has an opposite effect. The higher the return temperature, the lower the LMTD.

The total effect on a specific coil performance is a balance of the effect of the above factors. To illustrate the effect of high return temperature on coil capacity, look at the effect of return chilled-water temperature on the latent heat capacity of the coil. Dehumidification occurs only when coil surface temperature is below the dew point of the air touching the coils.

For a 100% fresh-air unit, the entering-air design conditions are that of the ambient conditions outside. Because the ambient design conditions should not be overestimated (a common mistake), it is best to use ASHRAE's latest published 0.4% values.

For example, the 0.4% weather design data for Abu Dhabi is a dry bulb of 43 C (109.4 F) and a mean-coincident wet bulb of 23.8 C (74.9 F). The dew point at the ambient design conditions 15.0 C (59.1 F), while the dew point at typical indoor comfort conditions (recycled return air for comfort air conditioning) is 14.4 C (57.9 F) at 25.5 C (78 F) dry bulb and 18.3 C (65 F) wet bulb. This means that whenever the coil surface temperature exceeds the above dew-point temperature values, the latent capacity of the coils will suffer.

To determine the exact impact on coil performance characteristics, use an ARI-certified cooling coil rating and selection program to assess performance in different conditions. The typical return-water temperature beyond which coil latent load capacities become too high is about 15.6 C (60 F). But this is only a rule of thumb and has to be checked based on actual load and coil selection information. That is not to say that special coils with more circuits per row and smaller coil diameters that can handle higher-than-typical return-water temperatures are not available from various manufacturers, but this usually has some cost penalty.

It should be noted, on the other hand, that low flows tend to reduce the overall costs of a building's HVAC system because of the following:

- Smaller pipes and headers to handle the lower flows. This means smaller fittings, valves and less insulation. This is where most of the savings are realized.
- Smaller pumps and pumping power requirements.

With proper control and chilled-water supply and leaving-air temperatures at design, a cooling coil should deliver better than design delta T at all load conditions.

With proper control and chilled water supply and leaving-air temperatures at design, a cooling coil should deliver better than design delta T at all load conditions.

Heat exchanger approach temperature

With indirect ETS connections, the heat exchanger's design has an impact on the chilled-water temperature on the customer or building side of the heat exchanger. There is a limit to how low the approach temperature (the difference of temperature between both sides of a heat exchanger) can be driven, after which its cost and size become determining factors. Typically this limit of temperature differential is around 1.1 C (2 F) between the between the entering-primary and leaving-secondary connections.

4.2.4 Best practice recommendation

It is critically important to give customers and their consulting engineers standards for building-side design. It is also important to verify that they commission and balance the building-side system and verify that the target delta T is achieved. Allocating time and resources to educate design and operating engineers will pay many dividends.

It is critically important to give customers and their consulting engineers standards for building-side design.

A successful district cooling system design should push towards maximizing the delta T. A district cooling system serving new buildings, designed with proper guidance, should be able to achieve a delta T of 8.9 C to 12.2 C (16 F to 22 F). For example, with a typical supply temperature of 4.4 C (40 F) delivered to the customer building system, return temperatures between 13.3 C to 16.7 C (56 F and 62 F) are achievable.

Strategies for achieving high delta T are discussed in Chapter 5.

4.3 Master Planning

In planning a major district cooling system, it is important to develop a long-range development plan at the initial design stage based on solid intelligence about the potential customer base. The plan should be regularly updated based on new developments and new information. Here are key steps in developing the initial plan:

1. Gather data on the potential load, including estimated peak demand, age and condition of current cooling equipment and refrigerant conversion status.

2. Identify the highest concentrations of cooling load.

3. Evaluate potential customers to identify which have the greatest likelihood of taking cooling service.

4. Develop a preliminary pipe routing that connects targeted load and appears feasible from an initial review of underground space availability and coordination with plans for other utilities and roadways.

5. Locate feasible potential plant sites that will utilize space well, are adjacent to the load concentration and have reasonable access to power supply and sources of condenser cooling water.

6. Perform pressure-drop calculations or computer modeling to locate trouble spots and refine the distribution design and plant locations as needed.

Consideration of condenser-cooling options is critical for district cooling plant siting in the Middle East.

7. Perform a business case analysis of design options.

Consideration of condenser cooling options is critical for district cooling plant siting in the Middle East. In addition to considering adequate supply of power for a district cooling plant, evaluating condenser cooling alternatives should be done at an early stage. Depending on the condenser cooling option, the plant site may require

- pipeline access corridor to the sea,
- pipeline access corridor to sewage treatment facilities or treated sewage effluent lines,
- access to municipal water supplies and/or
- plant site area for wastewater treatment facilities.

It is very important for the district cooling provider to work with the master developer to identify a strategic plant location(s) for reasonable piping distribution installation (sizes and pumping energy) and not be forced into placing an unreasonably sized plant in a bad corner of the development. Unfortunately, sometimes district cooling companies are pushed to site a huge single plant at an extreme end of a large development and pump chilled water long distances through giant pipes, when two smaller, more reasonably sized plants in more strategic locations would have been a much better solution. The developers deem their property so valuable that they don't want to allocate any space in prime locations for cooling plants and, unfortunately, the district cooling companies do not (or think they cannot) exercise any influence in these decisions.

Planning is critical to minimizing economic risks associated with decisions made at the design stage, including

- cost inefficiencies and/or constraints on expansion due to lack of a long-range plan;
- installation of more plant capacity than required;
- reduced distribution system capacity due to inaccurate estimation of the temperature difference between supply and return;
- inability to connect desirable customers due to routing or sizing of pipes;
- losing opportunities to purchase real estate for optimal location of plant facilities;
- inability to use the lowest-cost production facilities for base-load service due to routing or sizing of pipes; and
- high pumping costs, poor performance in customer heat exchangers and poor utilization of capital assets due to hydraulic imbalances caused by poor distribution design.

It is important to note that the initial master plan is only a guideline for decision-making, not a blueprint, because appropriate decisions about buildout of the district cooling system must necessarily be made in reaction to the actual timing and location of building development.

There is usually uncertainty regarding where, or at least when, development will occur, so the master plan must be based on assumptions regarding the pace, type and location of development. This is the plague of district energy system development: Inevitably, a building intended to be served by district cooling requires service before the district cooling loop was planned to be extended to that area. In these cases, a temporary chiller plant can be installed, the building can be dropped from district cooling plans, or (if the building is big enough) it can be built with its own chiller plant which can later be used for the district cooling system as backup or peaking capacity.

4.4 Permitting (Way Leaves)

Permitting requirements vary significantly depending on the location and will likely include interaction with municipal and national agencies relative to plant facilities, chilled-water distribution pipes, condenser cooling water supply and discharge piping. Here are some important related recommendations:

- Start early to work with permitting authorities.
- Communicate to these groups the benefits of district cooling relative to power demand reduction, air-conditioning quality and reliability, and air pollution and carbon dioxide emission reductions.
- Establish and maintain essential close coordination with roadway and other utility infrastructure construction.
- Proactively address potential concerns about disruptions caused by plant and distribution system construction – communicate early and often.

It is important to proactively address potential concerns about disruptions caused by plant and distribution system construction.

4.5 Integration of District Cooling With Other Utility Infrastructure

4.5.1 Growth and infrastructure stresses

The Middle East is a dynamically growing area, creating stresses on utility infrastructure including cooling, power, potable water, wastewater treatment and roads. District cooling has become a key strategy for reducing power demands as massive development takes place in the region. However, district cooling systems require water for optimal energy efficiency, thus creating stresses on water supply. Potential water sources include treated sewage effluent (TSE), brackish ground water, untreated seawater and partially or fully desalinated seawater.

There are great potential economic and environmental benefits from integrating planning for energy and water utilities.

Water has always been a fundamental issue in the region, even without considering air conditioning; what has changed is the scale of the challenge. Some countries, such as Saudi Arabia, Kuwait and Qatar, use nonrenewable groundwater resources in large quantities, causing depletion of these valuable resources and, in some cases, deterioration in water quality. Seawater desalination is a critical element in meeting growing water needs throughout the Middle East. At the same time, substantial investment will be made in wastewater treatment facilities to serve new developments.

There are great potential economic and environmental benefits from integrating planning for energy and water utilities, not only from the production side, but also relative to coordination of design and construction of necessary pipelines.

4.5.2 Paths for utility integration

There are a variety of paths for potential utility integration, as shown in Figure 4-7. Not all paths would be used in a given system. To simplify, however, this figure combines the multiple pathways.

There is now widespread recognition of district cooling's ability to cut power demand and energy, thus reducing government investment in power infrastructure as well as annual power utility operating costs, as discussed in Chapter 2. District cooling frees up power capacity to meet other electricity requirements of new developments. Another potential synergy between district cooling and power generation is the use of gas turbine inlet air cooling, which increases power generation when the ambient air temperature is high (which is when power demand is high).

> Cooling tower makeup water does not have to be drinking-water quality.

Although district cooling's power sector benefits are desired by governments in the Middle East, the need for utility synergy in obtaining the water that maximizes district cooling energy savings is less well understood.

Heat rejection

District cooling plants typically use cooling towers to cool the chillers' condensers. Towers require "makeup" water because some water is lost through evaporation, drift or "blowdown" (in which some water is periodically removed to maintain water quality in the towers). Makeup water does not have to be drinking-water quality. In fact, seawater can be used in cooling towers, but this requires much more expensive equipment and higher maintenance costs. Other low-quality waters can be used, including TSE, brackish ground water and partially desalinated water. As the quality of the makeup water decreases, the capital and maintenance costs of the cooling towers increase.

Alternatively, district cooling systems can use seawater or other water sources non-consumptively. With this approach, the water cools the chiller condensers directly rather than through a cooling tower. Heat is

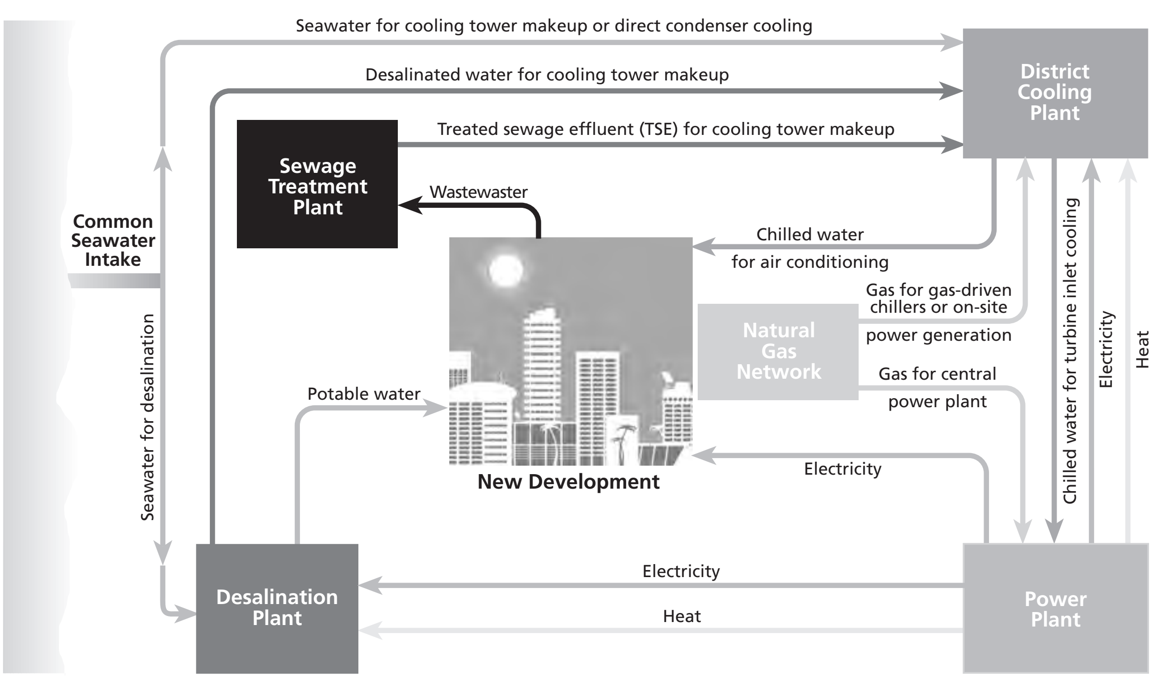


Figure 4-7. Paths for potential utility integration.

added to the water, but the same volume of water can be returned to the sea or used for other purposes.

Desalination

Desalination is energy-intensive. Multi-stage flash (MSF) plants are the most commonly used, accounting for the majority of global capacity. The use of reverse osmosis (RO) plants is growing due to technological advances and energy cost increases. MSF requires heat and some electricity, while RO generally requires only electricity (although some heat can optimize the process).

Power and desalination plants are often combined in a cogeneration process (combined heat and power) in which the waste heat from power generation is used for MSF desalination. Cogeneration can also be employed in RO plants by using exhaust steam to pre-heat feedwater or to run a steam turbine to power the pressure pumps required in the RO process.

The amount of energy for MSF is fixed for a given volume of water, but the energy for RO depends on how salty the water is to start with. For this reason, it is much more attractive to desalinate brackish (i.e., slightly salty) water or treated sewage effluent than it is to desalinate seawater. Typical salinity values, in parts per million (ppm):

• Seawater	35,000-45,000
• Brackish ground water	2,000-8,000
• Treated sewage effluent (TSE)	2,500
• Product water from MSF desalination	25-50

Salinity of product water from RO can vary significantly depending on the salinity of the feedstock and the specific type of RO process employed. In general, the cost of RO decreases as the minimum acceptable product-water salinity increases. If RO desalination is being used to produce district cooling tower makeup water, the trade-offs must be optimized: Lower quality makeup water means higher district cooling plant and operating costs, but lower RO plant and operating costs.

One possibility is combining district cooling with a hybrid MSF/RO desalination-power process, in which a seawater RO plant is combined with either a new or existing MSF plant. The MSF plant draws waste steam from a power plant and uses the energy in the steam to pre-heat seawater, which is then distilled in the MSF unit. The RO unit uses electricity from the power plant and operates during periods of reduced power demand, thus optimizing the overall efficiency.

This approach can reduce capital costs while providing for a variety of blends of MSF and RO product waters to meet a range of requirements, from potable water to irrigation water to optimized district cooling makeup water.

Natural gas

Natural gas is frequently the ultimate energy source for district cooling. Most often it fuels power plants that provide the electricity to drive district cooling plants. Sometimes it is used directly in district cooling plants to fuel gas engines that generate electricity for electric chillers, as Tabreed has been doing in some of its plants for more than five years. Natural gas can also be used to produce the shaft power to drive chillers directly.

Natural gas transmission and distribution networks are growing in the Middle East. As this occurs, the gas distribution networks can be planned with the potential for district cooling in mind. District cooling plants that use natural gas can relieve pressure on government investment in power plant, transmission and distribution infrastructure.

Natural gas-driven cooling technologies are discussed in Chapter 7.

> Integrating utility planning in the Middle East can reduce government capital and operating costs, increase energy efficiency and reduce harmful emissions.

The challenge of utility integration

Integrating utility planning in the Middle East can reduce government capital and operating costs, increase energy efficiency and reduce harmful emissions. Utility integration is a challenge, however, because typically different government entities are responsible for permitting and regulating district cooling systems, power utilities, potable water and wastewater treatment. Not only are different federal ministries involved, but municipal governments are usually also involved.

Consequently, although district cooling systems could provide multiple infrastructure benefits and, in turn, could be optimized through integrated utility planning, district cooling companies frequently encounter challenges in obtaining permits and achieving optimal integration with power and water utilities.

Tremendous economic and environmental benefits would result if governments created effective mechanisms for integrating utility planning across federal ministries and municipal governments. This will not be easy and will require strong, visionary leadership at the highest levels. But it will be well worth the effort because it will greatly enhance a country's stature as an attractive place for business investment.

4.6 Designing for Operations

As discussed in Chapter 3, it is crucial that district cooling be approached as a long-term utility business. To this end, it is important to involve the district cooling company operations and maintenance staff in the design process. Given the fast pace with which most district cooling systems are being designed and constructed, this may appear somewhat impractical. However, experienced operating staff can provide input that can reduce life-cycle costs and improve reliability. It is highly desirable for O&M staff to "take ownership" of these systems and for district cooling companies to approach operations proactively rather than reactively.

It is important to involve the operations and maintenance staff in the design process.

District cooling systems should be able to monitor their utility costs on continuous basis following these basic rules:

- Essence of measurement: If you cannot measure it, you cannot manage it.
- Accuracy is key: If you cannot measure it accurately, you better not measure it.
- Meaningful reporting: Data must be assembled and reported in structured automated reports.

5. Building HVAC Design and Energy Transfer Stations (ETS)

An energy transfer station (ETS) serves as the thermal energy transfer point between the district cooling company and each customer's heating, ventilating and air-conditioning (HVAC) system. It also demarcates the physical boundary for ownership, responsibility and maintenance of equipment. At the ETS, a revenue-grade flow meter and accurate temperature sensors are used to calculate cooling energy consumption and demand for customer billing.

There are both direct and indirect ETS connections, and there are optimal circumstances for the use of each. A direct connection is typically an economic decision to reduce costs and minimize the temperature rise; however, in most situations, an indirect connection (with heat exchanger separation) is preferred to reduce the static head and pressure requirements in the central plant and distribution system. Indirect connections are also applied in many systems to enhance reliability should a failure occur in a customer's building that would adversely affect the performance of other customers or the central plant.

It is important for a district cooling utility to work with its customers to establish the best practices for design, operation, control and maintenance of their building chilled-water systems. Without this effort, the entire district system may be destined to suffer from suboptimal performance and high operating costs, and customer comfort may suffer. Connection, capacity and consumption charges should be established to deliver a level of customer performance that also suits the utility's financial needs. If design or performance of the building system is poor and it affects the district cooling provider or other customers, there should be economic consequences for the building owner.

The solution to common delta T problems requires looking beyond the ETS into the building systems.

With or without an indirect connection, it is essential for the district cooling utility to maintain proper chilled-water supply temperature control in customer buildings. It is equally important for the customer building to deliver high return-water temperature to the plant. Even though it has been a relatively common practice in the industry to directly control delta T, chilled-water return temperature or peak flow, these practices are not recommended in normal operation except as measures to temporarily curtail the load or flow of problem customers. These tactics are likely to lead to problems relative to building pump and fan energy, capacity and comfort, as well as a loss in "latent" cooling revenue for the district cooling utility. The comprehensive solution to common low delta T problems requires looking beyond the ETS into the building systems as far as the cooling coil and control valves at air handlers and terminal units.

Building system design as well as district cooling contracts, tariffs, recommendations and technical support should all be aligned to facilitate customer achievement of high delta T.

5.1 Building System Compatibility

Total district cooling system performance depends on the design, operation and control of the chilled-water system within customer buildings beyond the ETS interface. Building system design as well as district cooling contracts, tariffs, recommendations and technical support should all be aligned to help customers achieve the delta T performance necessary for a cost-effective district cooling system.

A good way to approach this is to consider delta T performance in the context of the following questions:

- What do customers need from the district cooling provider in their buildings to ensure comfort, stability and humidity control without excessive building pump and fan energy consumption?
- What does the district cooling provider need to preserve available capacity and minimize energy use in the chilled-water plant(s) and distribution system?
- What steps may be taken early in design to reduce the capital and operating expenses and improve performance for the provider and its customers?

5.1.1 Cooling coil selection

Cooling coils should be selected to satisfy the load considering the expected supply-water temperature on the building side of the ETS. Temperature gain in the district cooling distribution pipes as well as heat exchangers should be taken into consideration when choosing the design entering-water temperatures. In an indirect connection, the cooling coil return-water temperature should be selected considering the design return-water temperature expected at the plant, plus the approach across the heat exchanger.

Figure 5-1 is an illustration of a typical cooling coil that illustrates the relationship between flow rate, cooling load (or capacity) and delta T at the cooling coil. At design entering-water and leaving-air temperatures, a typical cooling coil should achieve its design delta T or higher at all load conditions.

Space temperature, humidity and air-flow requirements create demand for cooling in the building. The cooling performed at each coil depends on the air flow as well as

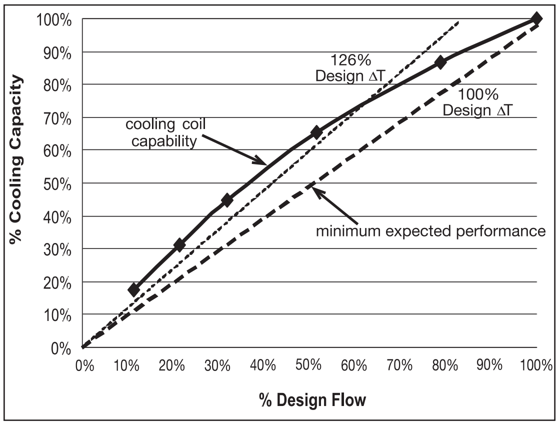


Figure 5-1. Expected coil performance over the design flow range for typical coil.

the entering- and leaving-air temperature conditions. If the chilled-water supply temperature is allowed to rise, cooling coil capacity and delta T is reduced, and it will take more chilled-water flow to satisfy the load.

Careful revaluation of coils in existing buildings is prudent when considering the load demand and available chilled-water supply temperature.

When existing buildings seek a contract for new district cooling service, careful evaluation of coils in existing buildings is prudent when considering the load demand and available chilled-water supply temperature. For this analysis a generic ARI-certified rating and selection program (available from numerous coil and air-handler manufacturers) is recommended.

Table 5-1 illustrates design conditions for a typical cooling coil. It also illustrates the flow rates required to satisfy the load at with lower supply-water temperature. The sensible and latent cooling loads remain constant for the same entering- and leaving-air temperature conditions and air flow. As would be expected, less chilled-water flow is required when supply-water temperature remains low. Delta T (and chilled-water return temperature) rise when less chilled-water flow is required to satisfy the load.

Parameter	Value	
Ventilation Air Flow	28,000 cubic feet per minute (cfm) [13,215 liters per second (lps)]	
Entering-Air Temp. – dry bulb	22.2 C (72.0 F)	
Entering-Air Temp. – wet bub	17.8 C (64.0 F)	
Leaving-Air Temp. – dry bulb	11.8 C (53.3 F)	
Leaving-Air Temp. – wet bulb	11.7 C (53.0 F)	
Latent Cooling	28.7 tons	
Sensible Cooling	47.2 tons	
Total Cooling	75.9 tons	
Entering-Water Temp.	7.2 C (45.0 F)	5.5 C (42.0 F)
Leaving-Water Temp.	12.8 C (55.0 F)	13.7 C (56.7 F)
Delta T	5.5 C (10.0 F)	8.2 C (14.7 F)
Water Flow	11.5 lps (182 gpm)	7.8 lps (124 gpm)
Normalized Flow	0.151 lps/ton (2.40 gpm/ton)	0.103 lps/ton (1.63 gpm/ton)

Table 5-1. Typical coil (and delta T) performance as entering-water temperature varies.

5.1.2 Bypasses and three-way valves

It is essential to eliminate bypasses and three-way (diverting) valves that bypass supply water into the return water to control cooling coil temperature. These systems operate with virtually constant flow, which is detrimental to the system delta T. Even a two-way control valve can act like a bypass if it does not fully close, or if wears and leaks internally. When an air handler or terminal unit de-energizes, control valves must be commanded closed. There should not typically be any bypasses installed to maintain minimum building pump flow requirements. Pump motors need to maintain a minimum speed (not minimum flow) to air cool the motors and avoid harmonics. A pump will not require a bypass around it unless the fluid temperature through the pump is expected to rise more than 5.5 C (10 F) at little or no flow. If a bypass is used, it should be installed with a motorized valve controlled by a temperature designed to protect the pump.

It is essential to eliminate bypasses and three-way (diverting) valves that bypass supply water into the return to control cooling coil temperature.

There may be a small bypass at the end of the distribution system designed and controlled to maintain cold supply-water temperature in the loop. This may be especially important in systems with night setback to minimize a sudden demand upon a new call for cooling in the morning.

In some cases a chilled water return-to-supply mixing valve can be justified because of different supply-temperature demands (i.e., chilled beams, induction units, process cooling).

5.1.3 Control-valve sizing and selection

ETS control valves (with actuators) are typically applied on the district cooling side of the ETS to control

Control valves should not be used to control the delta T or the chilled-water return temperature.

chilled-water supply temperature on the building side.

Cooling coil control valves (and actuators) in customer buildings are typically applied to control space temperature and humidity or coil supply-air temperature conditions.

In either application, valves should not be used to control the delta T or the chilled-water return temperature unless the intent is to temporarily curtail the load or the flow to prevent a loss of system capacity or cooling delivery to other customers.

To achieve high delta T across cooling coils and customer buildings through a range of load conditions, the control valves and corresponding actuators must

- be able to shut off against the full-rated head of the pumps;
- be properly selected and sized in the hydraulic gradient so that the valve uses its full stroke whether it is located close to or far from the pumps;
- have high rangeability for controlled operation at very low flow (leading to high turndown when properly sized); and
- open and close slowly, and not "hunt," even in the presence of real-time pressure fluctuations.

An oversized control valve will not use its full available stroke and will have limited system turndown in the location where it is applied. On the other hand, an undersized control valve doesn't have the capacity to deliver the flow required to serve the load with the available differential pressure.

Poor valve sizing is one of the most common problems leading to poor delta T performance.

Poor valve sizing is one of the most common problems leading to poor delta T performance. Most control valves in the industry are selected by line size, rule of thumb (for low pressure drop), or by an "authority" calculation that ignores the location of the valve relative to pumps. This may be partially due to the difficulty, uncertainty and cost of modeling the hydraulics, especially in a growing system. Manual balancing valves attempt to compensate for this by reducing excess differential pressure at each coil, but cannot adjust to growth or changes in the load profile. Flow limiters (automatic balancing valves) clip flow at 100% over a range of differential pressures, doing little to prevent low delta T or loss of comfort control.

With conventional pressure-dependent control valves, proper sizing requires knowledge of the differential pressure at each circuit over a variety of peak-load conditions. As a system expands, or as the load requirements change, even a properly sized valve may have to be replaced or readjusted to account for the change in differential pressure, otherwise it will be improperly sized for the application and won't control flow through the coil as well as it could.

A pressure-independent control valve can be properly sized by the design flow rate for the coil alone and adapts easily to changes in the differential pressure in the location where it is applied or as the system grows. This technology is not unlike pressure-independent VAV boxes that were developed in the 1970s. It is a fundamental change in design that, when properly applied, has been shown to help resolve low delta T and other performance issues in the district cooling and HVAC industries.

Cooling coil control valves can have an enormous impact on the total district cooling plant and distribution system performance. It is important for district cooling companies to help their customers broadly consider the system and delta T performance when choosing a control philosophy.

5.1.4 Building pump control

Building pump control may be a negotiating point between the building customer and district cooling provider. It is important to achieve high return-water temperature to the plant without adversely affecting comfort control in the building. Low return-water temperature increases the energy consumption and reduces available system capacity. High supply-water temperature or inadequate differential pressure may result in poor comfort control and lost cooling revenue. These issues can be avoided with proper district and building system design, control and operation. The district cooling provider needs to educate its customer on how to properly operate and control the pumps or negotiate to manage pump operation and control themselves. Ultimately, pump control must ensure that the cooling load is satisfied in each zone.

More than one differential pressure sensor in the building may be required for pump speed control. By locating these sensors at the hydraulically most remote point(s), the pump control system can ensure that there is always enough differential pressure to satisfy the load conditions. If the control point is too close to the pumps, it is difficult to set the appropriate differential pressure for all load conditions and may overpressure or starve portions of the system. If the control point is at the physically, but not hydraulically, most remote point(s), it may not enable the system to provide enough differential pressure to deliver chilled-water flow where it is required. Unless the intent is to curtail the flow or load, pumps should not be used to control the return-water temperature or delta T, as this may lead to issues with coil capacity, fan energy and comfort control. If necessary, the differential-pressure setpoint may be reset at part-load conditions to further reduce pump speed and energy consumption; however, reset should never compromise the system's ability to satisfy the air-temperature and humidity control requirements.

5.1.5 Water treatment and heat-transfer effectiveness

Proper chemical water treatment in the building system is essential. Cooling coil heat-transfer effectiveness is reduced by waterside fouling (i.e., slime, scale or corrosion on the inside of the coil tubes) and airside fouling (i.e., dirt buildup). Any reduction in coil effectiveness decreases coil capacity and increases the flow rate of water required to deliver the desired leaving-water temperature, thus reducing delta T. With direct-connected customers, water treatment should be managed by the district cooling utility or its water treatment supplier. It is good practice to have an inline cartridge filter that is mounted in sidestream configuration in each building, especially with direct connections.

5.1.6 Additional economic opportunities

When the district cooling system and the building systems are considered as an integrated whole, many opportunities arise to reduce system first cost while improving economics for both the utility and its customers. If chilled-water rate structures are established that drive the customer to make good economic decisions that also benefit the utility, then a framework is in place to capture savings and improve operations.

As an example, when building systems are properly designed and controlled, it is possible to rely on high delta T performance. This enables the building and district cooling system designers to reduce excess safety margins that can increase the capital, energy and operating costs of the system.

As another example, if lower temperature chilled water is produced using ice, low-temperature fluid, or series chillers, it can reduce the customer's coil, pump, pipe fan, duct and heat exchanger size in addition to the distribution pipe size. This enhances the district cooling benefit for the customer by reducing building first costs. It also can decrease building pump and fan energy consumption. For the district cooling utility, higher delta T reduces the distribution pipe size and cost. Peak loads and electrical infrastructure requirements may be reduced.

5.2 System Performance Metrics at the ETS

With good metrics it is possible to evaluate the district cooling distribution system performance at each ETS and to take steps to understand and address issues. District cooling companies should define their own metrics to evaluate performance for each customer. In the examples below the metrics are intended to establish that a system is performing well at peak and part load.

Chilled-water supply temperature on the building side of the ETS is at or below the design entering water temperature for cooling coils – While it is possible to raise the chilled-water supply temperature at part-load conditions and still serve the load, it isn't necessarily a great energy-efficiency strategy even with a reduction in chiller-compressor lift (work). See section 5.6.1 for more details about supply-water temperature reset.

> Raising chilled-water supply temperature at part-load conditions isn't necessarily a great energy-efficiency strategy even with a reduction in chiller compressor lift.

Distribution return-water temperature on the district side of the ETS is at or above chilled-water plant design – Plant energy efficiency and available capacity depend on high chilled-water return temperature. However, directly controlling the return-water temperature or delta T with pumps or control valves is not recommended in normal practice as it may compromise the differential pressure or building supply-water temperature required to deliver adequate cooling. Ultimately, high delta T is achieved with proper cooling coil and control valve selection, piping and pumping design and supply-water temperature control.

Supply-temperature rise between the chilled-water plant and ETS is reasonable – Modest temperature rise is expected in district cooling system supply pipes. It can be higher at low load when the surface area of the pipe is large relative to the flow rate. Depending on the climate, depth, geology and pipe design, chilled-water temperature may either rise or fall in the return pipes. If the supply-water temperature rise is too high, it can indicate a problem with pipe insulation integrity, poor control or return water blending at the central plant through a primary-secondary decoupler or non-operating chiller. Ultimately, the district cooling provider must deliver the supply-water temperature promised to customers and account for any heat rise in the plant's design and operation.

> A best practice emerging in the district cooling industry is to connect chilled-water tariffs to delta T performance.

Distribution delta T is at or above plant design – The distribution delta T on the district side of the ETS should exceed plant design in both peak- and part-load conditions. If delta T is low, more flow is required per unit cooling. This is inefficient, as it may increase the operating hours of equipment in the plant or reduce available system capacity. Ideally, the delta T will exceed system design. A best practice emerging in the district cooling industry is to connect chilled-water tariffs to delta T performance.

Maximum flow rate and load do not exceed contract capacity – Both the maximum flow and load should be monitored and managed because they may not always be coincident. Flow with low delta T at part-load conditions could be more than with high delta T at peak-load conditions. Some customers may shut off their cooling at night and let the temperature in the water rise. If it rises too high there can be a high demand for cooling as the system starts. This can be managed with controls, a flow limiter at the ETS, or a small bypass at the end of the loop in the building that doesn't permit the water temperature to rise too high. Another strategy in lieu of night setback is to cycle the air handlers at night.

Sufficient differential pressure is monitored and maintained at the ETS and hydraulically most remote point(s) in the building – This is intended to let the district cooling utility know if there is a problem preventing the delivery and sale of chilled water. A differential-pressure sensor at the hydraulically most remote point(s) within a customer's building will provide an indication if enough differential pressure is available to deliver adequate flow to each load. This is important whether a customer is directly or indirectly connected.

5.3 Selecting Direct or Indirect ETS Connections

Although connecting the customer directly to the district cooling system is an economical option (no heat exchanger to add to the cost or approach temperature to degrade performance), direct connections should be considered only for low-rise buildings or compact district cooling systems with a limited number of customers where a strong partnership between the district cooling service and building personnel can be built.

Since the water delivered from the plant is also circulated in the customer's internal building system, all involved must know and understand the risks and consequences if something unexpected happens in the system. For example, failure in one customer's system can cause the entire system to shut down, thus interrupting cooling to all the other customers. For reliable operation, it is important that the building owner be vigilant in detecting leaks and ensuring no contamination occurs to the circulating water. Also, in direct connections, water treatment is provided at the central plant, thus the treatment program is outside the customers' control.

When designing a direct-connect system, care must be taken to protect the safety of the customer installation and the reliability of the district cooling system. The district cooling owner must weigh the benefits of economy against the risk for a serious failure. If one customer fails to properly maintain and operate its system and causes a serious leak, this could cause the entire system to shut down if the system makeup supply cannot rapidly refill the system. Since the customer's system consists of many components, the offending source could be any cooling coil or other equipment in a hidden location.

Further complicating the design for direct connections are such devices as pressure-reducing valves in the supply line and pressure-sustaining valves in the return line. The need for such devices depends on the size and design of the district cooling system, elevation differences and types of customers and building systems.

Direct connections are most suitable in a system where with relatively flat ground and new low-rise buildings where the static head in the distribution system can be kept low.

Direct connections are most suitable in a system with relatively flat ground and new low-rise buildings where the static head in the distribution system can be kept low. The designer should be careful that in no case should the customer's building exert a static pressure on the distribution system greater than the system's return pressure (pressure holding).

In a system with a combination of direct and indirect connections, the district cooling provider may set a static column height limit where heat exchanger indirect connections are required. The building designer can then place a smaller heat exchanger on a higher floor to reduce the size and expense while not exceeding the maximum allowable return pressure in the utility's distribution line.

Direct connections may be appropriate in these instances:

1. The utility and customer may be the same owner or have a strong working relationship and contract. The customer and utility both know and understand the risks and consequences if and when unexpected problems arise in the system.

2. Building height and static head for the customer's building is not a concern for the utility and will not lead to higher pressure-rated pipe and equipment in the plant and distribution or issues with open storage or expansion tanks at atmospheric pressure. Components are capable of managing (possibly with pressure-reducing valves) the full spectrum of pressures induced by the tallest water column and the shutoff pressure of the distribution pumps. All system expansion compensation is accommodated at the district cooling plant and the compression tank has adequate capacity for the direct-connection water volume.

3. The distribution fluids in the plant and customer's building are the same and can mix. Water quality or contaminants in the customer's building can be addressed and won't adversely affect the plant or other customers. Water treatment will be managed by the district cooling utility or its treatment supplier.

4. Available space in the customer's building is limited. The customer will take advantage of space not otherwise taken by heat exchangers, pumps, expansion tanks, water treatment and other equipment. Significant first-cost reductions, including connection charges, are sought.

5. The customer seeks the simplest possible operation and will follow system configuration, control and maintenance recommendations. The contract reflects the importance of high chilled-water return temperature to the plant.

6. Chilled-water flow will be controlled in a manner that ensures high delta T and prevents demand in the customer's building from adversely affecting the available differential pressure and flow to another. Pumps can't overpressure the return.

7. The makeup water system in the plant has enough capacity to replenish the loop at a rate in excess of the possible loss at the customer's building. Alternatively, the customer has a system that will warn about and prevent chilled-water loss.

8. There are expected first-cost advantages since smaller fans, ducts, pumps and motors can be used and possibly no pumps are needed. Energy advantages could result from colder water supply to customer's coils and higher return-water temperature to the central plant.

An indirect connection should be considered when

- the static head increases the system return (holding) pressure in the plant or risks increasing the design pressure for the piping system,
- the district cooling utility uses chilled-water additives or has a different philosophy for water treatment than the building owner,
- there is a risk of equipment failure that could lead to a loss of water from the plant and adversely affect all customers and/or
- the district cooling company simply wants a clear physical break between their operations and their customers' buildings.

The disadvantages of indirect connections are higher installation costs, less efficient energy transfer and additional space and complexity for the customer. With typical heat exchanger and system design, about 1 C to 2 C (1.8 F to 2.7 F) is generally lost through the heat exchanger on both the chilled-water supply and return sides at peak design conditions.

The disadvantages of indirect connections are higher installation costs, less efficient energy transfer and additional space and complexity for the customer.

5.3.1 Direct connections

A decoupled direct connection as shown in Figure 5-2 is typically configured with a crossover bridge, building pump and building supply- or return-water temperature control valve. The crossover bridge permits return water to blend with supply and is intended to hydraulically decouple the building from the central plant and main distribution. The bypass at the end of the loop maintains chilled-water flow in the circuit to reduce the high load after night setback.

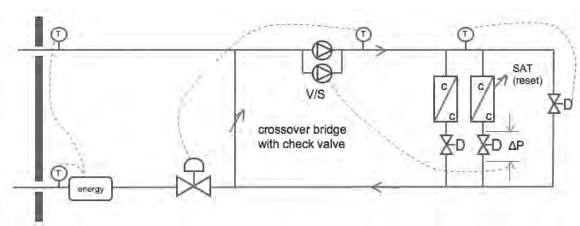


Figure 5-2. Decoupled direct ETS connection.

In district cooling operations, decoupled direct connections may be used when much colder supply-water temperature than coil design is produced at the plant. Return-water temperature control is not recommended in normal operation as it may lead to supply-water temperature instability, an increase in building pump and fan energy consumption, and possible comfort control problems. It can also reduce the (latent) cooling revenue for a district cooling utility.

If the load or flow must be temporarily curtailed for a problem customer, the control valve in the return line to the plant may be used to manage the return-water temperature on the load side of the crossover bridge; however, the supply-water temperature must also be managed to prevent latent cooling problems.

As an alternative, it is possible to provide cooling without a crossover bridge or building pump; however, it takes careful analysis of the hydraulics to be sure that the central plant(s) always generate enough head in the distribution to satisfy the load. In locations closer to central plant pumps, where sufficient differential pressure is available, a direct-connected building as shown in Figure 5-3 may require no more than a supply and return pipe with the appropriate water treatment, water filtration and energy metering.

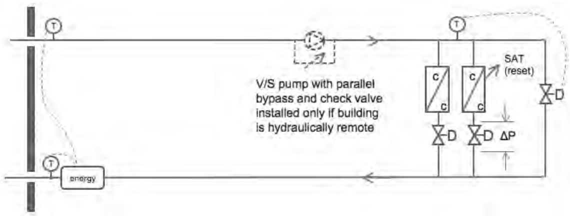


Figure 5-3. Simplified direct ETS connection.

For the customer building, this is the simplest interconnection but must be applied with care to avoid hydraulic issues and low delta T. It saves valuable real estate space and eliminates all the additional equipment required in a typical indirect or decoupled direct connection, including piping, pumps, controls, heat exchangers, chemical treatment and expansion tanks. This approach can also be modified at hydraulically remote locations with a series (booster) chilled-water pump that is installed with a parallel bypass and check valve so that the pump is only run when required.

Direct connection is the simplest interconnection, but it must be applied with care to avoid hydraulic issues and low delta T.

5.3.2 Indirect connections

An indirect connection uses heat exchangers (HEX) to physically separate the district cooling provider from the customer. A heat exchanger is a device used to separate the utility and customer's heat-transfer fluids and pressures. The district cooling provider supplies chilled water to heat exchangers to cool the chilled water used in the customer's building for comfort and process cooling. Heat is transferred through the device, but fluids and pressures don't mix.

Only one heat exchanger is required, but two or more heat exchangers may be installed in an indirect connection to facilitate maintenance of one unit and provide a level of redundancy (as shown in Figure 5-4 and Figure 5-5). Large installations (more than 2500 tons) may require multiple heat exchangers just to meet peak-load requirements. A y-strainer (not shown) is typically installed and maintained to keep the heat exchanger and the control valves clean and clear.

On the utility side a single (high-rangeability) control valve in the return line to the plant may be used to control the supply-water temperature to customer coils provided it is properly sized. Sometimes more than one control valve in parallel is used to increase rangeability and redundancy or to handle larger flows. Manual balancing valves are normally not needed for shorter runs with a properly sized header. For longer runs, a balancing valve may be used to ensure that differential pressure across each heat exchanger is held constant.

As an alternative, a control valve may be applied at each heat exchanger (Figure 5-5). This may be desirable when redundancy requirements are high. If it is properly selected and sized for the differential pressure in the application, it will eliminate additional balancing requirements.

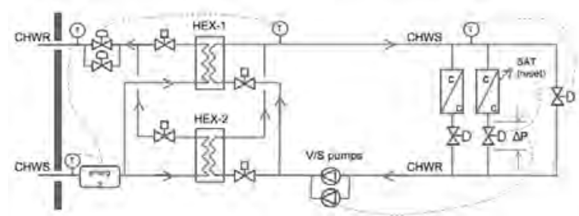


Figure 5-4. Indirect ETS connection (with combined HEX control valves).

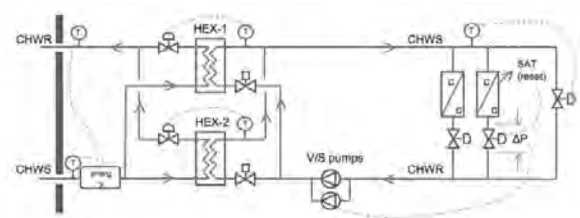


Figure 5-5. Indirect ETS configuration (with dedicated HEX control valves).

In an indirect ETS configuration, the district cooling provider typically takes responsibility for the heat exchangers and components on the district side. The building owner takes responsibility for the piping and components on the building side. Other components in an indirect ETS may include makeup water connections, expansion tanks (upstream of building pumps), water treatment and filtration equipment, backflushing valves and other indication and controls. Ultimately the district and building-side design and operation must be integrated for the ETS and total cooling system to work properly. It is generally recommended that the building-side water treatment procedures be reviewed by the district cooling provider to ensure that the water passing through the heat exchangers is sufficiently treated and chemical levels are maintained within recommended limits.

Figure 5-6 is an example of an indirect connection, including two heat exchangers, piping, valves and controls. It shows the district chilled-water supply (CHWS) lines and building chilled-water supply as well as the chilled-water return (CHWR) lines for each. This installation serves a 92,900-sq-m (1 million-sq-ft) building with a 3350-ton cooling load.

First cost, stability, energy, complexity and footprint should all be considered in evaluating indirect ETS design configurations.

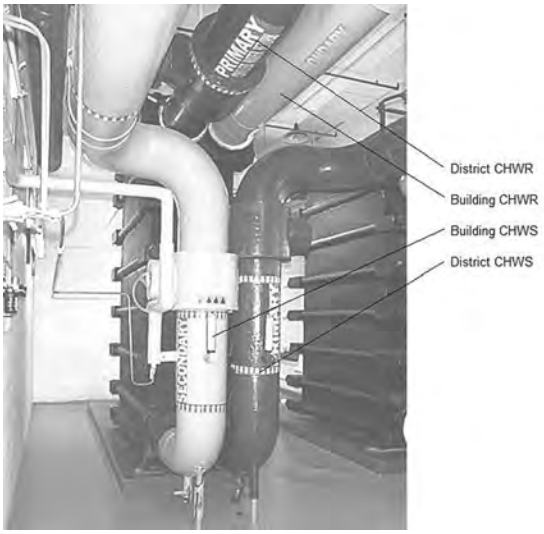


Figure 5-6. Plate-and-frame heat exchanger installation.

First cost, stability, energy, complexity and footprint should all be considered in evaluating indirect ETS design configurations. Ultimately, supply-water temperature control and sufficient flow to customer coils are the critical parameters for good comfort control, available coil capacity and building energy performance. If supply-water temperature is well controlled, piping configurations can vary.

5.4 Heat Exchanger Considerations

A typical plate-and-frame heat exchanger is illustrated in Figure 5-7. Since heat exchangers are one of the major components in an indirect ETS, it is essential that they be properly selected to serve the duty required based on both the district cooling provider and customer temperature, differential pressure and pressure-rating requirements.

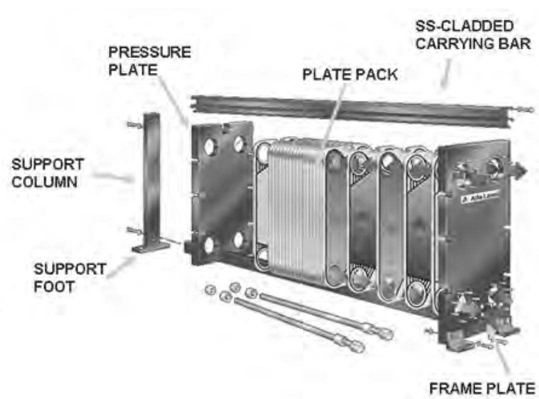


Figure 5-7. Plate-and-frame heat exchanger (courtesy Alfa Laval).

Heat exchanger selection should be broadly integrated with the total district cooling system design. The choices made in the system can have a very significant impact on the capital, energy and operating costs for a district cooling utility and its customers.

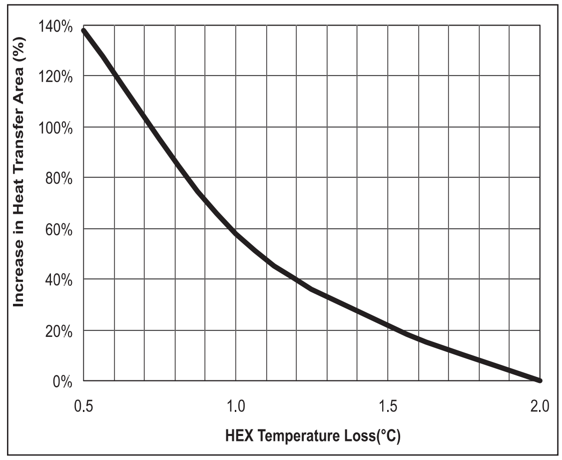


Figure 5-8. HEX surface area vs. "approach."

5.4.1 HEX temperature requirements

The "approach" (temperature difference between the district and building supply- or return-water temperatures) will drive surface area requirements and cost. A smaller approach requires a larger heat-transfer area. A larger approach requires a smaller heat-transfer area. Figure 5-8 shows how the heat exchanger area increases as the approach temperature on the supply side decreases.

With higher delta T, pipe and fitting size, system pressure and pump power requirements all decline as well as peak power and electrical system requirements.

Starting with a baseline district supply- and return-water temperature, it is easy to evaluate how increasing the approach on either the supply or return side will change the heat-transfer surface area and cost and can help deliver broader savings to the district cooling company or its customers. A typical district cooling system may have a design supply and return temperature of 4.4/13.3 C (40/56 F) on the district side and 5.5/14.4 C (42/58 F) on the building side of an indirect connection.

To reduce district cooling distribution and indirect ETS cost, the approach could be increased and chillers, ice

Heat Exchanger (HEX)	HEX 1	HEX 2
Cooling Load	1000 tons	
Inlet Temperature C (F)	4.4 (40)	2.2 (36)
Outlet Temperature C (F)	3.3 (56)	3.3 (56)
Flow Rate lps (gpm)	94.0 (1489.6)	75.1 (1190.7)
Pressure Drop kPa (psi)	60.1 (8.71)	40.9 (5.93)
Footprint sq ft (sq m)	2.62 (28.2)	2.16 (23.3)
Relative Cost Index	1.00	.690

Table 5-2. Sample heat exchanger differences with colder supply-water temperature and common building-side conditions.

storage or low-temperature fluid thermal storage could be added to lower the supply-water temperature to 36 F (2.2 C) (as shown in Table 5-2). A 20 F (11 C) delta T system design reduces the district flow-rate requirements by 20%. Pipe and fitting size, system pressure and pump power requirements all decline as well as peak power and electrical system requirements. Building equipment remains the same. Producing colder supply temperature for thermal storage may increase the chiller energy consumption; however, it may be offset by the energy saved with colder condenser water temperature (at night in dryer climates) and a decrease in pump energy consumption (with higher delta T).

Conversely, if customers have incentives in their contracts to achieve high return-water temperatures, they might be inclined to invest in greater capacity coils and better control to achieve the results that they seek. Again, a higher approach on the return side decreases the heat exchanger area and cost. Higher building-side delta T decreases building pump and piping system cost as well as pump energy consumption.

> Both the customer and the utility can benefit from careful technical and economic consideration of delta T optimization.

A combination of the two approaches could enable the customer to reduce the supply-air temperature to reduce air-flow requirements, duct and fan size and fan energy consumption while the district cooling company takes advantage of the expected savings in its system. Both the customer and the utility can benefit from careful technical and economic consideration of delta T optimization.

5.4.2 HEX pressure requirements

The design pressure and allowable pressure differential (DP) on both sides of the HEX must be assessed. The building side is very often the critical parameter because high-rise structures can exert high static pressures and low delta T forces the pumps to generate much higher head to serve the load.

In most large district cooling systems in the Middle East, the required design pressure on the cold side (district side) of the plate heat exchanger is typically 16 bar (232 psig); however, in the case of high-rise structures, the building chilled-water system pressure may dictate the design pressure classification for the heat exchanger as well as other piping components. High-rise structures may have higher design pressures. Generally, plate heat exchangers can be designed in the following design pressure steps: 10, 16, 18, 20 and 25 bar (145, 232, 261, 290 and 363 psig). Higher non-standard design pressures as high as 34 bar (493 psig) can also be accommodated by several manufacturers.

The allowable pressure drop across the heat exchanger (including pressure drop in ports, connections, and across the plates) is one of the critical parameters to be considered during selection. The higher the pressure drop, the smaller and less expensive the heat exchanger will be. For the customer at the hydraulically most remote location(s) it is *critical to minimize the pressure drop* because that customer will set the pumping requirements for the entire system. Minimizing the pressure drop at the critical customer will decrease pump requirements and annual pump energy cost. Figure 5-9 illustrates how the pump head requirement for the whole system depends on the design of this critical customer.

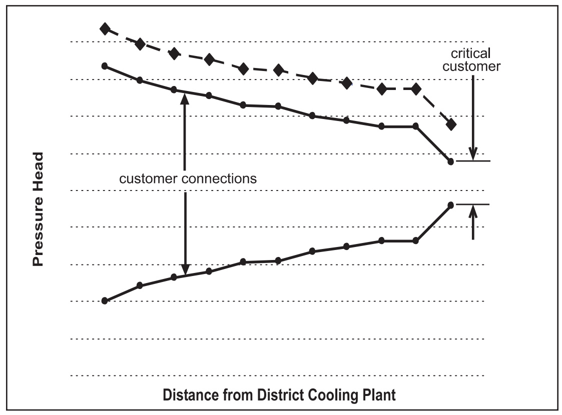


Figure 5-9. Importance of critical customer design.

When converting a building from self-generation to district cooling, it is important that the heat-exchanger differential pressure be compatible with the building pumps. This usually means the pressure drop of the heat exchanger should not exceed the pressure drop of the evaporator of the chiller being replaced. If the pressure drop is greater, then the building system pump-pressure curve will be changed, which could cause flow-balancing problems in the building system. However, building systems tend to be oversized, so after some investigation there might be more differential pressure available than is indicated from the project equipment schedules.

5.4.3 HEX redundancy requirements

When assessing redundancy requirements, it is important to understand the criticality of each load. For example, if there are 24-hour process loads (e.g., computer room cooling or other water cooled process equipment), then the engineer designing an indirect system might want to consider adding a separate heat exchanger for those loads. To minimize service disruptions to a hotel, hospital or data center, selecting two or more units increases system reliability.

With multiple heat exchangers, the customer can plan maintenance at part-load conditions or count on at least some cooling capacity when a heat exchanger is unexpectedly taken out of service. For especially critical customers, it might be necessary to use multiple units such that when the largest unit is out of service, the remaining capacity is sufficient to meet the critical load.

The redundancy requirements are typically established on an individual customer basis. Generally, the redundancy requirements are lower for a building served from district cooling compared to individual on-site chiller operation since a heat exchanger has no moving parts and is not likely to "break down" like a chiller might.

Tonnage	**Tonnage per heat exchanger**		
Demand	2-manifolded	3-manifolded	4-manifolded
1000	600	400	300
2000	1200	800	600
3000	1800	1200	900
4000	2400	1600	1200
5000	3000	2000	1500
6000	-	2400	1800
7000	-	2800	2100

Table 5-3. Tonnage capacity per heat exchanger.

For example, on a typical energy transfer station in the Middle East, the design would employ one of the scenarios (with 20% redundancy) shown in Table 5-3. The building yearly load profile usually defines the number of heat exchangers manifolded in an ETS.

5.4.4 HEX performance efficiency

In an indirect ETS configuration, the heat exchanger is a critical element in the efficient energy transfer from the district cooling provider to a customer. Having no moving parts, the risk of a major mechanical failure of the heat exchanger is very low, but this does not eliminate the need to manage the performance efficiency. Efficiency and reliability depend on system cleanliness, flow rates and temperatures. Performance monitoring coupled with predictive maintenance practices help ensure efficient energy transfer and system reliability.

HEX monitoring – With most heat exchanger connections it is very important to collect temperatures and pressure drops for both inlets and outlets as well as the water flow rate.

Other connections – It is also good practice to have connections to enable cleaning in place built into the heat exchanger piping as this is usually the first line of action when heat exchanger performance deteriorates.

5.4.5 Other HEX considerations

Strainers – Since the heat exchanger is essentially an interface device between the district cooling provider and the building, proper water treatment on both sides is essential. Heat-transfer effectiveness is reduced by fouling, i.e., slime, scale. During commissioning, blockage of the heat exchangers is a very present danger. It is essential to connect heat exchangers after proper flushing procedures are followed. A y-strainer with a maximum mesh size 75% of the channel depth must be used upstream to both circuits during startup. It may need to be smaller to protect the control valve(s) on the district cooling provider's side.

Water quality – The material of construction of the heat exchanger plates is mainly dictated by the level of chlorides present in the water passing through them. Table 5-4 illustrates recommended limits.

	T=20°C (68°F)		**T=80°C (176°F)**	
pH level	**AISI 304**	**AISI 316**	**AISI 304**	**AISI 316**
5	20	400	4	30
7	120	1150	32	120
9	500	10000	140	600

Table 5-4. Recommended maximum chloride content (ppm).

Utilities issue the chloride limits to building-side consultants and usually actively monitor or oversee that water treatment on the building side once the heat exchangers are in operation.

Partial load analysis – Many district cooling providers ask for a partial load analysis for heat exchangers to be issued by the manufacturer. This information is required to assess how the heat exchangers will perform at part loads as well as changing delta T and log-mean temperature differences (LMTDs).

A great deal of emphasis should be placed on selection of control valves and control strategy for both the district and customer.

5.5 Control-Valve Considerations

A great deal of emphasis should be placed on selection of control valves and control strategy for both the district and customer to ensure both the district and building systems are operating properly.

In customer buildings, demand for flow to cooling coils is driven by air-flow, temperature and humidity requirements. Cooling coil control valves typically manage the chilled-water flow through a circuit to maintain a given air-temperature setpoint whether it is in the duct or at the zone.

In an indirect or decoupled direct connection, ETS control valves are typically used to control the chilled-water supply temperature on the building side of the interface.

5.5.1 Location and applications

Table 5-5 identifies common applications at the ETS and in buildings that require flow control to manage air temperature and humidity, as well as chilled-water supply temperature. Managing all of these properly will lead to higher delta T performance. At an energy transfer station, flow control may be used to manage the chilled-water supply temperature. Further in the building, an end of the loop bypass (normally closed) may control flow to keep cold water in the loop so that high demand isn't created during morning startup. Alternatively, air handlers may be cycled at night to minimize excessive demand.

Application	Control Point(s)
Common fan coil unit	Space temperature/humidity
Advanced fan coil unit	Leaving-air temperature
Constant-speed air-handling unit	Space or return-air temperature/humidity
Variable-speed air-handling unit	Leaving-air temperature
Indirect energy transfer station	Chilled-water supply temperature
Decoupled direct connection	Chilled-water supply temperature
End-of-loop bypass	Supply-water temperature

Table 5-5. Control-valve applications and control points.

Direct control of return-water temperature and delta T are poor practices that lead to problems for both customers and the district cooling system.

Direct control of return-water temperature and delta T are poor practices that lead to problems for both customers and the district cooling system. When pumps are used as temperature (instead of pressure) control devices, they tend to starve hydraulically remote circuits of the flow they need to satisfy the load. When control valves are used to control the chilled-water return temperature or delta T, chilled-water supply-temperature control is typically lost, leading to other performance issues. These methods should only be considered temporary measures designed to curtail the flow or the load.

Control valves are usually connected in the return line to reduce condensation and should be installed is a way that prevents condensation from dripping onto an electronic actuator.

5.5.2 Control-valve types and characteristics

Control valves can be divided into two major categories: pressure dependent and pressure independent. With a pressure-dependent control valve, the flow rate through the cooling coil or heat exchanger served will vary with changes in load and differential pressure. Proper sizing depends on an accurate estimate of the differential pressure at the location where it is applied in the system. In contrast, with a pressure-independent control valve, the flow rate through a cooling coil or heat exchanger only varies with a change in load. Proper sizing is independent of the differential pressure at the location where it is applied in the system.

Pressure-dependent control

Figure 5-10 illustrates a common pressure-dependent "globe" valve. There are many types of pressure-dependent control valves used in the industry, with a wide range of quality, characteristics and performance. In practice, many of these valves are improperly sized and selected for lowest initial cost. It contributes to poor delta T performance, especially at part load, leading to longer-term issues and costs for the district cooling provider and its customers.

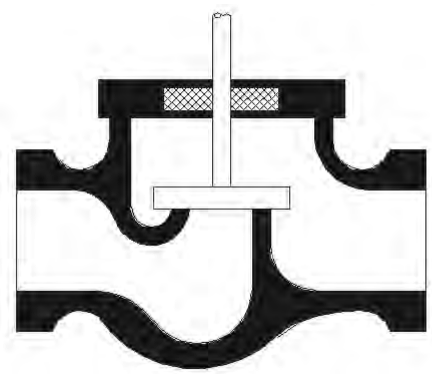


Figure 5-10. Pressure-dependent "globe" valve.

Control-valve rangeability is a ratio of the maximum to minimum controllable flow. High-rangeability v-port ball valves and double-acting globe valves are two types of high-grade pressure-dependent valves that have been successfully used to increase control. Commercial-grade characterized ball valves are another example. All these valves must still be properly sized in the hydraulic gradient to be effective and must be individually controlled to react to real-time pressure fluctuations in the system to maintain a reasonable setpoint.

Figure 5-11 illustrates the flow rate through control valves as a function of valve opening (or actuator position). "Equal percentage" characteristics as shown are intended to create a consistent linear gain through the flow range when combined with the cooling coil or heat exchanger capacity curve shown earlier in Figure 5-1. Unfortunately, the effect of poor valve rangeability, improper valve sizing and increased supply-water temperature is not reflected in the chart.

A valve with poor rangeability will not control well at low flow and may "hunt" for the right position to address changes in load and differential pressure. Common butterfly valves aren't typically considered control valves since they have very poor rangeability at low flow. Conventional (pressure-dependent) control valves will only use a portion of their stroke if oversized, poorly balanced or in a system suffering with low delta T. With poor control or rising supply-water temperature, the delta T performance suffers and far more flow will be required to serve the load.

If a pressure-dependent control is selected by the district cooling company and the building owner, it should be done considering the effort and accuracy required to size and select control valves for the system.

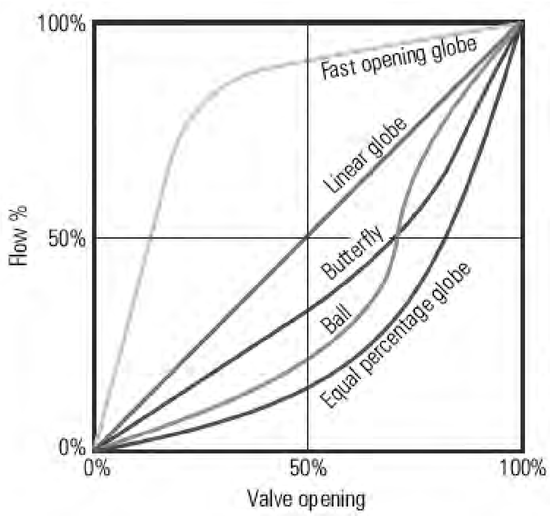


Figure 5-11. Common control-valve characteristics.

Pressure-independent control

Figure 5-12 is a schematic of a pressure-independent control valve. With this type of valve, the internal piston and spring operate to maintain a low but constant differential pressure across the control surface so that sizing does not depend on location and differential pressure in the system. In operation, the size of the passage between the piston and the valve outlet varies as the pressure varies to keep the differential pressure across the control surface constant. With a pressure-independent control valve, the only way to change the flow rate through the cooling coil or heat exchanger is to actively rotate the stem in response to a load change. Real-time system pressure fluctuations have no effect on the flow at any load condition.

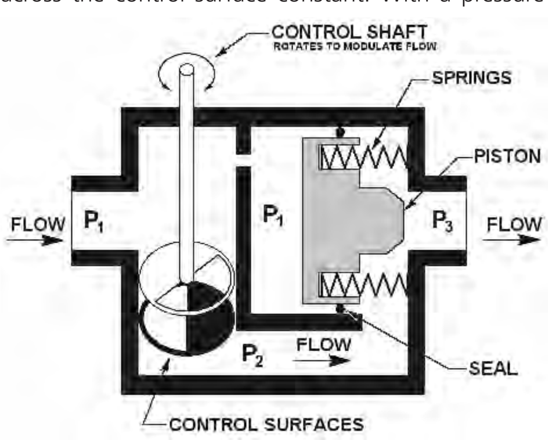


Figure 5-12. Pressure-independent control valve (courtesy Flow Control Industries).

If pressure-independent control is selected, it is an investment decision made by the district cooling company and the building owner to improve control-valve sizing, stability and delta T performance. When properly applied, pressure-independent control valves deliver more stable control and help optimize cooling coil performance so that high delta T can be achieved in both the district and building side of the ETS interface without compromising performance.

One of the most common problems in the HVAC industry is rule-of-thumb control-valve sizing.

5.5.3 Control-valve sizing

One of the most common problems in the HVAC industry is rule-of-thumb control-valve sizing. When control valves are selected by the same pressure drop as the coil served, one line size smaller than the pipe or low pressure drop, it does not account for the differential pressure in the location where the valve is applied in the system. Selecting valves for "control authority" to match the pressure drop through the other components in the circuit has the same effect if the hydraulic gradient is not considered. In fact, poor control-valve sizing and selection is one the main contributors to low delta T problems.

Selection of pressure-dependent control valves at the ETS and at cooling coils requires knowledge of the maximum differential pressure expected in operation at the location where it is applied. A building or coil control valve close to the pumps will always have higher differential pressure than those further out in the distribution.

This differential pressure varies at different elevations and locations relative to pumps and the plant. It will change as the system grows or the load changes. It will rise up and down with the delta T performance achieved at each building. There may be a great deal of uncertainty in modeling the differential pressure given all the variables that come into play. This may help explain why contractors in the industry almost always size pressure-dependent control valves poorly or use balancing valves and flow limiters to try and compensate.

Whether pressure-dependent or pressure-independent control valves are used, it is essential that they be selected to match the building's actual loads as closely as possible.

Whether pressure-dependent or pressure-independent control valves are used, it is essential that they be selected to match the building's actual thermal loads as closely as possible. Oversizing reduces valve and actuator life and causes valve "hunting." Undersizing limits the flow capability with the available differential pressure in the system.

If pressure-dependent valves are used, they must be properly sized with an accurate differential pressure to deliver acceptable performance. To enhance rangeability (controllability at low flow), sometimes pressure-dependent valves are installed in a 1/3, 2/3 arrangement to split the low and high flows. Proper sizing requires accurate hydraulic modeling as well as a good understanding of the loads, anticipated growth and delta T performance at each building. Rule-of-thumb valve sizing is not acceptable, as it will contribute to low delta T.

A pressure-independent control valve is sized by the flow rate alone. The designer doesn't need to accurately estimate the maximum differential pressure to properly size the valve in the hydraulic gradient. In general this enables it to be selected more accurately to use its full available stroke.

5.5.4 Actuator sizing and selection

Actuators and control valves should be selected together to ensure that they will operate properly as a system. There are numerous choices to be made regarding torque (or force), power input, control signal, fail position, feedback, manual override, stroke speed, etc., that are beyond the scope of this guide. Two-position actuators are acceptable with valves used for staging or isolation, but generally not for control if high delta T performance is sought. Modulating control-valve actuators that can accept a proportional-plus-integral control signal are recommended to improve adjustment, accuracy and response.

> Control-valve actuators should be sized to open and close the valve against the maximum possible differential pressure at the location where they are applied.

It is important for control-valve actuators to be sized to open and close the valve against the maximum possible differential pressure at the location where they are applied. In some cases this means full-rated shutoff head of the pumps. Low delta T issues will increase the flow requirements and pump head in operation near the ETS or plant. When actuators are undersized and there are low delta T issues, they can suffer from inadequate torque or force to function properly especially close to the pumps.

5.5.5 Quality and construction

Cooling coil and heat-exchanger control valve and actuator performance affects total plant, distribution, ETS and building system performance over the full life of the system. For this reason quality, construction and long-term maintenance requirements should be carefully considered when control-valve investments are made.

Industrial-grade control valves and actuators are preferred and should be selected for high rangeability (100:1 minimum) to enable them to control well at low loads and flows. Components should be high quality and built to last taking into consideration the flows, pressures, temperatures, chemicals and debris expected in the system.

5.6 ETS and Building Control Strategies

5.6.1 Supply-water temperature and reset

When chilled-water supply temperature reset or free cooling is planned at the central chilled-water plant(s), it is important to not lose control of the chilled-water or supply-air temperature required to satisfy the load and minimize energy consumption. District cooling contracts should specify the maximum distribution supply-water temperature provided to the ETS by the district cooling company. In addition, with indirect or decoupled direct connections, the supply-water temperature on the building side of the ETS should also be specified in the customer control guidelines and properly controlled.

Reset can have broad comfort, energy and economic implications and must be considered on a system (not component) level. Chilled-water reset is discussed in the chilled-water plant design and control section of this guide. Keep in mind that it makes no sense to reset the chilled-water supply temperature at the plant to reduce chiller-compressor lift and energy consumption if it leads to a loss of comfort control or a net increase in the total energy consumption for the district cooling company and its customers. Reset may also not be suitable in the plant if it adversely affects even one critical building on the distribution system.

> Low delta T can lead to high plant operating costs, return water blending with supply, overflow of running chillers and loss of thermal energy storage capacity.

As the distribution supply-water temperature rises, delta T declines, and there is an increase in distribution pump energy consumption. This must be balanced against the benefit of a reduction in chiller lift and energy consumption at the chiller. Depending on the plant, distribution system and ETS configuration, low delta T can also lead to (1) high plant operating costs, (2) return water blending with supply, (3) overflow of running chillers and (4) loss of thermal energy storage capacity. In addition, reset can reduce latent cooling capacity, humidity control and district cooling company revenue. Customer pump and fan energy consumption may rise as the supply water and supply air temperature rises. More water and air flow is required to satisfy the load.

Capability for chilled-water reset at the ETS is not discouraged, but it is imperative that the district cooling company and building owner fully understand the implications of reset throughout the entire system before implementation.

5.6.2 Supply-air temperature and reset at cooling coils

In North America, many chilled-water systems in buildings are designed with electric or hydronic reheat at individual zones. When a large air handler provides cool air to serve many zones, the reheat coil manages the space temperature at minimum air-flow requirements. This is intended to prevent overcooling in some of the spaces. This approach often wastes a lot of energy in simultaneous heating and cooling, even though the occupant of the space remains comfortable.

Fan-powered variable-air-volume (VAV) boxes are an alternative to reheat also used to prevent overcooling in individual zones. This approach recirculates the return air and blends it with the supply air from the larger air handler. When the supply-air temperature is too cold, it requires additional energy to operate the smaller fans at the zones.

A solution to eliminate overcooling and reduce customer building energy consumption is to reset the cooling coil supply-air temperature upward at minimum air flow. As soon as one of the primary VAV boxes reaches minimum air flow, the supply-air temperature is ratcheted up a notch. This process minimizes overcooling and, with proper control, will reduce the demand and increase delta T performance at low load.

5.6.3 Building pump and ETS control-valve control

Building pumps (if required) should be controlled by either the district cooling provider or the building customer to maintain a differential pressure at the hydraulically most remote point(s) in the system. This ensures that all circuits have enough chilled water to satisfy load conditions. Reset strategies may be applied to reduce the differential pressure setpoint at part-load provided the air-temperature and humidity requirements are met in all zones. To prevent comfort and control issues in customer buildings, pumps should not be run in normal operation to maintain minimum flow, delta T, supply-air temperature or return-water temperature for the building or individual loads. ETS control valves (if required) should control the supply-water temperature on the building side of the interface. Delta T or return water temperature control with ETS control valve may lead to capacity, energy, and comfort issues and is not recommended except as a temporary measure to curtail the load or flow with a problem customer.

Delta T and pump head are interrelated. In the decoupled direct connection shown earlier in Figure 5-2, low delta T at the coils forces the pump to generate more head to circulate the flow. This creates high suction pressure at the pump that draws more return water into the supply. As a result, the ETS control valve in the return line opens up to maintain the supply-water temperature in the loop at setpoint. The low delta T problem in the buildings transfers right through the ETS to the district side.

The same pump control strategy applies in an indirect connection with heat exchanger separation as shown earlier in Figure 5-4 and Figure 5-5. Given the physics of heat transfer, the chilled-water return temperature to the district will always be a little lower than the chilled-water return temperature to the building. This means it is vital to achieve good return-water temperature performance in the building to achieve high delta T in the district.

In a simple direct connection, there may or may not be a need for a building pump, depending on the location and height of the building relative to the district cooling plant(s). If a pump is used, it can be installed with a parallel bypass and check valve so that it is only run at high load if the differential pressure at the hydraulically most remote point(s) in the building falls below setpoint.

> If flow limiters are used at customer heat exchangers, an uncontrolled increase can occur in the building supply-water temperature if the design delta T is not achieved.

5.6.4 Capacity control after night setback

Flow limiters (or automatic balancing valves) are designed to limit the maximum flow rate through a heat exchanger, piping branch or cooling coil. A flow limiter is not a control valve and will not prevent low delta T issues. It is meant to prevent excess flow in one area from leading to lack of flow in another. These devices typically have an insert chosen for a fixed maximum flow rate.

When a customer chooses to shut off its cooling at night, the water temperature in the building can rise and create a high instantaneous demand for flow as the system is started in the morning. In district cooling systems, flow limiters have been used at heat exchangers to limit the flow rate to a maximum flow based on contracted tons and design delta T. A problem with this approach arises at peak load when design delta T is not achieved. Limiting the flow leads to an uncontrolled rise in supply-water temperature in the building.

Another concern if customers shut off their cooling equipment (including pumps) is that the zero-flow conditions in the building may cause system hunting problems and can also lead to a large district-side flow (leak flow) since the control valve(s) will open up to meet setpoint. To prevent this from happening, a pump status input should be provided to the ETS control system so that the control valves remain fully closed when the building pumps are not running.

An alternative to prevent high demand after night setback is for the customer to manage the flow and temperature control within the building to minimize the instantaneous load. This can be done with a normally closed bypass valve (<1% of design flow) at the end of the line that is controlled to keep the loop temperature from rising too high. Another strategy to limit high demand from night setback is to schedule the startup of air-handling equipment from unoccupied to occupied mode and operate with outside-air dampers closed until indoor-air setpoints are recovered from night setback conditions.

5.6.5 Staging multiple heat exchangers

With multiple heat exchangers, it is important to properly manage the flow. In an application with multiple heat exchangers, isolation valves on both the district and building side of each heat exchanger should be kept open unless heat exchanger maintenance is being performed. It is generally not necessary to provide valve actuators on the building side to automatically stage heat exchangers unless there is a desire to maintain a minimum flow. If water is flowing through a both heat exchangers on the district side and only one heat exchanger on the building side, there will be district supply dumping directly into the return, and poor delta T performance. Conversely, if there is water flow through a single heat exchanger on the district side and both heat exchangers on the building side, it will be challenging to achieve the supply-water temperature necessary for good control.

In general, an indirect ETS should be operated with variable flow through all heat exchangers, even at low load, to take advantage of the lower pressure drop and smaller approach. When parallel heat exchangers are installed, approach temperatures may be reduced below design in operation given the added surface area. Plate heat exchangers, unlike shell-and-tube heat exchangers, will almost always have turbulent flow conditions, even at 10% to 15% of full-rated flow. If the flow is less than 10% to 15%, excess plate heat exchangers can be shut down to maintain higher flow and cleanliness across operational units. Proper "seasonal" shutdown procedures include draining to avoid settling of fine dust, which is present in the water.

5.7 Metering and Submetering

5.7.1 Introduction[1]

The energy meter registers the quantity of energy transferred from the user's building system to the district cooling system. Cooling energy is the product of mass flow, temperature difference, the specific heat of the water and time. It is difficult to measure mass flow in an enclosed pipe system, so volume flow is measured. The result is corrected for the density and specific heat capacity of the water, which depends on its temperature. The effect of pressure is so small that it can be ignored. An energy meter consists of a flow meter, a pair of temperature sensors and an energy calculator that integrates the flow, temperature data and correction factors. It is desirable that the energy meter be supplied as a complete unit and factory calibrated with stated accuracy performance ratings in compliance with accepted metering standards.

5.7.2 Meter types

The meter is the district cooling systems' "cash register." Do not use cheap, inaccurate meters that may leave doubt in the mind of the customer that it is being fairly charged for chilled-water service from the district cooling provider.

The following are brief descriptions of the most common flow meters suitable for district cooling use. Meters can be divided into two major groups: dynamic meters, which register flow with the aid of moving parts; and static meters, which have no moving parts.

Dynamic meters

There are two types of dynamic meters used in district cooling: impeller and turbine meters.

Impeller meters measure flow with the aid of straight-bladed impellers. There are two types of impeller meters: multi-jet and single-jet.

Multi-jet impeller meters are very sensitive to impurities such as sand and sharp metal particles, but are not sensitive to flow disturbances. This type of meter is best suited to medium-sized buildings, but not for small buildings because it does not function well at small loads.

In single-jet impeller meters, the flow runs through a single nozzle directed tangentially to the impeller blades. Single-jet meters have properties similar to those of multi-jet meters, but they are more suitable for small buildings because a very weak flow is enough to start the meter.

In a **turbine meter**, the fluid in the pipe flows through turbine blades, causing them to rotate. A turbine meter records only the cumulative volume of chilled water supplied and does not take into account the difference in temperature (delta T) between supply and return. The meter's accuracy depends on the flow profile before the meter, so strong flow disturbances must be avoided. Generally, accuracy for turbine meters is in the range of +/- 1.5% to 3% depending on intermediate to low-flow conditions. The average pressure loss for a DN 40 (1-1/2") flow meter at 3.8 l/s (60 gpm) is approximately 0.55 bar (8 psi) – significantly higher than for a static flow meter.

The weaknesses of this meter are its high startup threshold and rapid wearing of bearings at high loads and in dirty water. Turbine meters are suitable for high flows, but are not suitable for small buildings.

Static flow meters

There are two types of static flow meters that are used in district cooling applications: magnetic induction (MID) and ultrasonic.

The **MID meter (or mag meter)** is based on induction of voltage in a conductor moving in a magnetic field. The conductor in this case is water. The recommended conductivity is ≥ 5μS/cm. Generally, district cooling water is conductive enough for MID metering. However, it is essential that this be confirmed in each specific case. Furthermore, the magnetite content of the water should also be checked to verify that the recommended value of 0.1 ppm (maximum) is not exceeded.

The water flows through a pipe made of non-magnetic material with an exactly known cross-sectional area. Electrodes connected to powerful electromagnets sense the flow. The voltage induced in the water is measured and amplified and the information is converted by the heat calculator.

Experience with MID meters in district cooling has been good. Although their initial cost is higher than dynamic meters, consideration should be given to their reduced maintenance and increased accuracy. The mag meter has excellent accuracy, low pressure drops and good rangeability, as well as low maintenance. These qualities usually justify the higher cost for mag meters compared to most dynamic type meters.

Ultrasonic metering is based on changes in the propagation of ultrasonic waves caused by the velocity of the flow. These changes are registered by measuring the time between the transmission and reception of ultrasonic signals over an exactly known distance or by measuring changes in the frequency of reflected ultrasonic waves.

The ultrasonic meter accuracy is in the range of +/- 1% to 2% depending on the intermediate to low-flow conditions. The pressure drop is very low; for a DN 40 (1-1/2") flow meter it is about 0.07 bar (1 psi) at 3.8 l/s (60 gpm).

Recent experience indicates that ultrasonic meters are also accurate and cost-effective for large flows.

5.7.3 Designing for meter installation and maintenance

The flow meter could be installed in either the primary supply or return pipe. In some instances, it may be beneficial to install the meter upstream of the heat exchanger and control valves to minimize the possible formation of bubbles in the flow stream, which could affect the meter accuracy. In most cases, for dynamic meters to ensure uniform flow and accurate flow measurements, there should be a length of straight pipe ten times the pipe diameter before the flow meter and a length of straight pipe five times the pipe diameter after the flow meter. This requirement is typically reduced to half the distance for static meters installed with reduced pipe-size diameter. The district cooling utility and meter manufacturer should be consulted for specific instructions.

Flow meters should not be installed in the low point of the piping system where dirt accumulates. Similarly, they should not be installed in the piping at the high point of the system, which would cause air to accumulate in the meter. To reduce wear on the bearings of a dynamic meter, it is important to fit the meter so that its impeller shaft is vertical. For magnetic meters, the pipes have to be grounded. Signal cables should be well protected from external disturbances.

Temperature sensors should always be installed against the flow, with the tip of the probe approximately in the center of the pipe. In addition, a properly sized measurement housing for the sensor and the water thermometer should be installed in the primary piping. Pipe increasers or a measurement housing will not be needed when sensor wells can be installed in pipe elbows or when pipe diameters exceed 100 mm (4 inches). In smaller pipes, wells for heat meter sensors can obstruct the flow. The sensors' surroundings should always be heat-insulated; otherwise, heat loss/gain from the sensors distorts the measurement. The sensors' wires should be of exactly the same length (e.g., matched pair) unless four-wire metering is used.

An MID meter should be fitted so that it is as easy as possible to clean the pipe and electrodes. Dirt on the electrodes creates an extra resistance that causes errors in the voltage measurement.

MID meters are not very sensitive to flow disturbances. Manufacturers state that a disturbance-free section of pipe five times its diameter before the sensor is enough, and they recommend that a pipe section two times its diameter should be free from disturbances after the sensor. However, any meter is more accurate if the disturbance-free sections of pipe are longer than the recommended minimums.

Meters are generally supplied and installed under the supervision of the district cooling company. The district may also supply a temporary spool piece, the same size as the meter, for installation in lieu of a meter until the system is clean and ready for operation or if the meter is removed for recalibration. Meter selection and sizing should be verified by the district cooling company and/or its engineer based on the information supplied by the ETS design engineer. For proper meter selection, it is essential that the district cooling company understand the building system operations under maximum and minimum flow conditions.

5.7.4 Standards

CSA C900 is a Canadian standard for thermal energy meters, but it is not commonly used throughout North America. There are international standards in place like the OIML-R75 and the European Standard EN 1434 that may be used as references. CSA C900 is adopted from EN 1434 with Canadian deviations.

5.7.5 Other equipment

Pressure gauges, thermometers and shutoff valves should be installed to enable proper monitoring, balancing and equipment isolation for maintenance.

A strainer with a mesh of 1.2 mm (3/64 inch) or smaller must be installed to adequately protect the critical components (i.e., heat exchanger, flow meter and control valves). To determine when the strainer should be cleaned, a pressure gauge should be connected to both sides of the strainer. The pressure drop through the strainer must be considered in the system design.

5.7.6 Submetering

Submetering of individual townhouses, condominiums or apartment units in multi-residential buildings is seldom practiced in district cooling systems. Normally the district cooling owner charges the building or subsystem owner and then it is up to the owner to allocate the costs based on floor area or some other metric.

However, sometimes the customer requires individual submetering to provide an incentive for a resident to conserve energy. In fact the European Union promotes individual metering of all utilities because it gives people the opportunity to be responsible for their utility usage and costs. For district heating systems this has been successfully implemented in many countries in Europe. Studies show that the energy consumption has been reduced by 20% in multi-residential buildings with submetering.

The implementation, however, is very capital cost expensive and is seldom cost-efficient for the building owner. For the district cooling owner it is important to make sure to include this cost as an installation or demand charge.

Primary energy metering will normally be performed according to local regulations or international standards, however submetering for allocate purposes are not included and does normally not have to follow any regulations.

Submetering can be employed in following ways:

1. Measure the thermal energy used for each customer.

2. Measure the total thermal energy used for the subsystem and consumed water volume for each customer.

3. Measure of room temperature in each apartment.

Measurement of room temperature is the least expensive, but also the most inaccurate. This method will not show accurate energy use when, for example, airing a room, and it is not recommended.

Submetering the water volume consumed is a cost-effective solution for subsystems with similar cooling usage, such as only residential customers etc. The solution provides not only an accurate measurement, but also a mechanism to reward conservation or penalize wastefulness.

For more complex subsystems where the usage is a mix of different cooling usages, the thermal energy needs to be metered. This will then be done in the same manner as primary metering (the metering unit comprises a flow meter and two temperature sensors together with an energy calculator).

Experience shows that subsystems are often a mix of different cooling usages and the incremental savings of using simple water meters versus energy meters is relatively small.

Meter reading

The other issue to be decided with respect to submetering individual townhomes or multi-residential apartments is how the data should be accessed, i.e., either by local readings taken inside the units or by remote readings taken from the outside. For either meter type, the data could be accessed in the following ways:

1. Reading inside an apartment/townhome unit. Data exchange occurs at the location of the energy meter, and in the most basic system, this would be done using a handheld device or a laptop computer interfacing either through the optical head or via a plug-in. Based on cost analysis, the capital-cost saving with local reading is not considered to be worth the additional ongoing labor and administrative cost. This approach also requires entry into the unit, which the resident could consider intrusive.

2. Remote reading via fixed or drive-by wireless network. Under this option, data would be transmitted via a radio signal from an output device included in the meter to a central receiver or a handheld receiver outside the residential unit. This method is commonly used in Europe and in North America. However, a radio frequency license may be required. This wireless approach is proven technology and is less expensive.

3. Remote reading via the telephone network.

4. Remote reading via Internet connection through the building fiber optic system. If this system will be in place, then each energy meter can be fitted with a TCP/IP module and transmit its data through TCP/IP (an internet communication link) to be read by a central computer. Further, the Internet connection must be within the room where the meter is located. One advantage of this system is that the energy meters can directly communicate over the building Internet line and a dedicated communication system is not required. However, this system would be dependent on the quality and reliability of the building's Internet connection.

Meter communication links via a fixed or drive-by wireless system is the recommended approach for individual town homes or multi-residential apartments. It is a proven technology and a cost-effective solution.

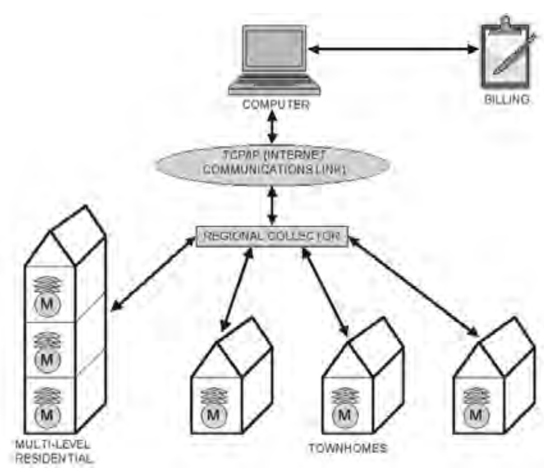


Figure 5-13. Submetering system via fixed wireless.

Submetering system via fixed wireless consists of energy meter equipped with radio frequency (RF) transmitter, concentrators/collectors, TCP/IP and computer software. See Figure 5-13.

Individual energy meters are fitted with radio frequency modules. Each transmitter collects the meter's data periodically and converts the measurement into a digital signal transmission. This data is transmitted via radio frequency to a central RF concentrator equipped with an external antenna. The concentrator collects the data from individual RF module, decodes the transmission and stores the meter reads for billing. The concentrator can handle up to approximately 650 energy meters and can be placed indoors or outdoors. Computer software is used to upload the data via the TCP/IP to a central computer and each submeter can be identified for billing purposes by its unique address.

Wireless communication between an RF module and an RF concentrator takes place within a dedicated frequency band without thereby disturbing other RF receivers. For this dedicated, uncluttered frequency strength, license would typically be required through appropriate local agencies.

Alternatively, at slightly higher cost, meters supplied with RF modules can also be read by a person driving by along a preset route with an RF handheld terminal, see Figure 5-14. When reading is performed, the handheld terminal is placed in a docking station and data is transferred to a central computer. Computer software is used to export this data to a billing or analytical purposes.


Figure 5-14. Submetering system with an RF handheld terminal.

Conclusions about submetering

The following are conclusions about submetering options:

1. Allocating costs based on floor areas or other parameters is simple and cheap to implement; however, it does not provide an incentive for a resident to conserve energy. There is no mechanism to reward conservation or penalize wastefulness.

2. Studies show that submetering reduces energy consumption. The implementation, however, is very capital-cost expensive and is seldom cost-efficient for the building owner.

3. If submetering is to be implemented, the incremental savings of using simple water meters versus energy meters are relatively small. Considering that impeller meters are less accurate and deteriorate faster and that static flow meters are more suitable for measuring chilled water, ultrasonic energy meters are recommended.

4. If submetering is to be implemented, meter communication links via a fixed or drive-by wireless system would be the recommended approach for individual townhomes or multi-residential apartments. Reading meters inside individual townhomes or apartments units is generally more costly and considered far too intrusive, and therefore is not recommended.

[1] This section on metering draws heavily on "District Heating and Cooling Handbook," a 2002 publication of the International Energy Agency, Report 2002:S6. The author of the cooling portion of the report was Bard Skagestad of FVB Energy Inc.

6. Chilled-Water Distribution Systems

A district cooling distribution system is designed to safely, reliably and efficiently deliver chilled water to connected customers to meet their cooling requirements. Chilled water leaves the plant(s) cold and returns warm after capturing the sensible and latent heat from process and comfort cooling loads. It also picks up heat from the ground as it is delivered and returned.

It is imperative for designers to carefully assess the load, diversity, flow rate and pressure requirements as well as heat gain to ensure available capacity and eliminate unnecessary waste or excess in the design. A chilled-water distribution system is one of the largest capital expenses in any district cooling scheme. The system should be designed to accommodate future expansion and designed to last, as it is very expensive to replace or resize buried pipe once it is installed.

Proper planning and design of the distribution system is critical to ensure that customer loads can be met while minimizing excess capacity.

In the Middle East, particular attention must be paid to corrosion protection of buried piping and insulation design to minimize heat gain. Buried chilled-water piping in the Middle East is often installed at or below the water table, and ground water can be highly saline, so it is critical that protection of metallic piping and components from corrosion be carefully considered. Without proper insulation, the chilled-water supply temperature to customers could become unacceptably high due to heat gain from the ground and ground water, especially during off-peak times. Proper piping insulation helps minimize the installed capacity of the plant and distribution system while reducing the added operating expense of heat gain in buried pipes.

It's equally important to develop a delta T strategy to optimize performance in operation. Low delta T continues to be a chronic problem that adversely affects energy, capacity, comfort and economics in the district cooling industry worldwide; however, sound design can eliminate these issues without compromising performance.

Developing a delta T strategy in the early stages of system development will allow distribution system costs to be minimized without stranding production capacity.

District cooling systems in the Middle East are among the largest in the world and located in one of the most severe climates. The large loads, large piping networks and rapid development growth in the region make efficient and effective chilled-water distribution especially challenging. If high delta T can be achieved throughout the system, it is possible to dramatically reduce both first costs and operating costs while providing a better and more economically advantageous service to customers.

This chapter highlights design considerations, challenges and best practices for distribution system design, pumping schemes and pressure control, and distribution piping materials and components.

6.1 Hydraulic Design

6.1.1 Hydraulic model

A hydraulic model is a critical investment when designing a chilled-water distribution system for a district cooling utility. Hydraulic modeling helps to

- properly size, select and locate infrastructure and equipment;
- evaluate pipe routing scenarios and the impact of loops;
- consider the impact of future customer connections and load changes;
- account for system diversity;
- integrate thermal energy storage or additional chilled-water plants;
- assess energy performance;
- troubleshoot performance issues (like low delta T);
- evaluate the impact of heat gain and temperature rise in supply and return piping; and
- identify hydraulically remote locations for pump speed control.

A hydraulic model is a critical tool for optimizing the design and operation of a district cooling system.

The hydraulic model is a tool that should be maintained and updated after initial system design to assist in system analysis and future decisions that affect the district cooling distribution network. Recent developments in software sophistication now allow for real-time hydraulic models that interface with utility SCADA systems, which can aid in distribution system operational decisions and may reduce network instrumentation requirements.

The topics discussed below are important to consider when developing an accurate and useful chilled-water system hydraulic model.

6.1.2 Customer loads and system diversity

As discussed in earlier chapters, market assessment and load estimation are critical exercises in the business evaluation and development of a district cooling sytem. Peak-load and usage-type estimates for the projected customer base also are key to proper planning and sizing the distribution system.

One of the big advantages of district cooling is the opportunity to take advantage of load diversity, as discussed in section 4.1.1. If customers connected to the distribution system are expected to have significant load diversity, then the designer should work to use coincident peak loads in the hydraulic model to size distribution mains, while ensuring that branch lines and service lines to customers are sized to accommodate non-coincident peak loads.

6.1.3 Startup and growth

The initial hydraulic gradient in a distribution system will change dramatically as more customers are connected and as the system changes and grows. Distribution system hydraulic modeling for design purposes must take this into consideration, particularly since the hydraulic model is used in the sizing and selection of control valves at customer buildings, sizing and selection of distribution pumps and defining system pressure limits. Future implementation of thermal storage, colder supply-water temperatures or additional plants may also come into consideration and should be assessed as part of the long-term distribution system strategy. System planning also should consider that in the early years of a developing district cooling system, before the distribution system is fully utilized, heat gain as a percentage of plant chilled-water sendout will generally be higher, and chilled-water supply-temperature rise will be higher. Heat gain and temperature rise are discussed further in section 6.4.4.

Future implementation of thermal storage should be considered during distribution system planning.

6.1.4 Piping layout

The distribution piping layout can be driven by a number of external factors including access, obstacles, elevations and geology. For district cooling distribution systems that will run in public streets or spaces, it is critical that the owner or the owner's representatives engage the municipality as early as possible in the district cooling system development process. This will give the owner the best opportunity to obtain a desirable utility corridor for distribution piping and minimize piping burial depth, which can provide substantial capital cost savings. Once the preliminary layout is defined, the hydraulic model can be used to size and select pipe and also can be used to consider alternative piping layouts, and pumping schemes and potential future system changes.

6.1.5 Delta T

The hydraulic profile in a system that achieves high delta T is dramatically different from a model for a system that doesn't, as illustrated in Figure 6-1.

Cooling coils within customer HVAC systems and control valves within customer HVAC systems and utility ETS

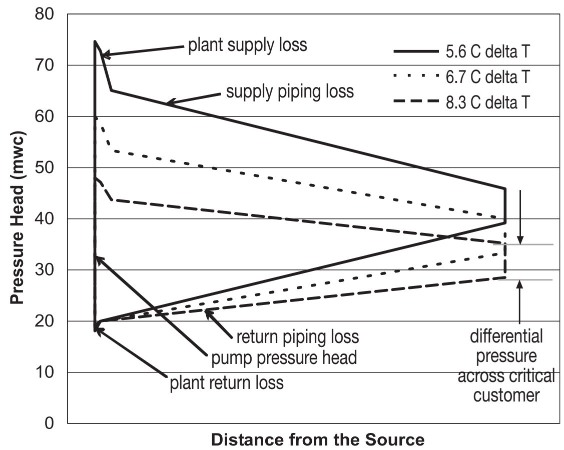


Figure 6-1. Impact of delta T on hydraulic profile.

are responsible for delta T performance in operation. If the delta T performance is overestimated, it can result in an undersized piping network, pumps without enough capacity or stranded production assets. If the delta T performance is underestimated, it can lead to an oversized system with larger pumps, pipes and other equipment, at a significant impact to first cost.

If the district cooling utility is not prepared to take the steps required to achieve high delta T, then this must be factored into chilled-water system hydraulic modeling and distribution system design. For example, many district cooling systems consist of a mix of both new developments and existing buildings, and the existing buildings frequently require a substantial retrofitting project to improve their building-side cooling systems to get a high delta T performance from the building. If the district cooling utility is not prepared to ensure that these retrofits happen, then the district cooling system designer must make a realistic, and likely lower than desired, estimate of the delta Ts that can be achieved from the existing buildings that are expected to be connected to the system. For systems that will consist primarily of new development, but also include a small number of existing buildings, it

Getting a realistic picture of the delta T to expect from a district cooling system is critical to "right-sizing" a chilled-water distribution system.

may be possible to achieve a satisfactorily high overall system delta T without substantial retrofit of existing buildings. However, this may require the district cooling utility to be more aggressive in ensuring that new developments are designed and operated to produce a very high delta T to offset poor delta T performance from the existing buildings. The key is that the district cooling utility must consciously prepare its delta T strategy before customer contracts are signed, and before final design of the district cooling plant and distribution systems.

6.1.6 Pipe sizing

Ideally, pipe sizing should be determined via life-cycle cost analysis, to find an optimal economic balance between first costs of distribution system capital and operating cost over the life of the system.

Designers should be cautious about using simple velocity rules of thumb to size district cooling distribution piping, especially for larger pipe sizes. When using hydraulic modeling software to size piping, initial sizing can be done using a constant pressure gradient (pressure drop per unit length) for the piping network and then manual adjustments made from there. For example, if the critical path for the distribution network is known and is not expected to change over time, then selective upsizing of smaller-diameter (and therefore less expensive) piping toward the end of the critical path can be prudent. Velocities in larger piping can be quite high and still have a reasonable pressure gradient, but the designer must evaluate water hammer risk and take care that velocities are within the manufacturer's recommended limits for the pipe type selected.

Special consideration should be given to fitting losses for distribution systems with large-diameter piping and installations in densely populated areas to ensure that the magnitude of pressure loss due to fittings has been accurately represented in the hydraulic model. For small diameter chilled-water pipe [e.g., less than 250 mm (10")] runs without too many elbows, fitting losses may add less than 5% to piping pressure loss, while large-diameter pipe [e.g., 600 mm (24") and up] runs requiring a significant number of fittings to avoid other buried utilities could have fitting losses that add more than 50% to straight-pipe pressure loss.

To minimize unnecessary design conservatism and cost, it is critical that the district cooling utility work with the customers through their contracts to ensure that the load and flow demands are realistic and that the delta T performance that is expected will be achieved.

Fitting losses can easily be underestimated for large-diameter distribution systems in congested urban areas.

There are numerous design tradeoffs that may be considered to reduce distribution pipe sizing and, therefore, the first costs and/or operating costs of the distribution system. These choices should be looked at as investments to improve project life-cycle economics and enable future growth. Some examples are as follows:

- lowering the distribution supply temperature
- achieving higher delta T across customer cooling coils
- adding a remote plant or thermal energy storage

Table 6-1 illustrates the tons of cooling that can be delivered at a 2.87 mps (9.4 fps) velocity limit in a 900 mm (36") steel pipe with different levels of delta T performance. Increased delta T has a significant impact on cooling delivery capacity.

Delta T		Approx. Capacity (tons)
C	F	
6.7	12	14,200
7.8	14	16,600
8.9	16	19,000
10.0	18	21,400
11.1	20	23,800
12.2	22	26,200
13.3	24	28,500

Table 6-1. Impact of delta T on 900 mm (36") pipe capacity.

Table 6-2 illustrates the tons of capacity of a 1000 horsepower (hp) pump set pumping through 1524 m (5000 ft) of 900 mm (36") supply and return piping (fitting pressure losses not considered) with different levels of delta T performance.

Delta T		Approx. Capacity (tons)
C	F	
6.7	12	22,400
7.8	14	26,100
8.9	16	29,900
10.0	18	33,600
11.1	20	37,400
12.2	22	41,100
13.3	24	44,800

Table 6-2. Impact of delta T on capacity of 1,000 hp pump set.

Maximizing system delta T has a dramatic effect on distribution system capacity.

Lastly, when making distribution system pipe size selection, the designer should be mindful of commercial availability of pipe sizes in the project region. Odd sizes that are not commonly available in the marketplace and/or are not available cost-effectively should be avoided. For some odd sizes, steel mills may be able to provide piping if ordered in quantity, but fittings will not be readily available. Since it is common that unanticipated fittings are required for piping projects during construction, this could cause significant construction delays.

6.2 Pumping Schemes

In the industry, there has been a lot of debate about pumping and piping schemes used in hydronic system design. In general, variable primary flow is the growing trend and is considered to have modest energy and first-cost savings advantages, a smaller footprint and some added control complexity. Primary-secondary system design is considered reliable, conservative and easy to operate. This section will highlight some of the main issues and concerns when considering alternatives for hydronic system design in district cooling applications. In the industry, some suggest that it is advantageous to start with primary-secondary pumping as a "base" design scheme and then consider the more complex variable primary flow as an alternative to reduce first costs, footprint, and pump energy consumption. On the other hand, others suggest that variable primary flow is more tolerant of low delta T issues than primary-secondary systems because the available capacity of chillers is not limited by flow.

Use of the variable primary pumping scheme for district cooling systems has been growing.

When delta T is low, extra flow is required to serve the load and will need to circulate through the plant and connected buildings. If delta T is low at the plant, the system operator must choose from three options:

- blending return water with supply
- overflowing running chillers
- running additional chillers

None of these choices is optimal. Also if the system has thermal storage, it may require running additional chillers sooner.

A strong delta T strategy will eliminate many of the control and operational complexities as well as energy waste, lost available capacity and comfort control issues that can arise in a poorly performing system. It also can minimize unnecessary added margin or conservatism in the design that will drive up the first cost. Delta T issues should be proactively addressed in any system.

6.2.1 Variable primary flow

A typical variable primary flow system as shown in Figure 6-2 has a set of pumps working together to independently serve multiple chillers. Flow is allowed to vary through each chiller as chillers are sequenced in and out of service. A minimum evaporator flow bypass and normally closed control valve serve to maintain minimum flow through running chillers to prevent freezing in low- and laminar-flow conditions. However, if the plant cooling demand is such that flow will never fall below the minimum flow requirements of one chiller, then the bypass is not required. Since greater demands are placed on chillers and pumps in variable primary flow applications, the system must be designed with accurate and reliable controls as well as metering and indication. Operators must be trained to run equipment properly within appropriate limits.

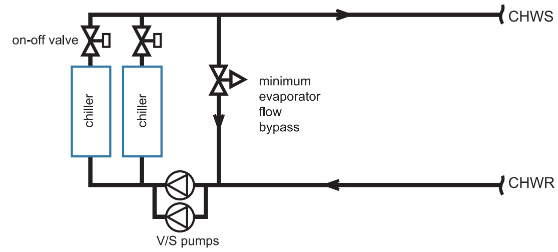


Figure 6-2. Variable primary flow.

The parametric study in a research project titled "Variable Primary Flow Chilled Water Systems: Potential Benefits and Application Issues" conducted and released by the Air-Conditioning and Refrigeration Technology Institute (ARTI) states this in its executive summary:

> *Variable flow, primary-only systems reduced total annual plant energy by 3 to 8%, first cost by 4 to 8%, and life cycle cost by 3 to 5% relative to conventional constant primary flow/variable secondary flow systems. Several parameters significantly influenced energy savings and economic benefits of the variable primary flow system relative to other system alternatives. These included the number of chillers, climate, and chilled water temperature differential. The following factors tended to maximize variable primary flow energy savings relative to other system alternatives:*
>
> - *Chilled water plants with fewer chillers*
> - *Longer, hotter cooling season*
> - *Less than design chilled water temperature differential*
>
> *Chilled water pumps and chiller auxiliaries accounted for essentially all savings. Differences in chiller energy use were not significant from system type to system type. Variable flow, primary only systems' chilled water pump energy use was 25 to 50 percent lower than that of primary/secondary chilled water systems. In systems with two or more chillers configured in parallel, chiller auxiliary energy savings were 13 percent or more relative to primary secondary.*
>
> *…it can be concluded that variable primary flow is a feasible and potentially beneficial approach to chilled water pumping system design. However, the magnitude of energy and economic benefits varies considerably with the application and is obtained at the cost of more complex and possibly less stable system control. The literature on effective application of variable primary flow is growing and should promote its appropriate and effective use in the future.*

Special considerations for district cooling systems

The ARTI study excerpt above notes that variable primary configuration offers greater energy savings to plants with fewer chillers. It is important to stress the significance of this in the context of large district cooling system design. Since typical district cooling plants, particularly those in the Middle East, have a large number of chillers in parallel, operating cost savings, on a percentage basis, will generally be very small compared to individual building cooling plants that may only have two chillers in parallel.

Operating cost savings, on a percentage basis, from use of variable primary vs. primary-secondary, is larger for plants with a small number of chillers.

To illustrate this point, consider first a building cooling plant with two identical chillers, with each sized for 50% of the building peak cooling load, and in a primary-secondary configuration. As the cooling demand moves beyond 50% of the plant design capacity and the second chiller is activated, the flow in the primary loop is 100% higher than the secondary loop flow. Then consider a district cooling plant with ten identical chillers, each sized for 10% of the system peak cooling load and in a primary-secondary configuration. As the cooling demand moves beyond 50% of the plant design capacity and the sixth chiller is activated, the flow in the primary loop is only 20% higher than the secondary loop flow.

This is a simple example that does not consider possible low delta T issues, or other operational considerations, but one can see how energy cost savings accrued from variable primary configuration versus primary-secondary will be much lower, on a percentage basis, for plants with a large number of chillers. The energy savings percentage will also generally be smaller for large chiller plants that operate less frequently under lightly loaded conditions, such as district cooling plants in the Middle East.

Another element that must be considered in the designer's analysis of whether variable primary is the best alternative for a large district cooling system is the impact to the distribution system. Depending on the system configuration, without primary-secondary decoupling the variable primary system may reduce the amount of pumping head available to the distribution system. This will have a more significant impact to systems with larger distribution systems, but the designer should consider, if applicable, the costs of distribution system piping upsizing and/or increased design pressure in the plant or distibution system required to accommodate a variable primary arrangement.

Design considerations

The chiller manufacturer needs to provide the minimum flow requirements for chillers used in variable primary flow applications. Depending on the manufacturer, chiller type and the tube design, this can range from as low as 25% to 60% design flow. Absorption chillers typically have less tolerance for variable flow than modern centrifugal chillers. Chillers used in variable primary flow applications must be designed for rapid response to changing flows with microprocessor controls. An accurate means of sensing flow and load is also required. Industrial grade magnetic flow meters and temperature sensors are recommended.

On-off valves used for chiller staging should be of high quality and high rangeability as well as slow-acting so transient pressures and flows don't create problems as additional chillers are sequenced in or out of operation. Modern sophisticated chiller controls should be able to respond to 25% to 30% flow change per minute or more. If the change is faster, the chiller may not unload quickly enough to avoid freezing and it may trigger controls to shut off the chiller to fail-safe (i.e., shutdown on evaporator temperature safety).

Depending on the application and design, it may be prudent to slightly unload a chiller before opening a chiller valve to bring another chiller online. Designers should also make sure that pressure drops through individual chillers in parallel are the same or very close. The intent is to design the hydraulic system to minimize rapid and large changes in flow rates while selecting chiller equipment that can handle it. Chillers can be sequenced in and out based on plant leaving-water temperature and calculated load.

Proper sizing of the minimum evaporator flow bypass valve is critical to variable primary plant operation.

The minimum evaporator flow bypass valve is sized for the minimum flow of the largest chiller. It must be able to deliver very low flow and is likely to see high differential pressure and real-time pressure fluctuations. It is controlled to supplement the flow rate through the chillers with enough extra flow to maintain minimum evaporator flow rate requirements. If this component is sized, selected or controlled improperly it will cause problems sequencing chillers and maintaining control in the plant. It must be properly sized in the hydraulic gradient even as the system grows and have high rangeability to modulate well at low flows. The actuator should be industrial-grade, rated for continuous duty and able to close off against the maximum differential pressure the pumps can produce.

Pump selection takes into account the pressure loss through the chiller evaporator as well as the piping network. Typically the pumps are installed upstream of chillers but can be installed downstream if necessary to reduce operating pressure in the chiller evaporator as long as suction head at the pump intake is well-managed. Flow is introduced through a chiller before it starts and maintained until it stops. Pumps are manifolded, so that they are not dedicated to chillers and can be staged to operate for the best operational efficiency. Pump speed should be controlled with variable-frequency drives to maintain a minimum differential pressure at the hydraulically most remote points(s) in the system.

A variable primary pumping arrangement at the plant is not the solution to system delta T problems.

Choosing variable primary flow to manage low delta T problems or to try to increase the available load capacity of chillers in "flow-limited" primary-secondary systems is not recommended. This approach falls short at peak load conditions when low entering condenser water temperatures aren't available and will contribute to other energy and performance problems. The best practice is to fix low delta T issues at their source, the customer buildings, no matter what flow configuration is selected.

When to use variable primary flow

It is most advantageous to use variable primary flow when the following apply:

1. The cooling load and flow varies – The system is designed for variable flow and isn't intended for constant process cooling loads or full thermal energy storage.

2. Footprint is a premium – Variable primary flow systems reduce the footprint taken up by extra pumps, pipes and connections. It may or not be possible to take advantage of the smaller footprint, depending on the facility and layout.

A variable primary flow arrangement should only be used if key operational criteria can be met.

Variable primary flow should only be used if the following apply:

1. Chillers are compatible with variable flow – Different types of chillers have different capabilities and limits. Absorption chillers are generally less tolerant of variable flow. The rate and magnitude of flow-rate changes must be compatible with chiller operation.

2. Modest variations in the chilled-water supply temperature are acceptable – There may be a temporary rise in supply-water temperature leaving the plant as additional chillers are sequenced in. This is because return flow is circulated through the additional chiller to protect it before it is started. Return water blends with the leaving water from other chillers.

3. Flow and temperature measurement equipment is accurate – There is less margin for error in a variable primary flow system so flow and temperature equipment must be regularly calibrated and maintained. Flow meters must accurately measure low flows to be an effective control input.

4. System designers understand and operators are trained to properly maintain minimum evaporator flow requirements – This is a critical control task that is required to minimize system faults no matter what the load or number of chillers running. Improperly sizing, selecting or controlling equipment can lead to significant issues.

5. The chillers can handle the pressure – In a large system, with pumps upstream of the chillers, the supply pressure may be high. It may continue to grow as the system grows. If delta T in operation is low, it will be even higher.

6.2.2 Primary-secondary pumping

A traditional primary-secondary system, as shown in Figure 6-3, combines a constant-flow primary (chiller plant) loop with a variable-flow secondary (distribution) loop. Primary pumps are constant-speed and sized for the head and flow required in the primary loop alone. Secondary pumps are variable-speed and sized to deliver chilled water through the distribution network to connected loads.

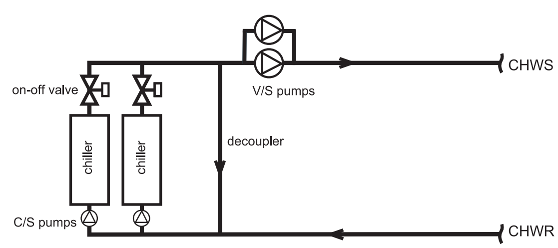


Figure 6-3. Traditional primary-secondary system.

In this configuration, a decoupler separates the primary and secondary loops. The flow through each chiller in the primary loop remains constant while flow in the secondary loop varies in response to the cooling load. To maintain design supply temperature leaving the plant, flow in the primary loop is maintained higher than (or equal to) the flow in the secondary loop. Flow through the decoupler, therefore, is intended to be in the direction from supply to return as additional chillers are sequenced in and out of operation. Temperature in the bypass can be used to indicate the flow direction, and a capacity shortfall, to trigger the start of another chiller.

An all-variable-speed primary-secondary system as shown in Figure 6-4 is similar to a traditional primary-secondary system except that the primary pumps are collected together so that any pump can serve any chiller. In this configuration, chiller flow generally remains constant but there is more opportunity to over-flow the chillers as necessary.

If delta T is low, it permits variable-speed drives to control primary pumps so that there is always more flow circulating in the primary loop than in the secondary loop. This prevents the secondary pumps from drawing return chilled water into the supply and degrading the temperature provided to connected customers. It also can be controlled to allow extra flow through the chiller so it can generate more than its design capacity when entering condenser-water temperature is less than design.

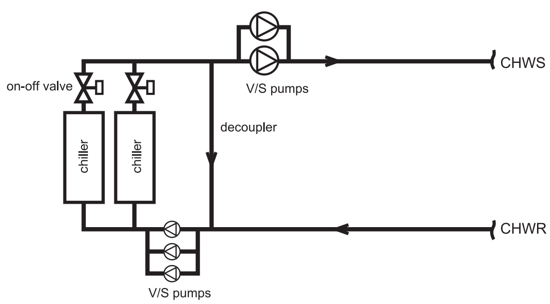


Figure 6-4. All variable primary-secondary system.

When to use primary-secondary pumping

It may be advisable to use a primary-secondary pumping scheme when the following apply:

1. Chillers can't handle variable flow – Chillers are used that can handle only minor flow variations. This could be the case with absorption chillers.

2. Chillers can't handle the pressure – It is a large system and the pumps are installed upstream of the chillers. High supply pressure now or in the future will exceed chiller capabilities.

3. Loads and flows don't vary – The system has steady process loads or full thermal energy storage. Variable flow doesn't offer an added energy advantage.

4. Owner values familiarity – The facility owners, operators, engineers and contractors are far more comfortable with primary-secondary and understand the long-term energy and cost implications.

It is possible to convert existing primary-secondary systems to variable primary flow. In fact, if delta T performance can be improved prior to the conversion, then existing secondary pumps may be suitable without replacement provided consideration is given to pressure management at the pump suction and to the minimum evaporator flow bypass location.

6.2.3 Distributed pumping

Distributed pumping is a scheme where chilled water is pumped through the district cooling distribution piping system via pumps located at individual customer buildings, rather than at a central cooling plant. The pressure profile for this type of system is opposite that of the pressure profile for a system with centralized distribution pumping; pressure in the return piping is higher than the pressure in the supply piping and the pumps generating the highest head are the ones that are most hydraulically distant from the central plant. Generally, this scheme is employed as a primary-secondary distributed pumping arrangement, where pumps in the central cooling plant handle in-plant head requirements, with a decoupler hydraulically separating the plant from the distribution system.

A distributed pumping system can offer significant pumping energy savings, but should generally be considered only if chilled water system loads and extents are clearly defined.

The main advantage of a distributed pumping arrangement is significantly lower distribution pumping energy. Centralized distribution pumps must produce the head required to serve the most hydraulically distant customer for the *full system flow*, with excess head consumed by customer control valves. With distributed pumping, on the other hand, distribution pumps at each customer premises produce the distribution head and flow required to serve *only that customer*, so there is no energy wasting consumption of excess head.

The main disadvantage of a distributed pumping arrangement is lack of flexibility. For a distributed pumping system to be practical and effective, the designer must have a clear picture of what the distribution system will look like over time, so that the distributed distribution pumps installed at a customer's building can be properly sized. For most district cooling systems that build out over time and where the ultimate customer base for the district cooling system is not known in the design phase, a distributed pumping system is generally not practical. However, for systems with well-defined system extents and a low level of uncertainly regarding future loads, it would be prudent for designers to consider a distributed pumping scheme. Figure 6-5 illustrates an arrangement where the customers are directly connected to the system and the distributed pumps at the customer premises also handle the pumping through the buildings' internal HVAC systems. It is also possible to have a distributed pumping system with indirect connections (heat exchangers separating the district-side and building-side systems) or direct connections with decoupled tertiary loops at customer buildings. In these cases, the pumps that handle head requirements for the customer's building-side chilled-water system are separate from the pumps providing the building with chilled water from district cooling distribution system.

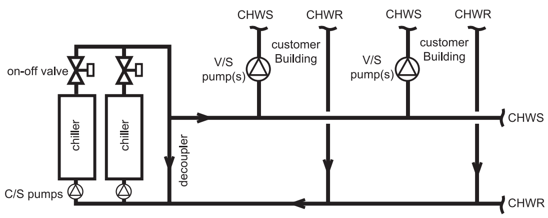


Figure 6-5. Distributed primary-secondary system.

It is also possible to have a "hybrid" system that combines central distribution pumping at the district cooling plant with distributed pumping at hydraulically distant customer buildings. However, designers should be very cautious about attempting to implement such a system. In addition to the challenges discussed above for a "pure" distributed pumping system, a hybrid system introduces the added complexity of having centralized distribution pumps at the plant operating in series with distributed pumps at customer buildings. Unless this type of distribution system is very carefully designed and managed, with a robust controls system and experienced operators, this can result in unexpected operational conditions and an unstable distribution system.

6.2.4 Booster pumps

For very large distribution systems, or for interconnection of multiple subsystems, it can make sense to have booster pumps at a strategic point in the distribution system. Generally, it is impractical to incorporate booster pumps into a looped network; booster pumps are used where a single pair of supply and return pipes feeds into a given area. Booster pumps allow for chilled-water transmission further away from a central plant, as an alternative to increasing distribution pipe size.

Booster pump stations can be expensive, especially if a dedicated facility must be constructed to house the booster pumps and associated equipment, and life-cycle costs should be evaluated carefully. A booster pump station may be the lower capital cost alternative versus increased piping cost, but will have increased pumping energy costs that must be considered as well. Very often, it makes more sense to have separate district cooling systems than to try to interconnect service areas that have significant distance between them.

In Europe, booster pumps have been installed in long transmission lines between hot water distribution networks.

However, in cases where there are significant differences in chilled-water production costs between two district cooling networks with a significant distance between them, booster pumping stations may prove to be an economical solution. Booster pumps may also be an attractive option for existing systems with constrained capacity, where replacing existing pipe mains is impractical or cost-prohibitive, but delta T improvement opportunities should generally be investigated first.

In most cases, the optimal design for a booster pumping station in the distribution system consists of booster pumps installed on both the supply and return lines, with identical sizing. The symmetry of boosting pressure on both supply and return mitigates water hammer effects in the event of booster pump trips. Also, this arrangement typically maximizes the amount of pressure boost that can be achieved at the booster pump station within the design pressure constraints of the system. Since booster pumps in the distribution system will be operating in series with distribution pumps at the central plant, the control strategy must be carefully considered so that the arrangement does not result in unexpected operating conditions or system instability.

6.3 Pump and Pressure Control

6.3.1 Distribution pumps

Horizontal or vertical split-case pumps are typically selected for chilled-water distribution pumps in district cooling systems, due to their high efficiency, ease of maintenance and cost-effective availability in large sizes. Although inline vertical pumps can reduce plant floor space requirements, among plant operations and maintenance personnel, selection of inline vertical pumps is generally discouraged, with some of the cited reasons as follows:

- Bearings are unevenly loaded.
- Greasing is critical, but difficult do with vertical pumps.
- Removing the casing is difficult and can be unsafe.
- Vibration measurement is more difficult.
- Resonance problems are worse.

Distribution pumps should be selected based on quality, reliability and a life-cycle cost analysis that includes first cost and operating cost at a minimum. Whenever

Plant O&M personnel prefer split-case pumps to inline vertical pumps.

possible, any difference in maintenance costs between different pump selections should be considered in the life-cycle cost analysis as well.

6.3.2 Variable-frequency drives

For a bank of distribution pumps operating in parallel on a common header, the energy savings benefit from the use of variable-frequency drives (VFDs) for variable-volume operation is highest for the first pump brought online and successively lower for each additional pump brought online. Depending on the quantity of pumps in the pump bank, the energy savings from variable-speed operation of the last pump engaged can be very small. However, for banks of distribution pumps with low-voltage motors, installing VFDs on all the pumps is best practice in most cases nowadays due to fact that low-voltage VFDs and soft starters have similar costs. Installing VFDs for all pumps in a bank of pumps also allows run hours to be balanced equally among all the pumps, and can simplify controls and operation.

VFDs for medium-voltage motors are very expensive and large. Therefore, in cases where pumps with medium-voltage motors must be used due to plant design constraints, or regulations imposed by local electrical utilities, it is worthwhile for the designer to evaluate life-cycle costs to determine the economically optimal number of VFDs for pumps in the distribution system bank. This can be especially pertinent to variable-flow primary systems, where chiller-loop pressure drop is added to the distribution-system pressure drop, which may push pumps from low voltage to medium voltage.

Regardless of the optimal economic breakpoint, if variable- and constant-speed pumps are mixed, best practice is to have at least three pumps with VFDs before mixing with constant-speed pumps. A single variable-speed pump must not be operated with one or more constant-speed pumps, since this could result in a situation where bringing on the constant-speed pump causes the variable-speed pump to back all the way up on its curve (deadheading), and thus operate at an unsafe condition.

Two variable-speed pumps can be safely operated with one or more constant-speed pumps as long as the control system is (1) sophisticated enough to interlock the VFDs such that the variable pumps both operate at the same speed at all times and (2) capable of ensuring that when only one of the two variable-speed pumps is in service, it is operated only with its speed fixed at 100%. It is recommended, however, that a minimum of three variable-speed pumps be included in a bank of pumps before adding constant-speed pumps. This way, if one of the variable-speed pumps is out of service then the bank of pumps can still be operated with variable-flow capability.

A bank of parallel pumps should have at least three variable-speed pumps before mixing with constant-speed pumps.

6.3.3 Differential pressure control

Variable-speed distribution pumps should be controlled to maintain the minimum required differential pressure (DP) at the most hydraulically remote customer in the distribution system. The minimum required differential pressure at a customer is the differential pressure required to maintain valve authority, and therefore controllability across the circuit. For district cooling systems with indirect connections or hydraulically decoupled direct connections, this valve (or valves) is located at the customer ETS. For district cooling systems without decoupled connections at customers, this valve (or valves) is located at the most hydraulically remote cooling coil within the customer building.

The amount of pressure drop required to maintain valve authority across the critical control valve in the distribution system will vary according to the amount of flow through (and therefore pressure drop across) the critical circuit. The minimum pressure drop required at times of lower flow, such as part-load times, will be lower than the minimum pressure drop required at peak flow. Therefore, it is good practice to reset the minimum DP at the critical customer to reduce pumping energy. One common way that this is achieved is to reset the minimum DP based on outside air temperature, or simply developing a reset schedule based on seasonality. More complicated schemes have also been used, such as resetting the minimum DP based on valve position at the critical customer, but such schemes are only recommended with an advanced control system and experienced system integrators.

Resetting minimum differential pressure at the critical customer saves pumping energy.

6.3.4 Pump dispatch

Control of variable-speed distribution pumps is achieved by increasing or decreasing pump speed to maintain the minimum DP requirement at the critical customer in the system. District cooling plants generally have several distribution pumps, and some plants may operate by simply bringing on-line another pump once the running pump or pumps cannot maintain the minimum DP requirement at full speed. This is not an optimal way to dispatch a bank of variable-speed pumps and will typically result in significant energy waste, due to pumps operating at inefficient points on their pump curves. Instead, best practice is for distribution pumps to be dispatched to minimize power consumption based on system flow and head requirements.

One way this can be achieved is for the designer to develop a dispatch schedule for the pumps that seeks to optimize pump efficiency. The first step in developing a pump dispatch schedule is to estimate the overall distribution system curve (plot of flow versus head) for the plant to be dispatched. Using flow and head figures from the system curve and the pump curve (or curves) for the distribution pumps, the designer can determine an efficient dispatch for the pumps, from minimum chilled-water flow for the plant through peak flow. A dispatch schedule can then be prepared that dispatches pumps based on plant flow. The operating logic for the pump dispatch should incorporate time delays and hysteresis to reduce pump cycling and minimize pressure fluctuations in the system. When preparing the dispatch schedule the designer must keep in mind that, as discussed above, when more than one variable-speed pump is operated at the same time they should always be operated at the same speed.

Banks of variable-speed distribution pumps should be dispatched in a way that optimizes pump efficiency.

After the initial distribution pump dispatch schedule has been prepared, the dispatch schedule should be revisited if there are substantial changes to the system that impact the system curve in a significant way, such as a major piping extension or a new plant added to the distribution network.

Another alternative for optimizing dispatch of distribution pumps is to utilize the new generation of sophisticated chilled-water plant management software to dispatch pumps automatically. This type of software, integrated with the plant control system, uses actual equipment pump curves to determine the optimal number of pumps to run for all system conditions. A significant benefit to this approach is that there is no dispatch schedule that needs to be revisited as the system curve changes over time, as is often the case for district cooling systems.

6.3.5 System pressure control and thermal storage

A very good arrangement for system pressure control can be an “open” thermal storage tank (i.e., one that is effectively open to the atmosphere), acting as an accumulator for the system. However, this means of pressure control is only optimal if the tank can be located at a hydraulically appropriate location in the system and with the right height. If a thermal storage tank can be constructed with a height that is tall enough for the thermal storage tank to meet the static pressure requirements of the highest point in the system, then the strong pressure holding of the tank can protect the system from surge effects in the case of distribution pump trips at plants due to power failure. Figure 6-6 shows an example of a thermal storage tank that is also used for maintaining system pressure. However, if the thermal storage tank cannot be constructed tall enough to cover static pressure requirements of the system, then the strong pressure holding of the open tank could compound surge effects due to pump trips, and special equipment such as surge tanks and fast-closing valves may have to be designed into the system.

Under the right circumstances an open thermal storage tank can be an excellent means of system pressure control.

In addition to thermal storage tank height and elevation, the designer should give careful consideration to the optimal location for the thermal storage tank. If the thermal storage tank will be chilled-water storage (versus ice storage), it does not necessarily need to be located in close proximity to the chiller plant. If there is an opportunity to locate the chilled-water storage tank at a hydraulically remote location in the system, this can improve system hydraulics dramatically and could allow the designer to reduce distribution pipe sizing in the system, or reduce pumping power requirements, or a combination of the two. Another benefit that open storage tanks offer is the ability to accommodate large system fillings quickly, while maintaining system pressure requirements.

Figure 6-6. Thermal storage tank used for maintaining static pressure in system.

If an open thermal storage tank cannot be used for pressure control, then the best arrangement is usually to maintain system pressure requirements via makeup water pumps feeding water into closed expansion tanks in the system. The pumps add water to increase system pressure and a control valve is opened to relieve system pressure. It is generally good practice to have a small pair of pumps for pressure control and a larger pair for rapid supply of water to the system for service line extensions, refilling lines that have been drained for maintenance and other such operational requirements.

6.4 Distribution System Materials and Components

6.4.1 Pipe materials

Welded steel, high-density polyethylene (HDPE) and ductile iron are the most common piping materials used in district cooling distribution systems worldwide. Glass-reinforced plastic (GRP) is also relatively common in some markets. Strength, toughness, installation ease, thermal expansion/contraction, availability with pre-insulation, corrosion resistance and contractor familiarity are some of the main characteristics of pipe materials that must be considered in addition to cost.

Stress analysis may be a necessary step in the chilled-water piping system design, depending on pipe material, climate and piping configuration. System pressures, operating and ambient temperatures, flow velocity, dynamic effects (surge), soil corrosivity and reliability requirements should all be taken into consideration in material selection and piping system design. Special attention should be paid to joints and joining processes to ensure reliable chilled-water service and avoid future problems.

Welded-steel pipe

Welded steel is the most common piping material used in large chilled-water distribution systems. Steel is the strongest and most forgiving material under most conditions.

> **In choosing pipe material, consider system pressures, temperatures, flow velocity, surge, soil corrosivity and reliability requirements.**

Although welded steel is generally more expensive to install than some of the other chilled-water piping options, its strength, ruggedness, water tightness and higher velocity allowance can justify the higher initial investment and also significantly reduce maintenance costs over the life of the system. With adequate protection from corrosion, such as watertight jacketing of a pre-insulated piping system, it can last indefinitely when properly designed, installed and operated. Steel piping is readily available throughout the world and in a wide range of sizes, ratings and specifications.

Whenever insulation is required, the recommended solution for steel piping is a pre-insulated piping system. Pre-insulated piping is available from a number of vendors and, when properly installed, the use of pre-insulated piping from reputable vendors can result in a contiguous, watertight piping system. Another substantial benefit to pre-insulated piping systems is the fact that they are available with integrated leak-detection sensor wires. This type of leak-detection system, which can significantly enhance system reliability, is discussed in section 6.4.5. Piping and fittings are pre-insulated with rigid polyurethane foam insulation and have a high-density polyethylene (HDPE) or fiberglass jacketing.

Characteristics of the foam insulation are discussed in section 6.4.4. Either HDPE or fiberglass jackets are suitable for pre-insulated chilled-water piping, but HDPE is usually a better jacketing choice because it is more cost-effective in most cases and fiberglass jacketing may be prone to stress cracking due to soil loading if piping is not installed properly. As an added layer of protection, the steel carrier piping may be epoxy-coated prior to application of insulation and jacketing. This also protects the carrier pipe from developing surface rust in high-humidity regions, such as those in the Middle East.

Field jointing kits are provided with pre-insulated piping systems to insulate and jacket the pipe in the field at welded carrier-pipe joints. It is generally recommended that field joint kits be of the type that allows for an air test of the joint jacket integrity before filling with insulation, which provides assurance that all joints in the distribution are watertight. However, joint kits of the type that do not have an air test, but have a double heat-shrink sleeve are also suitable, under the following conditions:

- Joint kit shrink sleeves/wraps are made of cross-linked PE (PEX).
- Sensor wire leak-detection system is installed and put into operation.
- Piping is not installed below the water table.

> **Whenever insulation is required, the recommended solution for steel piping is a pre-insulated piping system.**

Field joints should resist axial movement once they are bonded to the pipe jacket. Otherwise, if the bonding force is not great enough, the joint sleeve could shift relative to the pipe during thermal expansion/contraction and create and opening for groundwater to penetrate. Resistance of field joints to axial movement may be reviewed for compliance with relevant industry standards, such as EN 489.

As discussed in section 6.4.2, in addition to the pre-insulated piping itself, pre-insulated isolation valves with weld-end pipe stubs are also available, which allows isolation valves to be direct buried with the same watertight jacketing as the piping system.

External corrosion can occur in steel piping systems from ground water and soil chemicals if a proper corrosion protection solution is not implemented. As discussed above, properly installed pre-insulated piping system can preclude the need for any additional corrosion protection. For piping systems that do not require insulation, piping can be coated for corrosion protection.

Primary coating options are fusion-bonded epoxy, fiberglass and polyurethane. Steel pipes can also be manufactured with an outer polyethylene jacket. It is highly recommended that, in addition to external coatings, cathodic protection be considered in areas where chlorides or sulfates are present in the soil, or where there are exposed metal surfaces. If a cathodic protection system is employed, it must be monitored and maintained; this ongoing operating cost should be considered in any economic evaluation of corrosion protection alternatives. Generally, cathodic protection is not required with pre-insulated piping, even below the water table, as long as all the external jacket joints are watertight. Internally, steel pipe is not significantly corroded by clean, treated chilled water.

Since steel pipes expand and contract with significant temperature gradients, stress analysis is generally recommended for chilled-water systems in areas that experience very high ambient temperatures, such as the Middle East, especially for systems that will be installed in the summer or have long, straight runs of piping. Most chilled-water systems with frequent directional changes will not develop stresses that exceed code limitations. However, if a system has long, straight runs of piping, then high stresses may be developed at directional changes, especially at branch take-offs near the ends of such runs. This should be analyzed to determine if anchors or special branch take-off configurations are required to maintain stresses below code requirements or if foam pads should be installed at directional changes to accommodate pipe movement and relieve stresses.

If a pre-insulated piping system is used, it is important to ensure that the carrier piping, insulation and jacking are all permanently bonded to each other. The bonding strength should be strong enough to ensure the system moves together as a single unit and may be reviewed for compliance with industry standards, such as EN 253. If the carrier piping is not bonded to the insulation and is able to move within the insulation or jacketing with thermal expansion/contraction, then insulation at elbows could be damaged. In the worst case, the jacketing could be torn, allowing ground water into the insulation and compromising the corrosion protection of the pre-insulated piping system.

All-welded, standard-weight steel piping is highly resistant to damage from hydraulic shocks and water hammer due to its very high maximum allowable pressure rating at chilled-water temperatures and its resistance to buckling. However, due to the rigidity of steel as a material, the magnitude of surge pressure created due to a given velocity change will be higher for steel piping than for plastic piping such as HDPE or, to a lesser extent, GRP.

HDPE pipe

High-density polyethylene (HDPE) is a plastic piping material that has been gaining popularity in district cooling distribution-piping systems worldwide. It is considerably tougher than other plastic piping systems. It's strong and handles well in the field. It's flexible and easy to install, especially when crossing water, micro-tunneling or managing numerous bends and offsets in crowded street conditions.

The best means of joining HDPE pipe segments for chilled-water pressure pipe applications is via the butt-fusion thermal welding process that, when properly executed, creates a joint as reliable and strong as the pipe itself for all pipe sizes. Electo-fusion couplings can also be used to join HDPE pipe segments, but should only be used for smaller sizes where the joint created will be as strong as the pipe itself. Joints also can be flanged when fusion is impractical or at the interface with a piping system of a different material. The distribution system designer should carefully consider the local conditions and should only select HDPE if trained and experienced personnel will be available who are familiar with its installation. For these contractors, HDPE is relatively flexible and easy to install and can prove more economical than welded steel piping in many situations, especially for smaller pipe sizes.

HDPE has been gaining popularity in district cooling distribution system applications worldwide.

HDPE is virtually immune to internal and external corrosion but may be susceptible to embrittlement and loss of stress resistance with strong oxidizing chemicals. It is electrically non-conductive and immune to stray current attack. Though HDPE is a poor heat conductor, the piping itself does not have very significant insulation value. For example, the insulating value of a nominal 600 mm (24”) dimension ratio (DR) 17 pipe with 50 mm (2”) of polyurethane insulation is 24 times that of the pipe by itself. Therefore, for a piping application where insulating is appropriate for other piping materials, such as steel, it is unlikely that selection of HDPE as the piping material will allow insulation to be avoided.

However, HDPE piping is available pre-insulated with polyurethane insulation and an outer jacketing as required for local thermal conditions. That said, the economics of HDPE pipe versus steel pipe are more attractive for HPDE when insulation is not required, since uninsulated HDPE does not require pipe coatings or cathodic protection, even when buried in aggressive soil conditions.

In smaller sizes, pre-insulated HDPE pipe is available in the Gulf region in coils of up to 200m of pipe. This can significantly reduce the number of field joints required, making installation more cost-effective. Piping of this type is ideal for small chilled-water service lines to customers.

HDPE pipe wall thickness is designated by a dimension ratio (DR) number, which is the ratio of the pipe's outside diameter to the pipe's wall thickness. The pressure rating of HDPE pipe is dictated by a combination of the DR, safety factor and material class (PE 80 or PE 100). Thicker walls relative to steel reduce the carrying capacity for a given nominal pipe size and velocity, but a lower friction coefficient reduces the pressure drop. With large pipe sizes, such as those over 400 mm to 600 mm (16-24"); higher design pressures; and systems requiring a large number of fittings, HDPE can become prohibitively expensive. In addition, large pipe requires large fusing equipment that can make jointing in trenches difficult or impractical. In these situations, it may be sensible to have a hybrid system with both HDPE piping and steel piping, joined with flanged steel-to-HDPE couplings.

Thermal expansion coefficients are significantly larger for HDPE than metal pipe and other types of plastic pipe, so expansion and contraction must be considered during installation. Smaller-diameter pipes can usually be buried in a "snaked" arrangement to provide adequate allowance for thermal movement. For larger piping where this is not practical, careful consideration must be given to contraction issues, which can be minimized with anchors, especially at building, chamber and manhole walls. Pipe installed on the surface or in unprotected trenches may require extensive anchorage to ensure the movement is controlled when exposed to the sun.

Due to the fact that HDPE material can undergo deformation slowly over a considerable period of time, flanged HDPE connections may require tightening during the initial months following installation to prevent leakage. For this reason, whenever practical, flanged HDPE joints should be installed so they are accessible by maintenance personnel. If flanged HDPE joints cannot be made accessible, then it is recommended that flanges with a higher pressure class than the pipe be installed.

HDPE is an excellent material for crossing a body of water, such as a river or channel, with chilled-water distribution piping. Corrosion isn't an issue, and the smooth surface of HDPE piping discourages algae, barnacle or limpet growth when in contact with fresh-water and seawater. Pipes are quite flexible and can be produced in very long lengths or fused together on land and floated out into the body of water for deployment. The pipe bed will often be dredged and a minor cover applied to the pipes. If the bottom is muddy or soft it can be enough just to sink the pipes to the bottom and they will soon be covered by mud. If larger boats or ships are crossing the pipe route it may be prudent to cover the pipes with macadam, gabions or something similar. The location of the pipe crossing should be distinctly displayed and identified on local marine charts.

Care is required when pressure testing HDPE, and manufacturer's instructions should be followed closely. HDPE pipe exhibits a relatively rapid radial deformation rate initially, followed by a slower and more constant deformation rate over time. As the pipe expands the pressure decreases and more water must be pumped into the pipeline to maintain pressure. Also, when pressure testing HDPE piping, the relationship between temperature and pressure rating must be considered and the test pressure adjusted accordingly. This can be especially important to consider in hot climates like the Gulf region and for sections of piping that are exposed to direct sunlight.

Ductile-iron pipe

Ductile-iron pipe and fittings are generally more expensive than steel piping, but the overall installation cost is often less than welded steel due to ease and speed of installation. The interior of ductile-iron piping is typically mortar-lined, which provides a smooth, corrosion-resistant interior to the pipe. This mortar lining, however, is subject to erosion at higher fluid velocities, so ductile-iron pipe is subject to velocity limitations. The traditional push-joint (bell-and-spigot) design for ductile-iron pipe is more susceptible to leakage due to construction practices, misalignment, thermal expansion/contraction and pressure surges. The push-joint installation is also an unrestrained jointing, which requires thrust blocks to restrain the piping at directional changes. Ductile-iron pipe is also available with a lugged mechanical pipe joint design that is more rugged and leak-tight than push jointing. The lugged ductile piping installation is also more expensive than push joints, but is a restrained system that does not require thrust blocks.

A common misconception is that ductile-iron pipe is inherently corrosion-resistant. Ductile-iron pipe can have a very long useful life when installed without corrosion protection in non-corrosive or very mildly corrosive environments. However, without proper corrosion protection, ductile-iron piping installed in corrosive soil is susceptible to pitting corrosion and microbiologically enhanced corrosion as well (e.g., sulfate reducing bacteria), which can result in an unacceptable useful life and/or reliability.

A common misconception is that ductile-iron pipe is inherently corrosion-resistant.

Research indicates that in corrosive soils ductile iron and carbon steel have similar corrosion rates. There is also controversy regarding whether the most common traditional means of corrosion protection for ductile-iron pipe, loose polyethylene encasement, is an effective means of corrosion protection. The best solution for corrosion protection of uninsulated ductile-iron piping, when required, is likely to be a combination of bonded piping coatings and cathodic protection – similar to recommended corrosion protection schemes for uninsulated steel piping.

If ductile iron is being considered as the pipe material for a chilled-water distribution system, it is important that a materials expert be consulted to determine the impact that local site conditions will have upon the ductile-iron pipe and what type of corrosion protection, if any, is required to meet expectations for system life and reliability. If corrosion protection of ductile-iron piping is required, then the first cost advantages of ductile iron over other pipe materials will be reduced.

In some markets, such as the U.S. market, there are often more contractors available that are familiar with ductile-iron pipe than other materials since it has been around for many years in the municipal water industry. Familiarity generally leads to reduced installation costs. However, in other markets, such as the Middle East, the use of ductile-iron piping is quite uncommon, especially for chilled-water applications.

GRP pipe

In certain markets, such as the Middle East market, glass-reinforced plastic (GRP) piping has been used with some frequency in chilled-water distribution systems. In other markets, such as the U.S. and European markets, GRP piping is not typically used for chilled-water service.

A significant benefit of GRP is that it is virtually immune to corrosion. It also can be more cost-effective than other piping alternatives, like steel piping, especially in the large sizes. The significant disadvantage to GRP pipe is that it is not as rugged or impact-resistant as piping of other materials and so is more vulnerable to accidental damage than other piping alternatives, which may be unacceptable to some system owners from a reliability perspective. Also, if the GRP piping is joined using laminated joints (layup joints), this type of jointing requires controlled conditions and skilled personnel.

GRP is virtually immune to corrosion and can be cost-effective, particularly in large sizes.

GRP pipe can be a very good alternative for installations where corrosive fluid, like seawater, is being carried. This is especially true for terrestrial installations of very large-diameter piping, where HDPE piping is either cost-prohibitive or unavailable in the required size and pressure rating.

Pipe material selection summary

The following summarizes the pipe material characteristics discussed above and provides initial guidelines regarding pipe material selection for chilled-water distribution systems. These bullet points are generalizations and cannot, for brevity's sake, address the many subtleties related to variations of materials and components. For example, more robust jointing technologies exist for ductile iron and GRP that can eliminate requirements for thrust blocks and boost reliability. However, these jointing options are more expensive and can defray the capital cost advantage that these piping materials can have over welded steel.

Steel pipe

May be good choice of material if

- a tough and leak-tight piping system with high reliability is valued,
- insulation is required,
- clean water can be maintained in the chilled-water distribution system and
- the ability to operate at high velocities is desired.

Consider different material if

- speed of installation is a high priority,
- insulation is not required and
- minimizing first cost is a top priority.

HDPE pipe

May be good choice of material if

- insulation is not required and trench conditions are aggressive,
- the system is a lower-pressure system (HDPE is expensive at higher pressure ratings),
- the system has routings with many small directional changes that can be accommodated by natural flexibility of pipe,
- pipe sizes are smaller (where HDPE is more cost-effective) and
- the routing is a water crossing (channel, river, etc.)

Consider different material if

- flexibility to increase system design pressure in the future is desired,
- piping network requires a large number of fittings and
- the region has low labor costs.

Ductile-iron pipe

May be good choice of material if

- soil conditions are not corrosive to ductile iron,
- insulation is not required and
- minimizing first cost is a top priority.

Consider different material if

- the ability to operate at high velocities is desired;
- long-term, leak-free, reliable service is a top priority;
- pipe routing is complicated, with many horizontal and vertical directional changes; and
- the pipe corridor available cannot accommdate thrust blocks (if unrestrained system).

GRP pipe

May be good choice of material if

- insulation is not required and trench conditions are aggressive and
- minimizing first cost is a top priority.

Consider different material if

- flexibility to increase system design pressure in the future is desired,
- toughness and impact resistance to maintain reliability of service are a top priority and
- the pipe corridor available cannot accommodate thrust blocks (if unrestrained system).

6.4.2 Isolation valves

When planning a new chilled-water distribution network, there is usually a struggle between individuals responsible for operations – who would like to install many isolation valves in the piping network – and the individuals responsible for the financial side, who would like to minimize the number of valves for cost considerations.

In evaluating the quantity of isolation valves to include in the system, these are the main questions to address:

- If a section of pipe must be drained for repair, how long can this be allowed to take?
- How many customers will be affected by shutdown of a pipe section?
- Which customers on the system have the most critical cooling requirements (e.g., hospitals, laboratories, housing for the elderly), and can the reliability of service to these buildings be improved by location of isolation valves?

As a baseline, a distribution system should have isolation valves at all major branch points. Service lines to customers should have isolation valves, with the optimal location for these valves typically being just inside the customer building wall. If distribution system development or expansion is to be phased, isolation valves at the connection point between the phases may be prudent.

Some systems have implemented automatic actuation of distribution system isolation valves. Automatic actuation can increase responsiveness and reliability, but the additional cost can be significant, especially for valves that are not near a power source or communication network. The added expense of automatic valve actuation may be justified if it prevents or minimizes interruption of service to customers who have critical cooling requirements and demand high reliability. There may be opportunities to pass the capital cost premium of automatic isolation to these customers. Also, if there are valves in the system that are regularly opened and closed to optimize system hydraulics, then these valves would be good candidates for automatic isolation.

As a baseline, a distribution system should have isolation valves at all major branch points.

There are two main methods of installation for buried chilled-water distribution system isolation valves: in-chamber and direct-buried.

Valve chambers

Historically, valve chambers have been required for maintenance to make it possible to reach isolation valves, system drains and air vents for operation and maintenance. Now, with modern fittings and components available in the market, valve chambers can be eliminated in many cases. However, chambers can be justified at locations with large cross-sections, branches, numerous isolation valves and drainage requirements. In general, the chilled-water distribution system designer should strive to minimize their use, as they are often the more expensive alternative and may require a lot of maintenance.

When valve chambers are located under the groundwater table it is very difficult to keep them free of water. With a cast chamber, the critical waterproofing points are the pipe entrance and the joints between the roof and the walls. Special water barriers have been developed to address different needs. Even with adequate waterproofing there may be humidity issues that can adversely affect electronics and components.

Direct-buried isolation valves

Use of direct-buried isolation valves in an underground chilled-water piping system allows for the elimination

Use of valve chambers should be minimized whenever possible.

of valve chambers, which take up a lot of space, are expensive, and can be troublesome to maintain. Some types of direct-buried isolation valves also eliminate flanges, which are potential leakage points in the system.

For a distribution system of pre-insulated, buried steel piping, the best solution for direct-buried valves for most pipe sizes is the use of pre-insulated, weld-end ball valves. Versus isolation valves in chambers, this solution has been used throughout Europe for many years and is considered the best and most cost-effective practice in this market for all but the largest sizes. Along with the benefit of eliminating the valve chamber, use of weld-end valves eliminates flanges (a potential source of leaks) and results in a contiguous welded piping system, where the valves are as strong as the pipe itself.

When pre-insulated valves are used in conjunction with a pre-insulated piping system from a reputable vendor, the result can be a distribution system with a contiguous, watertight jacketing that is immune to corrosion. Figure 6-7 shows a weld-end ball valve before pre-insulation. Standard weld-end ball valves are rated up to 25 bar (363 psi).

Pre-insulated weld-end ball valves can be direct buried and provide reliable service, allowing for the elimination of valve chambers.

Prior to pre-insulation, weld-end isolation valves can also be combined with vents, drains, bypasses, etc. to form a complete pre-insulated supply- and return-valve assembly. These types of assemblies reduce fieldwork and pipeline installation time and can allow for a more compact installation. Since these assemblies are constructed under controlled shop conditions, utility owners are ensured leak-free jointing.

One disadvantage to pre-insulated, weld-end ball valves for direct burial is that they get very large and expensive in the large pipe sizes. Weld-end, metal-seated butterfly valves can be also be pre-insulated and direct-buried and are a more economical alternative to ball valves for large pipes [e.g., more than 600 mm (24”)]. However, with metal-seated butterfly valves, shutoff may not be as tight, and there is a risk of debris collection at the seat impeding shutoff. Figure 6-8 shows a weld-end, metal-seated butterfly valve before pre-insulation.

Another disadvantage to direct-burying valves, of course, is that if there is a problem with the valve, the

Figure 6-7. Weld-end ball valve.

owner would have to excavate the street to repair or replace the valve. However, weld-end ball valves are designed to operate for more than 20 years without need for maintenance or replacement, as long as valves are exercised at least once a year. This has been substantiated by hot water systems in Europe that have had direct-buried ball valves in place for more than 35 years without significant problems.

Figure 6-8. Weld-end butterfly valve.

Direct-buried valves can be installed with mechanical actuation via a shaft extended to the surface directly above the valve stem/gearbox. This is the most typical and cost-effective solution for actuation of direct-buried valves. Figure 6-9 shows a partial installation of this type.

Another solution that is available is a hydraulic actuation system. This system can be used when it is a priority to get the access point to the valve actuator out of the street. With this system, hoses from hydraulic actuators on the valves can be run to a pit or cabinet located off of the street so that operators do not need to disrupt

Direct-buried weld-end ball valves have been used successfully in some European district heating systems for over 35 years.

traffic to actuate the valves, and valves are actuated using a hydraulic pump. The valves are direct-buried, and the hydraulic actuator typically resides in a small well or handhole.

Figure 6-9. Direct-buried valve with mechanical actuation.

Figure 6-10 depicts such an arrangement. Note that for deeper pipe installations (with direct-buried ball valves), the hydraulic actuator can be installed in a vertical orientation, jutting up into the bottom of the well. This hydraulic actuation system could be an excellent solution for valves requiring relatively frequent actuation and located in a busy thoroughfare. This type of actuation also is commonly used in Europe for large valves where mechanical actuation is slow or cumbersome. This system could be installed with a permanent hydraulic pump at the site to drive the hydraulic actuators on the valves, but more commonly and cost-effectively, the system is installed without a permanent hydraulic pump, and utility personnel use a portable hydraulic pump to actuate the valves instead.

If use of direct-buried isolation valves that are not pre-insulated is considered, then it is recommended to consult with a materials expert to ensure that the valve

Figure 6-10. Direct-buried valve with hydraulic actuator.

Hydraulic actuation of isolation valves allows valves to be operated off to the side of busy streets.

material will survive the environment for the particular application since there may be different requirements for materals, connections or corrosion protection depending on the aggressiveness of the soil or ground water.

Cost considerations

In the European market installation of direct-buried, pre-insulated, weld-end isolation valves is generally more cost effective than installation of valve chambers. In markets where manual labor costs are cheaper, such as the Middle East, valve chambers with flanged butterfly valves can be the least-cost option, depending on pipeline size and bury depth.

Cost considerations are obviously very site specific but, as a general rule, for installations of welded steel chilled-water pipelines in the Middle East at shallower bury depths (~1-2 m), direct-buried, pre-insulated weld-end valves tend to have a lower first cost for 150 mm (6") sizes and below, while valve chambers with flanged butterfly valves tend to be more cost-effective on a first-cost basis for sizes above 250 mm (10"). However, for pipelines with a deep bury depth (4+ m), where civil costs are substantially higher, the direct-buried, pre-insulated valves tend to be more cost-effective up to sizes of around 600 mm (24").

In the Middle East, valve chambers can have a lower first cost than direct-buried, pre-insulated valves, especially for shallower bury depths and larger pipe sizes.

Whenever possible, the life-cycle cost of the isolation valve installation should be considered, including maintenance and replacement costs for valves and chambers.

6.4.3 Branch connections/service line takeoffs

When the owner of the district cooling system has a high level of confidence that a potential customer will contract for district cooling service, it can be prudent to install service stubs for the potential customer when the main pipeline is installed. It also may be necessary to install service stubs to connect future customers if there is a moratorium on opening up the road that could result in customer opportunities being missed.

The issuance of such moratoriums is often the case for district cooling systems being installed in greenfield developments or in conjunction with rehabilitations of major thoroughfares. If a service stub is already in place, then service can be extended to the customer without disrupting service to other customers. If a service stub is not already in place, then it can be highly desirable to be able to extend service to the new customer without having to drain the main pipeline, which can be accomplished by hot tapping. The term “hot tapping” is used to describe any operation where a branch connection is made to a pipe main while the pipe remains in service or “hot” (a bit of a misnomer for chilled-water pipes).

Hot tapping can be performed on all of the pipe materials previously discussed and has the following benefits:

- No interruption of service to existing customers.
- Eliminates costly and time-consuming draining of the main pipe.
- Defers capital outlay until customer contract is secured.

Hot tapping is cost-effective enough in small sizes [up to 100 mm (4”) or so] that it can preclude the need to install service stubs in the main even in cases where a future customer connection is highly probable.

For steel piping there are two main types of hot taps:

- Branch pipe is welded directly to the main pipe.
- Mechanical clamp fitting is attached to the main pipe and the branch pipe welded to this fitting.

For a pre-insulated steel distribution piping system, whenever it is feasible to do so, the welded type of hot tap is recommended to maintain the integrity of an all-welded piping system. Welding onto an active chilled-water line for a hot tap can be performed as long as care is taken. ASME piping code requires preheat to 10 C (50 F) to ensure the weld’s integrity. This preheat can be achieved using thermal blankets, or other means of heating the pipe, while operating the pipe section with as low a chilled-water flow as possible. Most pre-insulated piping manufacturers supply insulation kits for branches that can be installed over the welded type of hot tap, such that a contiguous water-tight pipe jacket can be maintained at the hot tap branch.

Hot tapping is cost-effective enough in small sizes that it can preclude the need to install service stubs in the main.

For situations where it is desirable to have a valve immediately after the service line branch off the main pipe, a weld-end ball valve can be welded to the hot tap branch tee, which then remains in place once the hot tap is completed. In most cases, the best practice is to use a full port valve so that there is not a high pressure-loss constriction at the branch takeoff point. In some situations, however, it is difficult to accommodate the weld-end ball valve given space constraints, especially for larger sizes.

Hot tapping can be done with a special sluice plate fitting when a valve is not needed at the hot tap location.

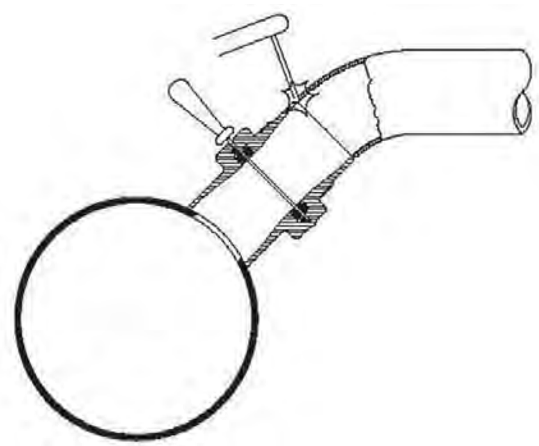


Figure 6-11. Sluice plate hot tap.

There is another very useful hot tap method, pictured in Figure 6-11, where a sluice plate is used in conjunction with a special fitting to hot tap the line without the need for a valve to be used to execute the hot tap. This method results in an all-welded connection and is especially helpful when there is not room to accommodate a weld-end ball valve due to pipe bury depth or branch configuration. This scheme can be used on pipelines with pressures up to 25 bar (363 psi).

6.4.4 Insulation

Evaluating insulation requirements

The following general steps should be taken when evaluating whether to include insulation on distribution piping:

1. Estimate the ground temperature at pipe bury depth throughout the year.

2. Prepare heat-gain calculations for each pipe material to determine if annual energy and peak capacity loss economically justify insulation.

3. Use heat-gain analysis to evaluate supply-water temperature rise against customer supply-temperature requirements throughout the year.

Estimated ground temperatures at various bury depths and times throughout the year can be calculated using mean annual ground temperature and surface temperature amplitude figures. Figure 6-12 is an example of results of these calculations.

When considering whether insulation is economically justified, the designer should consider both the energy cost of thermal losses throughout the year and the capital cost of lost capacity at peak times. If considering a steel distribution piping system, only the marginal life-cycle cost of pre-insulated piping over the cost of coated piping and/or cathode protection should be considered, since properly installed pre-insulated piping system from reputable vendors precludes the need for other means of corrosion protection.

Even if insulation is not economically justified on the basis of thermal losses, insulation may be required on certain pipes to limit supply-temperature rise to customers. When using the heat-gain analysis to evaluate the acceptability of supply temperature rise, the designer should consider

- contractual customer supply-temperature requirements,
- the supply temperature required to maintain customer comfort and
- impact of increased supply temperature to utility ton-hour sales.

The economic evaluation of whether to insulate piping should consider both the energy cost of thermal losses and the capital cost of lost capacity.

In addition, the designer should consider that the optimal operation of some of the technologies used in district cooling systems, such as deep water cooling and thermal storage, may be sensitive to degradation in supply temperatures.

It is useful to highlight the fact that temperature rise is generally less significant in larger piping due to smaller surface area relative to pipe volume and higher velocities. Conversely, temperature rise can be quite extreme in smaller-sized piping – particularly at part-load operation. Therefore, even if economics don't justify insulation, often times it is still necessary to insulate smaller supply lines. Figure 6-13 shows an example of calculated supply temperature rise along the chilled-water piping path from a cooling plant to a customer interconnection, at part-load service and illustrates the dramatic difference in temperature rise for smaller pipe versus larger pipes.

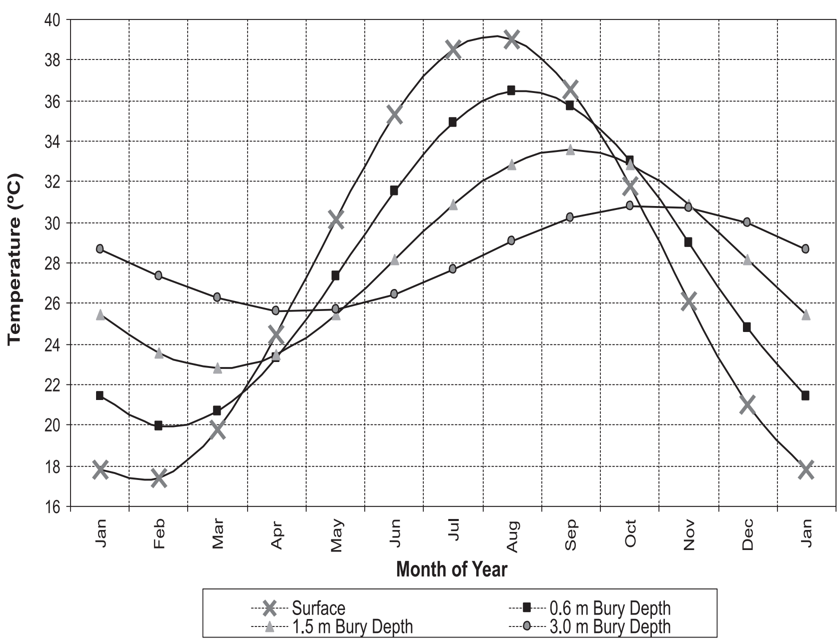


Figure 6-12. Example of estimated average ground temperatures at various depths.

Pre-insulated piping insulation considerations

The insulating material for all pre-insulated piping for buried chilled-water applications is polyurethane foam, but the properties of the polyurethane foam can vary significantly. The polyol and isocyanate components of the insulation are fairly standard among manufacturers and do not have a significant impact on the foam's insulating properties.

However, the choice of blowing agent (the gas that fills the foam's hollow cells) has a direct effect on insulating value and aging of the pipe. HCFC-141b has the best

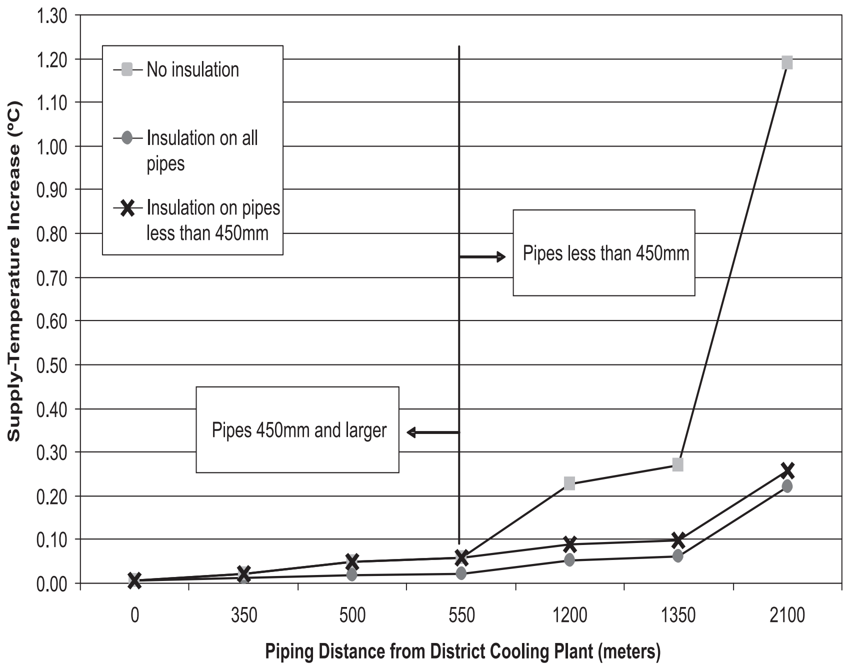


Figure 6-13. Distribution system supply-temperature rise for example system at part load.

> Supply temperature rise is higher in smaller pipes, so insulation of smaller pipe may be required to meet customer contractual commitments, regardless of economic payback.

thermal insulating value of the blowing agents still in use, but production of this HCFC has been phased out in most countries due to its ozone depleting potential; it is only in use as a blowing agent by certain manufacturers and in certain regions. Most of the blowing agents developed as replacements for HCFC-141b, such as HFC-245fa and cyclopentane, have very similar insulating properties and have thermal conductivity coefficients that are around 20% higher than HCFC-141b. These replacements are being used worldwide. The other blowing agent still in use by some manufacturers is CO_2, which has a thermal conductivity coefficient that is approximately 60% higher than HCFC-141b.

The other main parameter that has a significant effect on insulation performance is the foam cell structure. Polyurethane foams that have small, uniform cells and have a high closed cell content have better insulating performance, and are also more effective at preventing ingress of water vapor. Foams with small, uniform cells also have better mechanical properties (compressive and sheer strength) for a given foam density.

It is strongly recommended that pre-insulated piping be procured from vendors that have documented quality control procedures in place and test their piping and components in accordance with international standards. The type of manufacturing process used to produce the pre-insulated pipe can also impact the quality of the piping. Insulation that is spray-applied is preferable to injected, as it has more uniform foam density and mechanical properties and there is much less likelihood of voids in the insulation. Generally, these issues are less important for chilled-water piping than they are for hot water piping, but should still be taken into consideration. Also, for higher-quality foam applied at field joints, it is optimal to use a mobile foaming machine instead of hand-mixing and pouring techniques.

One parameter that should be considered in selection and procurement of pre-insulated piping is the “aging” of the insulation, i.e., the degradation in the insulating value over time. One significant influence on the aging of the insulation is the blowing agent and its diffusion rate through the urethane cell boundaries of the foam. The HCFC, HFC and cyclopentane blowing agents all have similar diffusion rates and, therefore, pipes of the same construction with these blowing agents have similar rates of aging. Carbon dioxide, however, more readily diffuses through urethane cell boundaries and therefore ages more quickly. Note that some pre-insulated pipes are available with a diffusion barrier between the piping insulation and the outer jacketing, which prevents the insulating gas in the polyurethane foam from diffusing through the pipe jacket over time. This barrier effectively eliminates “aging” of the pipe, and so the life-cycle cost implications of this benefit should be considered during pipe selection and procurement.

6.4.5 Leak-detection systems

Sensor-wire leak detection

Pre-insulated piping systems from several reputable vendors are available with a leak-detection system that includes alarm wires integrated into the pre-insulation of the piping. This system uses electric resistance to detect moisture in the insulation. A major benefit to this system is that it will detect if the outer jacket of the pre-insulated piping has been compromised, which can give the system owner time to schedule maintenance on the pipe well in advance of the carrier pipe corroding to the point of potential failure.

Pre-insulated piping systems are available with integrated sensor wires for leak detection.

In the early years of their development these types of leak-detection systems, initially used on district heating systems, gained a bad reputation for false positive alarms on chilled-water systems. These bugs were worked out and today the systems are used successfully in chilled-water systems, provided they are properly installed and maintained. This type of system should only be considered if the district cooling owner is committed to closely monitoring the distribution system contractor's work to ensure that the leak-detection system is implemented and documented properly. Accurate record keeping is critical to operation of the leak-detection system, and it is in the owner's interest to make sure the installation is properly documented before the piping is buried and inaccessible. Due to the specialized nature of these systems, whenever possible, contractors with experience installing them should be used.

Accurate record keeping by the contractor during installation is critical to a properly functioning sensor wire leak-detection system.

For district cooling systems installing new distribution systems utilizing pre-insulated steel piping, installing a sensor-wire leak-detection system is recommended, due to its accuracy and its capability to give early warning when the pipe jacket has been breached.

Acoustic leak detection

This method of leak detection is done with acoustic leak-detection sounding equipment. This acoustic equipment includes listening devices such listening rods, aquaphones (or sonoscopes) and geophones (or ground microphones). Acoustic equipment also includes leak noise correlators.

Listening rods or aquaphones are used to listen for leak sounds at any accessible contact points with the pipe, such as in valve chambers, or within customer ETS rooms. Acoustic leak instruments can listen to flow noise through sensors coupled to a pipe magnetically or mechanically. Leak noise is transmitted through the pipeline either as a pressure wave through the water or conducted through the wall of the pipe itself, and can be transmitted over long distances. Pipe leaks also induce vibration in the soil that is transmitted to the surface, which can then be identified using a ground microphone, but only within close proximity to the leak.

Typically a leak is initially identified using a listening rod or aquaphone at an accessible, but remote, contact point and then pinpointed using a ground microphone. Use of manual listening devices is straightforward, but the effectiveness of this method is highly dependent on the user's level of experience. Leak noise correlators are sophisticated portable devices with microprocessors that can automatically detect a leak and access its location. Acoustic data loggers can be used in conjunction with leak noise correlators to remotely record leak noise data as it occurs.

Metallic pipes transmit leak noise over long distances very effectively, so it may be possible to locate leaks with only leak noise correlation at a remote contact point, without the use of ground microphones. Non-metallic pipes do not transmit water-leak noise as well as metallic pipes and will generally require more ground microphone readings in between pipe contact points.

Software-based leak detection

If the physical leak-detection systems described above cannot be used, one other possible solution for leak detection is a software-based solution. Real-time hydraulic modeling software linked with a district cooling utility's SCADA system can compare actual SCADA data to model results in real time to determine the approximate location of a leak in the system. However, this technology is still being refined and at this time can only detect leaks of substantial magnitude, and the accuracy of the leak detection will be highly dependent on the accuracy of flow and pressure measurements from the utility's SCADA system.

7. Chilled-Water Plants

This chapter provides an overview of the key topics related to design of large district cooling plants operating in a Middle Eastern climate:

- chilled-water production technologies
- thermal energy storage (TES)
- plant configuration
- major chiller components
- refrigerants
- heat rejection

7.1 Chilled-Water Production Technologies

There are essentially two major categories of commercial chilling technologies: compression and absorption.

7.1.1 Compression chillers

The three basic types of compressors used in packaged water chillers are reciprocating, rotary and centrifugal.

Table 7-1 below summarizes the size ranges of the various packaged compression-chiller types at ARI conditions. For Middle East design conditions, packaged single-compressor chillers are available up to ~2500 tons, and packaged dual-compressor chillers are available up to ~5000 tons.

Chiller Type	Range
(tons)	
Reciprocating	50 - 230
Screw	70 - 400
Small centrifugal	200 - 1500
Large single-compressor centrifugal	1500 - 3000
Large dual-compressor centrifugal	2000 - 6000

Table 7-1. Summary of packaged chiller types and capacities (ARI conditions).

Reciprocating

A reciprocating compressor uses a piston driven from a crankshaft. Similar to a car engine, refrigerant is drawn into the cylinder during the downstroke and compressed in the upstroke.

Rotary

Although rotary compressors can use scrolls or rotating vanes: the more common type for packaged water chillers is the helical screw-type.

Centrifugal

Large commercially available compression chiller systems are based on centrifugal compressors. Usually the compressors are driven with electric motors, but it is also possible to drive chillers directly with reciprocating engines, combustion turbines, steam turbines or a combination of technologies, as discussed below.

Like centrifugal pumps, an impeller provides the force to compress the refrigerant vapor. Centrifugal chillers can use single-stage or multiple-stage compressors. With multiple-stage compressors the efficiency can be improved through the use of inter-stage economizers. Compressors can be either open or hermetic.

With open drives the compressor drive shaft extends through the casing to the motor. Since the motor is outside the refrigerant, all motor heat is emitted outside of the refrigerant cycle. A major element in selecting a chiller is efficiency; when evaluating chiller performances one must properly account for the motor heat rejected to the environment by open-drive chillers. In the event of a catastrophic motor failure, an open-drive machine can be repaired and placed back in service relatively easily. However, open-drive machines have seals that can leak and are subject to failure. On high-pressure machines refrigerant can leak out and on low-pressure machines air can leak in, causing more purge compressor run time and loss of efficiency.

With hermetic drives the motor is contained within the same housing as the compressor and the motor is in direct contact with the refrigerant; consequently, the heat emitted by the motor is absorbed by the refrigerant. Since hermetic machines do not have a seal like an open-drive machine, they are less likely to leak refrigerant. Motor failures (although rare) tend to be catastrophic, contaminate the refrigerant and cause the unit to be out of service a long time, with a great repair expense.

Centrifugal-chiller capacity control

The three common forms of capacity control for centrifugal compressors are inlet guide vanes, variable-speed drives and hot-gas bypass. With all of these forms, the manufacturer must be careful to prevent compressor surge. Surge is a condition that occurs when the compressor is required to produce high lift at low flow, thus it often sets the lower limit to how far a compressor can be turned down.

Inlet guide vanes

For capacity control, centrifugal chillers use inlet guide vanes (also called pre-rotation vanes). The adjustable vanes are located in the suction of the impeller and exert a rotation to the refrigerant in the direction the impeller is moving. These pre-rotation vanes change the impeller's flow characteristics and thus allow the chiller to operate at partial load.

Variable-speed drive (VSD)

Along with inlet guide vanes, capacity can be changed by varying the speed of the impeller. The impeller must provide the lift to move the refrigerant from the evaporator to the condenser. The lift required determines just how slow the impeller can be rotated. Lift is the pressure difference between evaporator and condenser, and since the refrigerant is operating at the saturation point, the lift is directly related to the corresponding temperature difference. When the impeller speed has been reduced as much as it can, further capacity reductions are made using the inlet guide vanes.

Variable-speed drives on chillers can dramatically improve part-load efficiency, but this is primarily because ECWTs are typically lower than design ECWT at part-load operation. VSDs on chillers are not especially helpful to efficiency for part-loaded units operating at design ECWT. VSDs on chillers also do not appreciably improve how much chillers can be unloaded.

Since VSD chillers allow for more efficient operation of chillers at lower ECWT than chillers without VSDs, it can be very advantageous to include VSDs on some chillers in a large central plant, even though individual chillers in large central plants are rarely operated at lightly loaded conditions. Low-voltage VSDs are very economical and can also be unit-mounted on smaller chillers. Medium-voltage and high-voltage VSDs are very expensive, cannot be unit mounted, and take up considerable space. Also, some system operators report that medium-voltage VSDs are not as reliable as low-voltage VSDs.

If space is available for VSDs, then the cost of the VSDs must be weighed against chiller energy savings on a life-cycle cost basis. It is important to stress that a life-cycle cost exercise is required to determine the quantity of VFDs that are appropriate for a given application, especially for medium- or high-voltage chiller applications. For the more cost-effective low-voltage chillers, there may be an economic payback to putting VSDs on most of the chillers in a district cooling plant, and it could even make sense to put VSDs on all chillers to be able to balance run times. For medium- and high-voltage chillers, however, it may only make economic sense to put VSDs on one or two chillers; additional VSDs must be carefully evaluated.

It is typically advantageous to put VSDs on some chillers in a district cooling plant, but life-cycle costs must be evaluated, especially for medium- or high-voltage chillers.

Hot-gas bypass

As the name implies, the hot gas from the compressor discharge is bypassed to the suction. This control method can be used to unload a machine to zero; however, this is usually not required for district cooling plants in the Middle East. As hot gas is bypassed, the kilowatt requirement remains the same while the load is decreased; thus, efficiency is poor when hot-gas bypass is used for capacity control.

Meeting low loads

It is not uncommon that a large plant is envisioned, but in the early years must supply only a fraction of the ultimate load. The question then is how to meet low loads, particularly in these early years of operation.

Some people believe that a pony chiller (small chiller) should be incorporated into the design for this purpose. However, in general, there usually are few systems that have a small enough load initially for this to be considered; in these cases, the loads exist only for a few seasons.

With current technology and controls, chillers can be operated down to loads in the range of 15% to 20% of full load. Also, variable geometry diffusers (VGD) can significantly reduce compressor noise at low-load operation. With optional hot-gas bypass, a chiller can be operated down to 10% load or even all the way down to 0% load depending on bypass valve size. However, as noted above, when hot-gas bypass is used, the chiller efficiency is poor. With hot-gas bypass the chiller will operate with lower efficiency, but with consistent loading. In contrast, with on/off cycling there is more wear and tear on the chiller. Given the importance of efficiency and the fact that with district cooling chillers need not be cycled frequently, specifying chillers with hot-gas bypass is usually not required or recommended.

For district cooling systems that have such small loads in the off-peak season that one chiller cannot operate at a low enough loading (generally systems in their early years that are under-subscribed), a common strategy is to operate the chillers at a higher load by "subcooling" the chilled-water distribution loop and then shutting the chiller down and using the thermal inertia in the distribution system to meet the load. Using this strategy a chiller would typically be operated for an hour and then shut it off for three hours. It is important that if this strategy is used, the district cooling provider should be conscious of customers' requirements regarding supply temperature and supply-temperature variations. It also would be advisable to inform the customer about this operating scheme – or potential operating scheme – preferably through contractual terms with the customer.

In systems with thermal storage, part-load operation is not a concern because the storage provides the thermal inertia.

7.1.2 Natural gas chillers

Technologies for directly producing cooling with natural gas include

- engine-driven chillers using reciprocating gas or diesel engines or gas turbines; and
- direct-fired natural gas absorption chillers (double-effect).

Technologies for indirectly producing cooling with natural gas include

- engine power generators feeding electric chillers;
- gas turbine power generators feeding electric chillers;
- boilers with steam turbine chillers; and
- boilers with steam absorption chillers, including single-effect and double-effect.

In addition, there are integrated technology systems that combine multiple types of drives and chiller technologies. These approaches can optimize cost-effectiveness, increase energy-efficiency, promote operational flexibility and enhance the ability to deal with uncertain future costs of natural gas and electricity. For example, engine-driven chillers could provide base-load chilled-water capacity, with peaking provided by electric centrifugal units. In addition, waste heat from engine-driven or turbine-driven chillers could be recovered to drive absorption chillers.

7.1.3 Absorption chillers

The absorption cycle uses heat to generate cooling using two media: a refrigerant and an absorbent. Water/lithium bromide is the most common refrigerant/absorbent media pair, but other pairs can be used. The absorption process uses an absorber, generator, pump and recuperative heat exchanger to replace the compressor in the vapor-compression cycle.

The absorption cycle, illustrated in schematic overview in Figure 7-1, can be summarized as follows:

- Generator – Gas, steam or hot water is used to boil a solution of refrigerant/absorbent (water/lithium bromide). Refrigerant vapor is released and the absorbent solution is concentrated.
- Condenser – The refrigerant vapor released in the generator is drawn into the condenser. Cooling water cools and condenses the refrigerant. Heat will be rejected from condenser to the cooling tower stream.
- Evaporator – Liquid refrigerant is dropped in pressure when it flows through an orifice into the evaporator. Due to the lower pressure in the evaporator, flashing takes place. The flashing cools the remaining liquid refrigerant down to the saturation temperature of the refrigerant at the pressure present within the evaporator (approximately 4 C or 39 F or for a water/lithium bromide chiller). Heat is transferred from the chilled water to the refrigerant, thereby cooling the chilled water and vaporizing the refrigerant.
- Absorber – Refrigerant vapor from the evaporator is drawn to the absorber section by the low pressure resulting from absorption of the refrigerant into the absorbent. Cooling water removes the heat released when the refrigerant vapor returns to the liquid state in the absorption process. The diluted solution is circulated back to the generator.
- Solution heat exchanger – The heat exchanger transfers heat from the relatively warm concentrated solution being returned from the generator to the absorber and the dilute solution being transferred back to the generator. Transferring heat between the solutions reduces the amount of heat that has to be added in the generator and reduces the amount of heat that has to be rejected from the absorber.

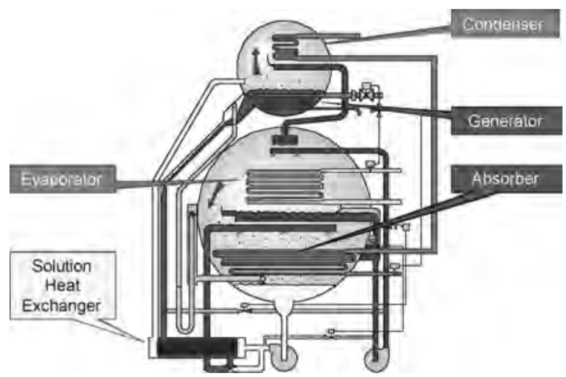


Figure 7-1. Single-effect absorption cycle (courtesy York/Johnson Controls).

Direct-fired absorption chillers work in the same manner as the traditional steam or hot water absorption chillers and are available in the double-effect configuration.

In double-effect absorption cycles, heat derived from refrigerant vapor boiled from solution in the first stage generator is used to boil out additional refrigerant in a second generator, thereby increasing the efficiency of the process. Double-effect absorption requires a higher temperature thermal source, but uses less thermal energy per ton-hour of cooling produced.

Three types of double-effect absorption chillers are commercially available and all offer comparable performance. These three types – series-flow cycle, parallel-flow cycle and reverse-flow cycle – are differentiated by the path that the absorbent/refrigeant solution flows to the primary and secondary generators.

Pros and cons

Absorption chilling technology it is not very common in the Middle East, because of the

- very substantial capacity and performance degradation due to the high design wet- bulb temperatures typical for the Middle East,

- higher heat rejection (cooling tower load) than centrifugal chillers,
- larger space requirements (about 40% larger footprint than electric chillers of the same capacity) and
- extremely high installed cost per ton of cooling capacity.

In addition, absorption chillers require an extremely low-cost heat source to be potentially economically viable.

Absorption cooling is not very common in the Middle East due to significant performance degradation at high condensing temperatures, high heat rejection requirements and lack of suitably inexpensive heat sources.

Some of the benefits of absorption machines over vapor-compression chillers:

- lower electrical requirements for chiller operation
- lower sound and vibration levels during operation
- ability to utilize recovered heat and convert it to cooling energy
- refrigerant solutions typically do not pose a threat to ozone depletion of the atmosphere

Efficiency

Single-effect absorption systems have a coefficient of performance (COP) of about 0.65, i.e., 0.65 Btu of cooling is produced with 1.0 Btu of driving thermal energy. Double-effect absorption chillers have a COP of about 1.0.

As noted above, absorption chillers require more condenser heat rejection than electric centrifugal chillers, which means that either additional power will be required for cooling tower fans and pumps – ~110% more for single-effect and ~60% more for double-effect – or cooling towers and condenser-water piping must be larger.

Capacity derate

For absorption chillers, nominal equipment capacity is based on ARI conditions of 6.7 C (44 F) for chilled-water supply temperature (CHWST) and 29.4 C (85 F) entering condenser-water temperature (ECWT). Typical chilled-water supply temperatures are 5.5 C to 6.7 C (42 F to 44 F). To operate at the 35 F (95 F) ECWT and 4.5 C (40 F) CHWST that is typical for district cooling systems in the Middle East, absorption chillers are substantially "derated", i.e., more nominal capacity must be installed to achieve the desired tons capacity at these conditions. The capacity derate for absorption units operating at typical Middle East conditions is much larger than it is for centrifugal chillers. For a double-effect absorption chiller selected for design conditions of 4.4 C (40 F) CHWST and 35 C (95 F) ECWT, the loss in capacity is about 40% compared with nominal ARI conditions of 6.7 C (44 F) CHWST and 29.4 C (85 F) ECWT. For example, to meet a cooling load of 1000 tons at these conditions, the absorption chiller must be sized for 1667 nominal tons, 67% higher than the design cooling load.

Since absorption units are not well-suited for low supply-temperature production and undergo a substantial derate to do so, it may make sense to develop a plant configuration where absorption chillers are installed in series with centrifugal chillers, which are better suited for producing low supply temperatures. In this configuration, chilled-water return water would be partially cooled by absorption units first and then cooled down to design supply temperature by centrifugal chillers.

If absorption units are intended to be used by themselves (i.e., not in series with centrifugal units) with a higher supply-water temperature, then the designer should take into consideration the impact of reduced chilled-water delta T on the system. With higher flows from a reduced delta T either pumping energy for the system will be higher, or larger sizes for plant piping/equipment, distribution piping and customer energy transfer stations (ETS) will be required.

It is also important to remember that there is an upper limit to the ECWT. As the condenser-water temperature increases, the pressure in the absorber/evaporator section increases, resulting in a higher boiling point and the potential inability to meet chilled-water design temperatures. In addition, the pressure in the condenser section is also increased, which elevates the pressure in the generator section of the chiller. As the condenser temperature and pressure increase, the pressure inside the generator can go above atmospheric and the system will shut down to avoid solution being forced out of the system. Typically, absorbers are not rated for use with condenser-water temperatures over 35 C (95 F) and are not considered safe to operate at these temperatures.

Capital costs

Absorption chiller plants require a smaller electric service than electric centrifugal plants. However, an exhaust stack is required for direct-fired absorption. In addition, the chillers are more costly, and cooling towers are more expensive because absorption chillers require more heat rejection than electric chillers, as discussed above.

Equipment manufacturers

Direct-fired absorption chillers are available in sizes ranging from about 100 tons through 1000 tons from a wide variety of manufacturers. One manufacturer makes units as large as 3300 tons (at ARI conditions).

Operating costs

Operating costs are primarily related to the cost of generating heat used to drive the absorption cycle. In addition, higher operating costs are incurred due to the increased electricity, water and water treatment chemical consumption associated with higher condenser cooling requirements. Maintenance costs depend on how the unit is loaded and operated but, generally, maintenance costs for absorption chillers are similar to those for electric centrifugal units.

7.1.4 Engine-driven chillers

Engine-driven chillers (EDCs) are vapor-compression chiller systems using a reciprocating engine instead of an electric motor to rotate the compressor shaft. They are typically provided as a packaged system with the compressor and engine closely matched and optimized to maximize performance. Engine-driven chillers use variable-speed engines to maintain high efficiency through all operating ranges. The EDC provides the highest fuel-to-cooling efficiency of any chiller (COP = 1.5 to 1.9). Efficiency can be further enhanced by adding engine heat recovery to drive absorption chillers or provide domestic hot water.

Important issues such as costs, space, exhaust stack venting, vibration, noise, maintenance and environmental emissions need to be addressed to provide a highly efficient and reliable chiller system. Engine-driven chillers are considerably more expensive than electric motor-driven chillers, and they also require more space.

The EDC is a combustion system and therefore requires fuel supply, combustion-air supply and exhaust removal. It also requires heat removal from the engine (which can be used to drive absorption chillers or provide heating), vibration control and sound attenuation around the engine and in the stack. If engine heat is recovered and used (for example to drive absorption chillers), the rest can be rejected to the chiller cooling tower by slightly increasing its size (about 10% compared with electric centrifugal chillers).

Engine-driven chillers are generally employed where there is insufficient electric infrastructure or when electric power costs are high compared to natural gas or oil costs. The major costs to operate an EDC are made up of fuel and maintenance. Maintenance is significantly more expensive and requires more specialized expertise than for an electric chiller.

Engine-driven chillers consume fuel directly on site to generate cooling and thereby create emissions at the site. Emissions associated with the engine are dependent on the type of fuel used and generally can be made to comply with local regulations. Exhaust after-treatment options are available to further reduce the stack emissions if required.

Key technical considerations for an engine-driven chiller:

- Ventilation air is required to provide combustion air as well as remove the heat radiated by the engine and exhaust stack. It is important to maintain proper ventilation air to the machine room to maintain combustion, efficient engine operation and to protect electronic components and equipment.

- Fuel supply piping should be designed to provide the required quantity of fuel at the required pressure. Natural gas engines' pressure requirements can vary from 0.5 to 50 psig depending on engine type and size.

- The exhaust system should be designed to remove the products of combustion as well as reduce engine exhaust noise by installing a muffler or silencer. Many exhaust heat-recovery systems are designed to also act as silencers.

- Sound attenuation is required for most plants and generally consists of baffles, insulation and enclosures.

- Vibration isolation is required to prevent engine vibration traveling through piping and floors and to prolong the life of the equipment. This is normally accomplished through the use of spring isolators mounted to a steel frame.

7.1.5 Combined heat and power (CHP)

There are also integrated technology systems that combine multiple types of drives and chiller technologies. These approaches have the potential to increase energy-efficiency, promote operational flexibility and enhance the ability to deal with uncertain future costs of natural gas and electric energy. Depending on price factors, they also can improve cost-effectiveness. Of particular note is the potential for cogeneration or combined heat and power (CHP).

For example, one configuration is a central electrical combined heat and power plant consisting of reciprocating engines with heat recovery driving single-stage absorption chillers. The electrical power generated would be used to supply large package electric motor-driven centrifugal chillers. The concept of this plant configuration is shown in Figure 7-2.

A similar concept using combustion turbine CHP is illustrated in Figure 7-3.

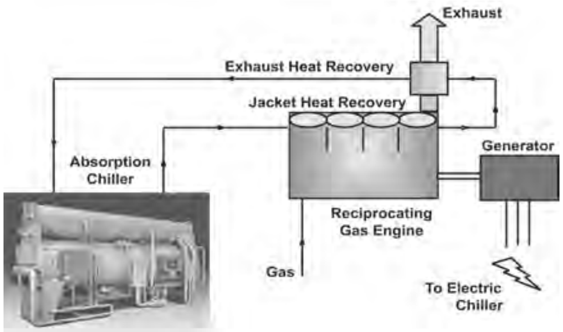


Figure 7-2. Engine-based CHP with electric and absorption chillers (courtesy York/Johnson Controls).

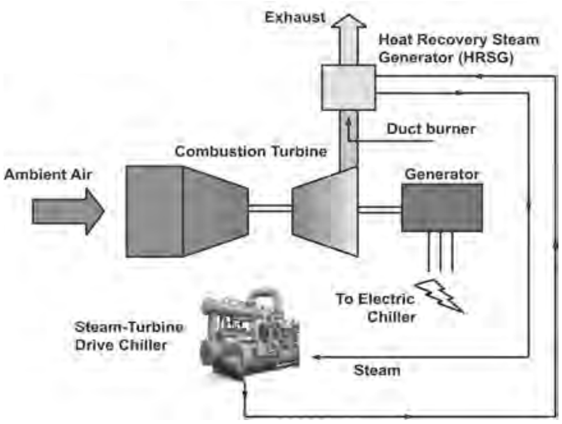


Figure 7-3. Turbine-based CHP with electric and steam turbine-drive chillers (courtesy York/Johnson Controls).

7.1.6 Choosing chiller type in the Middle East

With relatively low power prices currently prevailing in the Middle East, electric-driven centrifugal chillers are very cost-competitive. The high capital costs of absorption chillers, particularly with the capacity derate required at regional ambient design temperatures, make them an uneconomical choice. Natural gas engine-driven or turbine-driven chillers are potentially competitive depending on natural gas costs, electricity tariffs and chiller load factor.

Most promising are hybrid configurations in which the natural gas-fired chillers are installed for a portion (e.g., 50%) of the installed plant capacity, with the balance being electric-driven centrifugal chillers. In this case, the natural gas engine-driven chillers would be operated as primary baseload, which increases utilization and energy cost savings. The electric-driven chillers would be operated as load-following and peaking-capacity units. The selection of the optimum configuration is dependent on the assumptions for electrical utility price, natural gas fuel price, and the cost of capital.

The most promising gas-driven option is a hybrid configuration in which natural gas-fired chillers are installed for a portion (e.g., 50%) of the installed plant capacity, with the balance being electric-driven centrifugal chillers.

7.2 Thermal Energy Storage (TES)

Storage of chilled water, low-temperature fluid or ice is an integral part of many district cooling systems. Thermal energy storage (TES) allows cooling energy to be generated at night for use during the hottest part of the day. This process helps manage the electrical demand and reduce the need to build power plants and transmission and distribution lines. Thermal energy storage also allows a reduction in installed chiller plant capacity, often reducing net capital cost.

Figure 7-4 illustrates an example of cooling loads during a peak day in the Middle East, showing how TES can shift cooling loads from on-peak to off-peak periods. Cooling energy can be stored during the night for use during the peak-load period. In this example, there is a potential 20% reduction in peak power demand via utilization of load-leveling thermal storage, when compared to operating only chillers to serve the load, and a similar reduction in the required installed chiller plant capacity. This is a representative value for Middle East district cooling systems serving a mix of customer types (office, residential, hotel, retail, etc.).

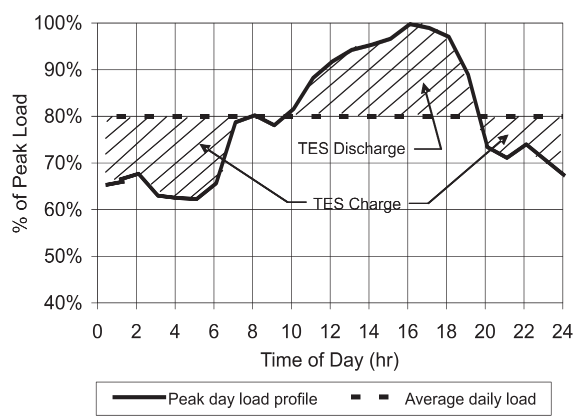


Figure 7-4. Load-leveling potential with thermal energy storage.

Load-leveling thermal energy storage can typically achieve a 20% reduction in peak chiller plant load for district cooling systems serving a mix of building types in the Middle East.

7.2.1 Thermal energy storage (TES) types

Chilled-water thermal energy storage

Chilled water is the most common and simplest form of TES, using concrete or steel tanks to store chilled water at 39 F to 42 F (3.9 C to 5.6 C) that is generated with conventional chillers. Under normal conditions a chilled-water storage tank is always filled with water. During discharge, cold water is pumped from the bottom of the tank, while an equal amount of warm return water is supplied to the top of the tank. Due to the different densities for water at different temperatures, a stable stratification of layers of water can be obtained.

Where space is cost-effectively available for chilled-water storage, the economies of scale for this technology can provide significant economic advantages over ice storage.

Ice thermal energy storage

Ice generation and storage is a well-developed technology, and allows storage in a more compact space – often a key issue in urban environments where land is expensive. Ice is blended with chilled water to produce a chilled-water supply temperature typically in the range of 1.1 C to 4.4 C (34 F to 40 F). The volume required for ice storage is 15% to 25% of the volume required by chilled-water storage for the same energy storage capacity. Ice storage provides an opportunity to reduce the distribution supply temperature, increase the delta T, and thereby reduce distribution and ETS system costs.

District cooling with ice storage can also reduce capital and operating costs in customer buildings. Colder chilled-water supply makes it possible to supply colder air to satisfy the cooling load. Colder air requires less air flow, smaller fans and reduced duct space in customer buildings. Colder air could also cause condensation on ductwork, so it must be done with caution, especially for existing buildings that were not initially designed for colder supply air. When implementing ice storage, the economic advantages must be weighed against the higher capital and operating costs for ice-making equipment relative to water chillers alone.

Low-temperature fluid thermal energy storage

Low-temperature fluid storage uses additives in chilled water to enable storage at temperatures in the -1.1 C to 2.2 C (30 F to 36 F) range. Like chilled-water storage, low-temperature fluid TES is sensible cooling and does not undergo a phase change. However, low-temperature fluid TES, with its lower supply temperature and larger Delta T, requires a somewhat smaller tank volume than does chilled-water TES. Like ice storage, low-temperature fluid storage provides colder supply, but requires chillers to operate at lower temperatures. Also, unless the low-temperature fluid is also used in the distribution system, heat exchangers and pumps are required to isolate the low-temperature fluid system from the chilled-water distribution system.

7.2.2 Thermal energy storage benefits

Peak-load management

One of the key benefits of TES is a reduction in electrical demand at peak-load conditions. This is especially important in dense urban areas where the electrical distribution grid is capacity-constrained. Thermal energy storage is charged at night when the electrical load in the grid is reduced. Off-peak charging is important to electricity producers who see variations in real-time generation costs, even when they sell power at a flat rate.

In markets where there are time-of-use rates, peak power "ratchets" or wholesale power purchasing by large district cooling providers, there can be large and direct economic benefits to district cooling providers implementing TES. Although this is typically not the case in the Middle East, the economics of power generation will ultimately result in some type of premium on power during peak-load periods. In addition, by reducing the peak electrical demand, less efficient electric power production facilities may remain offline, thereby reducing fuel use and emissions of air pollution and carbon dioxide. For those district cooling providers with on-site CHP or power generation, implementing TES provides a large economic benefit by reducing the amount of installed generation required.

Energy efficiency

There are numerous opportunities to improve on-site energy efficiency with TES. Chillers (and their auxiliaries) may be operated in a narrow output range to maximize their efficiency. Nighttime operation, depending on the climate, can rely upon cooler condenser-water temperatures to reduce chiller lift and minimize the kW/ton of chilled-water production.

With ice and low-temperature fluid storage, chilled-water supply temperatures can be reduced, enabling higher distribution system delta T and less pump energy consumption. When colder supply water is provided to buildings, it can enable colder air production to reduce air volumes and fan energy consumption as well.

Capital avoidance

TES should be considered early in the design process to minimize capital investment. Thermal energy storage used for load-leveling can reduce the necessary installed chiller plant capacity and also provide for redundancy requirements. A remote and unmanned "satellite" chilled-water storage facility may be installed in a growing system to serve more load without increasing the size of buried pipes or distribution pumps at the main chiller plant. Chilled-water storage can also double as fire protection and could even serve as a water reservoir for cooling tower makeup. Ice or low-temperature fluid can be used to lower the supply-water temperature and raise the delta T, enabling the use of smaller pipes and pumps.

Operational flexibility

Another significant TES benefit is increased operational flexibility. Thermal energy storage helps facilitate chiller maintenance, even during high-load conditions. Storage plus emergency pump power enables service even after an electrical power outage. A TES tank could also be used to provide fire protection water and emergency condenser water or chilled-water makeup.

7.2.3 Thermal energy storage challenges

Sizing

It is generally not practical or cost-effective to size a district cooling system for full TES. Full storage enables the system to deliver the peak load with the storage capacity alone. Partial energy storage uses the storage capacity to supplement chiller operation. Since there are typically very few hours at peak load during the year, even a partial storage system may be operated as full storage for much of the time.

The capacity of both chilled-water and low-temperature fluid systems is directly proportional to the delta T performance. As an example, Table 7-2 illustrates the capacity of a 10,221 cu m (2,700,000 gal) chilled-water TES tank in operation with a six-hour discharge rate and an 8.9 C (16 F) design delta T. Thermal energy storage capacity is reduced with low delta T performance and enhanced with high delta T.

Delta T in Operation		Energy Capacity, ton-hr	Load Capacity, tons (6 hours)	Capacity vs. Design
deg C	deg F			
5.6	10	18,750	3,125	63%
6.7	12	22,500	3,750	75%
7.8	14	26,250	4,375	88%
8.9	**16**	**30,000**	**5,000**	**100%**
10.0	18	33,750	5,625	113%
11.1	20	37,500	6,250	125%
12.2	22	41,250	6,875	138%
13.3	24	45,000	7,500	150%

Table 7-2. Impact of delta T in operation on chilled-water storage capacity.

Siting

All large-scale district cooling TES technologies require a tank. Volume requirements are higher for chilled-water and low-temperature fluid storage than for ice storage, but the footprint can be minimized with a tall tank if it is feasible relative to the site (See Figure 6-6 in Chapter 6 for an example of a tall chilled-water TES tank). A large delta T will also reduce the TES tank footprint for a given tank height. Tanks are made of concrete and steel and can be above ground, below ground or partially buried. Round tanks are generally most cost-effective for chilled-water and low-temperature fluid TES. Ice TES tanks can be round as well, but are often rectangular when space is at a premium, since this allows coil density to be maximized. Ice storage requires a physical location that is relatively near the ice production chillers. In contrast, chilled-water storage tanks may be located at a remote location in the distribution system, far away from chillers.

For the large-scale TES used in district cooling applications, TES tanks are almost always atmospheric tanks (versus pressurized). Therefore, it is very important to give careful consideration to tank height and the location of the tank hydraulically in the system. If an atmospheric TES tank must be located at a geographic low point in the system and/or cannot be constructed tall enough to meet the system's static head requirements (dependent on customer ETS or building elevation), then pressure-reducing valves may be required on the tank return. These pressure-reducing valves waste energy, and this arrangement can also make the system more vulnerable to water hammer. Ideally, the TES tank would be located at a geographic high point in the system or constructed tall enough that the system's static pressure requirements are met without the need for pressure-reducing valves. However, the designer should be cautious that TES tank height and location does not result in a significantly higher static pressure than the system requires, otherwise distribution pump head may be unacceptably limited, or a higher pressure class required for the distribution system.

The static pressure issues discussed in the previous paragraph are avoided if the TES tank is isolated from the chilled-water distribution system via heat exchangers, but this solution results in increased capital cost for exchangers and additional pumps, increased pumping energy and increased supply chilled-water temperature due to approach across the heat exchangers. However, this solution can be attractive for low-temperature fluid TES, since it precludes having to use low-temperature fluid throughout the distribution system. It is useful to note that the chemical investment required to enable low-temperature operation is partially offset by the supplemental benefit of chemical treatment provided by the low-temperature fluid.

Timing

To capture the greatest benefit from an investment in TES, it is imperative to assess the benefits and costs early in the design effort. Low-temperature supply water or a hydraulically strategic TES tank location can reduce distribution pipe size requirements. However, once the chilled-water piping is procured or the footprint is allotted for the plant, it may be too late to take advantage of all of the significant capital and/or operating cost savings that are possible with TES. Also, whenever possible, the cost-benefit of TES should be evaluated before customer contracts are signed and new customer buildings are designed to take full advantage of the benefits of low-temperature supply water to customer buildings.

Architects involved in the master planning of developments that will be served by district cooling systems should be consulted early in the planning process regarding the aesthetics and siting of chilled-water (or low-temperature fluid) storage tanks. This will likely minimize possible issues late in the planning efforts and result in the best chance to implement TES tanks with optimal dimensions and at optimal locations.

7.3 Plant Configuration

7.3.1 Chiller sizing and configuration

The type, number and arrangement of chillers for a district cooling plant is dependent upon the cooling load profile for the system and the magnitude of cooling load to be supplied from the plant. For the very large chilled-water plants typically required in the Middle East, the best practice is generally to use the largest packaged chillers available, configured in a series-counterflow, variable primary arrangement. The variable primary pumping configuration is discussed in Chapter 6.

7.3.2 Series-counterflow configuration

The series-counterflow configuration puts pairs of chiller in series with one another, with flow through the evaporator and condenser-water circuits running in opposite directions (counterflow). This configuration reduces the lift between the evaporator and condenser, thereby reducing the amount of work done by the chiller compressors, as illustrated in Figure 7-5. A series-counterflow arrangement enhances chiller performance and can improve overall chiller plant efficiency. However, it is important to note that the energy savings from increased chiller efficiency is typically partially offset by the increased pumping power required.

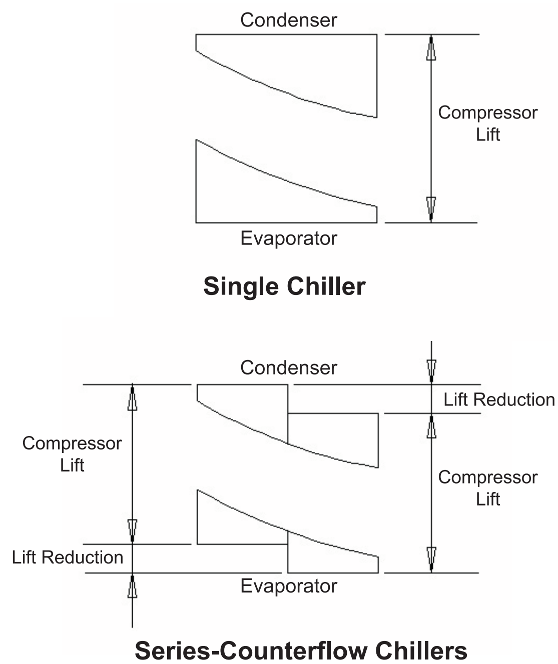


Figure 7-5. Lift in single and series-counterflow chillers.

In the example summarized in Table 7-3, the performance of a 20,000-ton plant was evaluated for parallel and series-counterflow. In the parallel chiller case both the evaporator and condenser are assumed to be two-pass. For the series-counterflow case the evaporators and condensers were both assumed to be single pass. Even with single passes, the pressure drop through the chiller heat exchangers is higher for the pairs of series-counterflow chillers than it is for the single chillers in the parallel case.

In both cases the chillers were dispatched against a typical Middle East load configuration. The results are

> For the very large chilled-water plants typically required in the Middle East, the best practice is generally to use the largest packaged chillers available, configured in a series-counterflow, variable primary arrangement.

> A series-counterflow arrangement enhances chiller performance and can improve overall chiller plant efficiency. However, the savings in the chiller can be partially offset by the increased pumping power required.

Parallel Chillers	Series-Counterflow Chillers
10 chillers at 2000 tons each	5 chillers at 4000 tons per pair
2-pass evaporator 13.3 C (56 F) entering 4.4 C (40 F) leaving Flow: 189 l/s (3000 gpm) Pressure drop: 3.45 m (11.6 ft)	1-pass evaporator 13.3 C (56 F) entering 4.4 C (40 F) leaving Flow: 379 l/s (6000 gpm) Pressure drop: 4.14 m (13.6 ft)
2-pass condenser 33.9 C (93 F) entering 39.2 C (102.6 F) leaving Flow: 379 l/w (6000 gpm) Pressure drop: 6.25 m (20.5 ft)	1-pass condenser 33.9 C (93 F) entering 39.2 C (102.5 F) leaving Flow: 757 l/w (12,000 gpm) Pressure drop: 7.32 m (24.0 ft)

Table 7.3. Inputs to series-counterflow example.

	Savings (cost) kWh/yr	15-yr present value at 10.5% at US$.03/kWh	at US$.04/kWh	at US$.05/kWh
Chiller	1,267,058	$281,052	$374,736	$468,420
Condenser	-476,721	($105,744)	($140,992)	($176,239)
Evaporator	-172,984	($38,370)	($51,160)	($63,951)
Net Savings	**617,354**	**US$136,938**	**US$182,584**	**US$228,230**

Table 7-4. Performance results for series-counterflow example.

summarized in Table 7-4 and show that the power consumed by the series-counterflow chillers (compressors) is substantially less than the parallel chillers, but the additional pumping power required due to higher pressure drop across the condenser-water and chilled-water circuits is a significant offset to the savings in chiller power.

It is common to consider a series-counterflow pair of chillers to be one production unit, rather than two separate production units. It is often sensible to omit bypasses around each of the chillers in the series-counterflow pair. Bypasses add cost and require more space, and failure modes where flow could not still be pumped through the chiller tubes – even if the chiller is not operating – are uncommon. Also, regular maintenance that does not allow flow though the chillers, such as tube cleanings and overhauls, can be scheduled for off-peak times when both chillers in the pair can be taken out of service. Thus, bypasses are generally not justified for chiller plants that have many series-counterflow chiller pairs in parallel, such as the large tonnage plants that are typical in the Middle East.

7.4 Major Chiller Components

7.4.1 Motors

This section addresses options for motor enclosures, costs for standard- and inverter-duty motors and motor efficiency.

Enclosure types

Open drip-proof (ODP) enclosures are the standard motor enclosure suitable for most industrial applications. Cooling air enters through louvered openings, passes over the rotor and stator, and exits through the openings in the sides of the frame. This open enclosure design should not be selected for outdoor installations, or wash-down areas. These motors will typically meet an 85 DBA sound-level requirement. All heat from the motor is rejected into the room or surrounding area.

Weather-protected type II (WP-II) is an open enclosure designed for use in adverse outdoor conditions. The air intake is in the top half of the motor to minimize entrance of ground level dirt or rain. The air passage includes abrupt 90-degree changes in direction plus an area of reduced velocity to allow solid particles or moisture to drop out before the ventilating air contacts active parts of the motor. Virtually all particulates except for super-fine dust are eliminated. WPII motors are typically 2-3 DBA quieter than ODP motors, and all heat from the motor is rejected into the room or surrounding area.

Totally enclosed water-to-air-cooled (TEWAC) enclosures isolate all critical motor components from the surroundings. They can be used indoors or outdoors and in clean or dirty environments. TEWAC enclosures include a water-cooled heat exchanger mounted in the top portion of the motor to cool the recirculated ventilating air. Motor heat is conducted away by circulating water and not by discharged air. TEWAC motors will require some heat exchanger maintenance to maintain optimum performance, and the heat exchanger must be constructed to resist ambient conditions that could cause corrosion. Heat from the motor is rejected into the cooling water rather than to the room.

Totally enclosed air-to-air-cooled (TEAAC) enclosures are similar to the TEWAC in that the enclosure also isolates critical motor components from the surroundings. The enclosure uses a top-mounted air-to-air heat exchanger where external air is drawn in by a shaft-mounted fan. The air is forced through the cooling tubes at high velocity to promote efficient cooling and cleaning of the tubes. A TEAAC motor tends to be noisier than an ODP, WPII or TEWAC motor. Typical sound levels are around 90 DBA. Unless the motor heat is ducted outdoors it is rejected into the room or surrounding area.

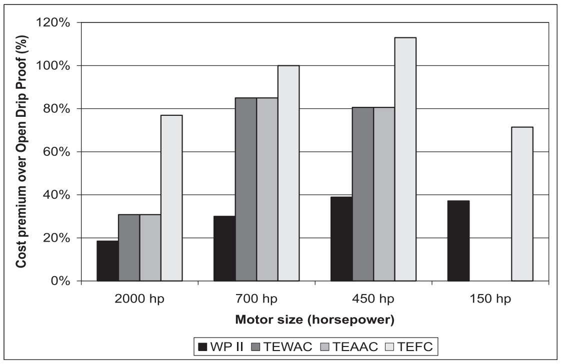


Figure 7-6. Enclosure premiums above open drip-proof.

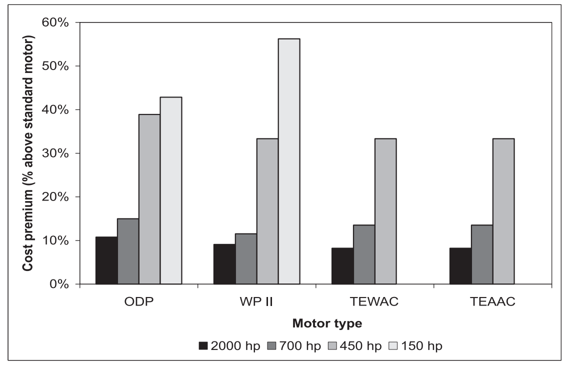


Figure 7-7. Inverter-duty motor cost premium.

Totally enclosed fan-cooled (TEFC) enclosures are often supplied on smaller motors for compressors where isolation of critical motor components from the surroundings is required. Due to the cooling fan the sound levels can be 90 DBA or above unless lower levels are specified. All heat from the motor is rejected into the room or surrounding area.

Standard motor enclosure costs

The premium for enclosures that provide better protection of the motor from the ambient conditions ranges rather dramatically as shown in Figure 7-6 (note that 150 hp motors are not available in TEWAC and TEAAC). It should also be noted that the values graphed represent only the cost premium associated with the enclosure. Thus the costs of piping and pumps must be added to the cost of the TEWAC enclosure.

When specifying motors for open-drive chillers in the Middle East, it generally makes sense to use totally enclosed water-to-air-cooled (TEWAC) enclosures because this type of enclosure allows rejection of motor heat to the cooling tower as opposed to the chiller room where it would have to be removed, requiring additional investment in chiller capacity and air-handling equipment.

> In the Middle East, it is generally best to use totally enclosed water-to-air-cooled (TEWAC) enclosures for open-drive chillers motors.

Inverter-duty premium

Motors rated for inverter duty should always be used with variable-frequency drives (VFDs). The premium for inverter-duty motors (compared to standard motors) is relatively independent of the enclosure type, as shown in Figure 7-7 (note again that 150 hp motors were not available in TEWAC and TEAAC). Since enclosures with heat exchangers cost more, the percentage increase is a bit lower. On a percentage basis, the inverter-duty premium ranges from about 10% at 2000 hp to more than 40% for 150 hp motors.

Motor efficiency

Motor efficiencies typically run from 95.5% to 96% for the larger motors to 94.5% to 95% for smaller motors. Efficiency tends to remain fairly flat to 50% load. Figure 7-8 graphs motor efficiency versus load for the four sample motor sizes.

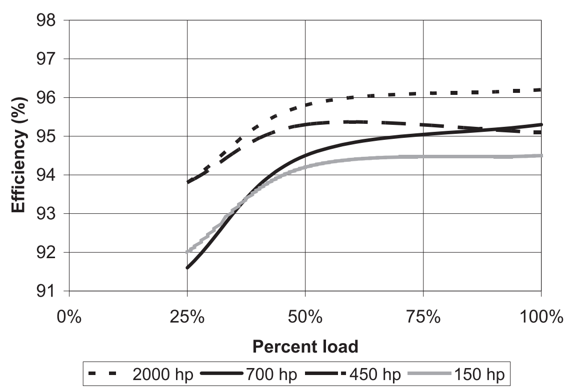


Figure 7-8. Motor efficiency.

Motor physical size

Within a given motor horsepower size, the open drip-proof enclosure is the smallest. Since the heat exchangers for totally enclosed water-to-air and totally enclosed air-to-air enclosures are mounted on top of the motor, those enclosures are taller. The TEFC enclosure is generally not as tall as TEWAC or TEAAC (except for the 2000 hp motor), but they tend to be longer because the enclosure must accommodate the motor cooling fan.

Voltage options for chiller motors

For large-tonnage chillers, it has been common to use medium-voltage (3.3 kV) motors, but it is becoming more common to use high-voltage motors (11 kV). The

Motor dimensions in feet (L x W x H)				
Enclosure Type	**2000 hp**	**700 hp**	**450 hp**	**150 hp**
ODP	62″x30″x29″	34″x30″x29″	44″x21″x22″	39″x21″x22″
WP II	64″x30″x54″	56″x30″x54″	48″x42″x48″	42″x32″x36″
TEWAC	64″x30″x54″	56″x30″x54″	48″x42″x48″	N/A
TEAAC	64″x30″x54″	56″x30″x54″	48″x42″x48″	N/A
TEFC	106″x42″x85″	62″x36″x32″	56″x30″x34″	44″x21″x22″
Motor weights in pounds				
ODP	9600	3700	2350	1350
WP II	10,600	4500	3200	1900
TEWAC	11,400	4500	3200	N/A
TEAAC	11,400	4500	3200	N/A
TEFC	15,000	10,200	4600	2400

Table 7-5. Example dimensions and weights of motor types.

advantages of high-voltage motors are that

- soft starters may not be required,
- step-down transformers may not be required,
- space for electrical equipment is reduced,
- transformation losses are reduced and
- plant efficiency is increased.

In circumstances where the electric utility only provides medium-voltage power, it is important to verify restrictions on ampere draw and to assess the need for soft starters.

7.4.2 Heat exchanger materials and design

Today's centrifugal chillers almost always come with enhanced copper tubes for the evaporators and condensers. However, depending on the water quality, it may be necessary to consider alternate materials and smooth-bore tubes. This is true for condensers and especially true when the coolant is seawater from direct cooling or seawater cooling towers. When seawater is used for condenser cooling, copper tubes are not appropriate and tube materials that better resist the corrosive nature of seawater must be selected. The traditional alternatives are titanium or copper-nickel alloys, and recently special super-ferritic stainless steel alloys are being proposed. All of these alternative tube materials are not as efficient in transferring heat as standard copper tubes, which results in less efficient chiller operation, to varying degrees.

> Alternative tube materials must be used for chillers in seawater applications, which increase chiller cost dramatically and also impose a substantial efficiency penalty.

Copper-nickel 90/10 has been used in the past for heat exchange applications using seawater, but is not corrosion-resistant enough to be suitable for reliable, long-term service as a chiller condenser-tube material when using seawater. Copper-nickel 70/30 offers seawater corrosion resistance that is far superior to 90/10-copper-nickel and may be a suitable chiller tube material, but it is critical to have a corrosion specialist conduct a corrosion analysis using seawater samples from the intake area. For some areas, such as polluted harbors with especially aggressive seawater, copper-nickel 70/30 may not be an acceptable selection. Titanium is the best tube material for seawater applications and is virtually immune to corrosion, but it is the also the most expensive alternative. Major chiller manufacturers are still evaluating the super-ferritic stainless steel alloys that are being proposed by tube manufacturers to assess their impact on chiller efficiency. These super-ferritic tube materials have a lower first cost than titanium, but also have a bigger impairment to chiller efficiency than titanium as well.

Table 7-6 shows the level of seawater corrosion resistance and the approximate performance degradation for various tube material alternatives (and indicates if efficiency reduction figures are for internally enhanced or internally smooth-bore tubes). The costs for these alternative tube materials have been highly volatile over the past several years based on supply and demand, and have seen enormous increases since the year 2000. Between 2005 and 2008 quotes for chillers outfitted with titanium condenser tubes and tubesheets compared to

Condenser Tube Material	Seawater Corrosion Resistance	Approximate Reduction in Chiller Efficiency
Copper (enhanced)	N/A	0% (Base)
CuNi 90/10 (enhanced)	Somewhat Resistant	-3%
CuNi 70/30 (enhanced)	Resistant	-6%
CuNi 70/30 (smooth)	Resistant	-8%
Super-ferritic SS (enhanced)	Highly Resistant	-10%
Titanium (enhanced)	Immune	-9%

Table 7-6. Corrosion-resistance and performance of condenser tube material options.

chillers with standard copper tubes and tubesheets have ranged from a cost premium of 50% to a cost premium of more than 100%. Due to this price volatility, specific costs have not been listed here, but the material types listed in Table 7-6 are listed in order of relative cost in 2008, with standard copper tubes the cheapest and titanium the most expensive.

In addition to using alternative materials for seawater applications, unless titanium tubes are used, it may also be necessary to use smooth-bore tubes instead of enhanced tubes. The primary concern is under-deposit corrosion associated with an aggressive fluid with fine solids, such as seawater. If enhanced tubes are used, it would be necessary to increase the frequency of tube cleanings, and the cleanings would have to be done very carefully. Under-deposit corrosion occurs when deposits collect at the base of the tube. The roots of internal tube enhancements act as collection points for deposits, increasing the potential for under-deposit corrosion, and also make the tubes difficult to clean thoroughly enough, even with automatic tube-cleaning systems.

Smooth tubes, on the other hand, resist collection of deposits, are much easier to clean and can be cleaned thoroughly with automatic tube-cleaning systems. However, the reduction in chiller efficiency by using smooth-bore tubes is quite significant, approximately 1.5% to 2%, but the reduction in chiller efficiency is offset somewhat by reduced pressure drop across the condenser. Given the risk of under-deposit corrosion, smooth-bore tubes are recommended for copper-nickel 70/30 tubes used in a seawater condenser cooling application.

7.5 Refrigerants

Until recently, chlorofluorocarbons (CFCs) were the most common refrigerants in the world. However, these compounds were discovered to cause the destruction of stratospheric ozone layer, which is the protective part of the Earth's atmosphere that filters out and reduces the sun's harmful ultraviolet radiation.

The world's developed nations responded in 1987 with an international agreement, called the Montreal Protocol, establishing CFC phaseout requirements. These requirements were modified by various amendments, leading to the complete phaseout of CFC production on January 1, 1996. The Copenhagen Amendment (1992) brought hydrochlorofluorocarbons (HCFCs) under the same scrutiny. Table 7-7 lists the phaseout schedule for refrigerants.

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

Table 7-7. Refrigerant phaseout schedule (Montreal Protocol, Copenhagen Amendment, with MOP-19 adjustment).

Ozone depletion potential (ODP) is a scale that compares the relative abilities of chemicals to deplete the ozone layer compared to CFC-11 as the base. In addition to ozone depletion potential, another significant environmental issue for refrigerants is global warming potential (GWP). This is the "greenhouse" effect in which these gases absorb infrared energy leading to the warming of the earth. GWP is the relative ability of the gas to contribute to global warming compared to CO_2 as the reference gas.

An HCFC known as R-22 has been the refrigerant of

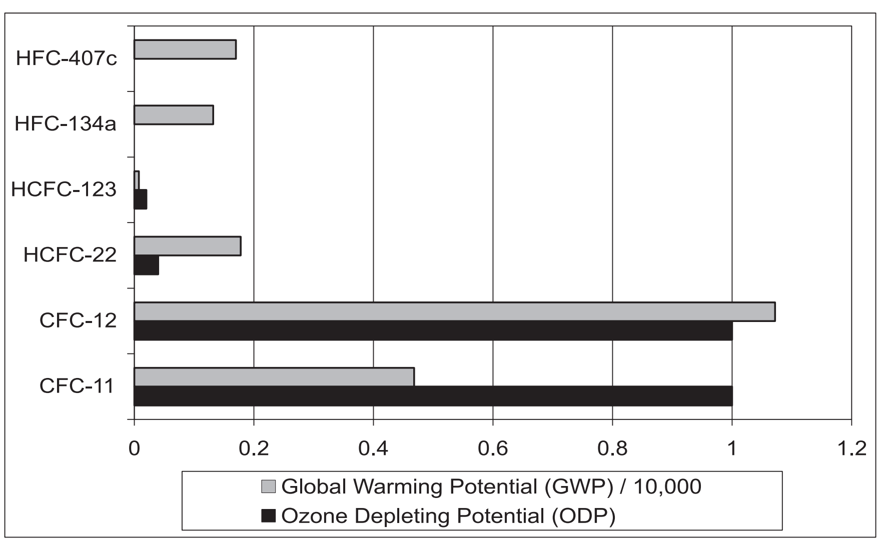


Figure 7-9. Refrigerant environmental impact comparison

choice for small cooling systems (residential and light commercial) for more than 40 years. Currently many major HVAC manufacturers use R-22 in the majority of the systems they build. However, use of this refrigerant in new equipment will be banned in 2010. R-123 is also an HCFC, but it faces a longer-term schedule for phaseout.

Even though HCFCs are considerably safer for the environment (at least 95 percent less damaging to the ozone layer than CFCs), they still have an adverse effect on the environment.

HFCs (halofluorocarbons) currently have no phaseout requirements under the Montreal Protocol. HFCs are targeted for reduction under the Kyoto Protocol because of their GWP, but there are currently no specific phaseout dates for HFCs under the Kyoto Protocol. The Kyoto Protocol, a treaty that came into force on February 16, 2005, was ratified by most industrialized countries with the notable exceptions of the United States and Australia. Gulf countries such as Qatar and the UAE have ratified the Kyoto Protocol, but Bahrain is currently not a participant. The Kyoto Protocol specifies reduction targets for emissions based on a GWP-weighted basket of six specified gases or groups, which include HFCs. HFCs are a small fraction of the total emissions, but are the component that is increasing the fastest.

Figure 7-9 illustrates the comparative environmental impact of various old refrigerants (CFC-11 and CFC-12) and the recent replacement refrigerants (HCFC-123 and HFC-134a) that are now being used. The data indicates that HFC-134a and HCFC-123 are more environmentally friendly refrigerants than R-22.

While there is scientific justification for the current regulatory reprieve for HCFC-123 and HFC-134a (under the Kyoto Protocol), the political and economic aspects are hard to predict. The 19th Meeting of the Parties to the Montreal Protocol (MOP-19) on substances that deplete the ozone layer concluded with a historic agreement to accelerate the phaseout date of manufacturing equipment using hydrochlorofluorocarbons (HCFCs) by 10 years.

Condenser Flow – 3 gpm/ton	Condenser Flow – 2.3 gpm/ton
5 chillers at 4000 tons per pair	5 chillers at 4000 tons per pair
1-pass evaporator	1-pass evaporator
13.3 C (56 F) entering	13.3 C (56 F) entering
4.4 C (40 F) leaving	4.4 C (40 F) leaving
Flow: 379 l/s (6000 gpm)	Flow: 379 l/s (6000 gpm)
Pressure drop: 4.14 m (13.6 ft)	Pressure drop: 4.14 m (13.6 ft)
1-pass condenser	1-pass condenser
33.9 C (93 F) entering	33.9 C (93 F) entering
39.2 C (102.6 F) leaving	40.8 C (105.4 F) leaving
Flow: 757 l/s (12,000 gpm)	Flow: 582 l/s (9231 gpm)
Pressure drop: 7.32 m (24.0 ft)	Pressure drop: 5.09 m (16.7 ft)

Table 7-8. Inputs to low condenser flow example.

As part of the MOP-19 agreement, developed countries (Article 2) will phase out all new equipment using HCFCs (including HCFC-123) by 2020 instead of 2030, the previous deadline. The new agreement also calls for reduction steps of 75% in 2010, 90% in 2015 and allows 0.5% for servicing chillers during the period 2020-2030.

As of 2008, no specific phaseout dates have been established under the Kyoto Protocol for HFC-134a, and it is likely that production will be allowed for another 20 to 30 years. For all HFCs and HCFCs it is likely that the refrigerant quantities needed to service both HFC and HCFC chillers will be available for at least several decades beyond existing or proposed phaseout dates.

7.6 Heat Rejection

This section includes condenser and cooling tower issues as they specifically relate to large district cooling plants in the Middle East:

- overview of condenser cooling options
- optimum entering condenser-water temperature
- cooling tower considerations
- condenser-water piping arrangement

7.6.1 Overview of condenser cooling options

Heat generated from the chilled-water production process must be rejected from the chiller condenser to the outside environment – to the atmosphere or a river, lake or sea. The proper selection and control of the heat-rejection equipment is a significant component of district cooling plant operating costs. Heat-rejection systems in the Middle East are typically based on one of the following types:

- cooling towers with potable water for makeup
- cooling towers with seawater for makeup

	Savings (cost) kWh/yr	15-yr present value at 10.5%		
		at US$.03/kWh	at US$.04/kWh	at US$.05/kWh
Chiller	(925,124)	($205,206)	($273,608)	($342,010)
Condenser	1,535,855	$340,675	$454,234	$567,792
Net Savings	**610,732**	**US$135,469**	**US$180,626**	**US$225,782**

Table 7-9. Performance results for low condenser flow example (3 gpm/ton vs. 2.3 gpm/ton).

- cooling towers with recycled wastewater for makeup
- chiller condensers for direct use of fresh water or seawater through condensers for heat rejection

A larger condenser delta T increases chiller compressor power cost, but this cost is offset by cost savings from lower pumping power or smaller pipes and equipment in the condenser-water circuit.

7.6.2 Optimum entering condenser-water temperature

When determining the optimum condenser flow rate, the impact on the chiller must be weighed against the impact on the condenser system and cooling tower. Common practice in the past was to size the condenser system based on 3 gpm/ton condenser-water flow, equivalent to approximately 5.3 C (9.5 F) rise across the condenser. Current trends are to use a larger condenser-water delta T. A larger condenser-water delta T increases the power required by the chiller, but results in lower flow and therefore lower pumping power or smaller pipes, and reduced tower sizes or fan power, which offsets the increased chiller power cost.

To put this into perspective, an evaluation was prepared of the combined effect on chillers, pumps and towers for a 20,000-ton plant operating under a Middle Eastern climate and load profile, with 5 series-counterflow pairs of chillers in parallel. The analysis is based on the inputs listed in Table 7-8. Although the power required by the tower fans will be somewhat different, this example assumes the tower power remains the same between the two cases. The results are summarized in Table 7-9 and show that the extra power required by the chiller compressor is more than offset by the savings in pumping power due to lower pressure drop through the condenser water circuit. Designers should evaluate the optimal condenser-water flow for a district cooling plant in lieu of using a rule of thumb such as 3 gpm/ton.

7.6.3 Cooling tower considerations

The large cooling towers that are typically used for district cooling plants are designed in two different configurations, counterflow and crossflow, which refer to the direction of air flow relative to water flow in the cooling tower. For crossflow cooling towers, air flow is perpendicular to water flow, while for counterflow cooling towers air flow is parallel to water flow, but in the opposite direction. These differences in water- and air-flow configuration give crossflow and counterflow cooling towers different efficiencies and characteristics, which must be evaluated to determine which cooling tower type is appropriate for a given application. For both of these cooling tower types, condenser water is cooled primarily by the latent heat of vaporization, with drier air entering the cooling tower and moister air leaving the cooling tower.

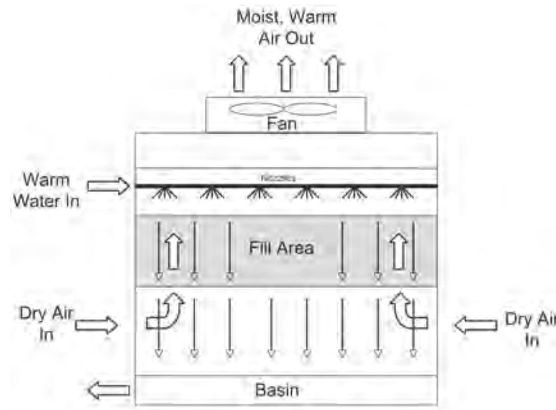


Figure 7-10. Counterflow cooling tower.

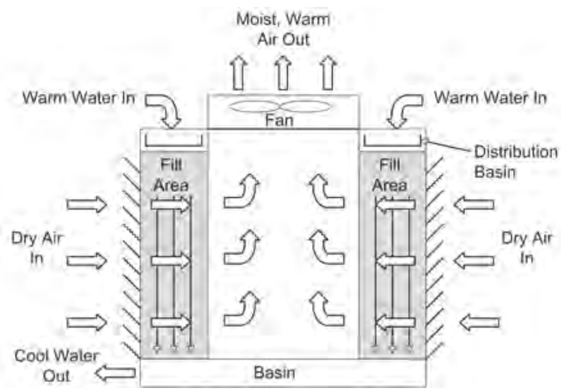


Figure 7-11. Crossflow cooling tower.

Counterflow towers use high-pressure spray nozzles to distribute warm condenser water uniformly over the tower fill. Inlet air flow enters the tower below the fill and then passes vertically upward through the fill, against the downward flow of water through the fill. A result of this counterflow design is that the driest air comes into contact with the coolest condenser water, which maximizes the performance of the tower. Figure 7-10 is a diagram of a counterflow cooling tower.

Crossflow towers have warm condenser-water basins over the top of the cooling tower fill, and orifices in these basins are utilized to distribute water uniformly across the tower fill. Inlet air enters the tower horizontally, and passes through the fill perpendicular to the condenser water flow though the fill. Figure 7-11 is a diagram of a crossflow cooling tower.

Counterflow towers generally have a smaller footprint than crossflow towers, but require additional height and operating cost. Condenser-water pumping costs will be somewhat lower with crossflow towers versus counterflow towers, since water distribution though the fill is achieved via gravity for crossflow towers versus nozzles with head loss for counterflow towers. Fan power costs will also be lower for crossflow tower, due to a larger inlet louver area and less resistance to falling water than counterflow towers. Crossflow towers also offer easier access to the water distribution system for maintenance and a larger range of acceptable condenser-water flow while maintaining efficient operation.

Both counterflow and crossflow cooling towers are cost-effective means of heat rejection for a district cooling plant and can serve the end user well. In general, the decision to consider one over the other is based upon site-specific criteria and limitations and is typically driven by space constraints. Counterflow towers are generally the best selection when space requirements are a primary concern, which can be the case when towers will be located on the roof of the cooling plant and are driving overall plant building footprint. Crossflow towers are a good choice if space is not limited or at a premium, or if it is a high priority to minimize operating costs.

Cooling tower sizing

The space needed by roof-mounted cooling towers tends to drive how large the building footprint must be. When space is at a premium, the engineer is often faced with tradeoffs. However, it is a mistake to undersize the cooling towers. Undersized tower capacity could limit chilled-water production at a time when it is most needed. It doesn't make sense to skimp on towers if they will constrain chiller output of the chillers, which are more costly than towers. On the other hand, oversizing the tower doesn't make sense either. . The key is to size cooling towers based on a realistic wet-bulb temperature and an appropriate approach that balances cooling tower size against chiller performance. A practical general guideline for sizing cooling towers is to use a 3.9 C (7 F) approach to the ASHRAE 1% wet bulb.

When determining an appropriate operating control scenario, there are tradeoffs to consider. Chillers are more efficient with lower entering condenser-water temperatures. However, the cooling tower requires more fan power to produce colder temperatures. In Figure 7-12, the power consumption from two chiller types (hermetic-type and open-drive type) is plotted along with the power consumption of a cooling tower. This relationship must be analyzed for the specific situation to determine what the optimum control strategy should be.

To further illustrate this point, the data from Figure 7-12 is recast in Figure 7-13 showing the rate of change in power requirement versus ECWT. This example is based on 15.6 C (60 F) wet-bulb temperature (common during off-peak periods in the Middle East). At 15.6 C (60 F) wet bulb, cooling towers selected for a 3.9 C (7 F) approach at design conditions generally cannot achieve ECWTs colder than around 24 C (75 F) at full fan-speed operation. The key point from this figure is that for Chiller A, around 24 C (75 F) ECWT is also the point where the additional power consumed by the tower starts to exceed the power saved in the chillers. Therefore, for Chiller A, the wet-bulb temperature would have to be lower than 15.6 C (60 F) before there is any net energy savings by reducing fan speed, and therefore power consumption. Note that for Chiller B, at 15.6 C (60 F) wet bulb, the tower and chiller lines never cross; it is likely that for this chiller the tower fans could run at full speed at all times and the overall plant power consumption would be minimized. Although this example does not consider the impact of providing lower than design condenser-water flow to the cooling tower, for the counterflow towers typically installed in the Middle East, flow cannot be

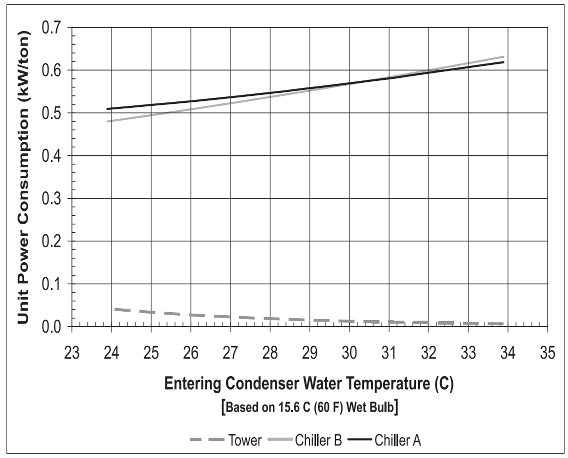


Figure 7-12. Chiller and tower kW/ton versus ECWT.

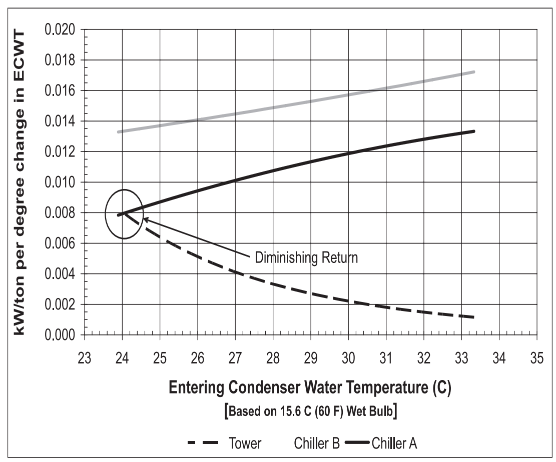


Figure 7-13. Rate of power change for chillers and cooling towers.

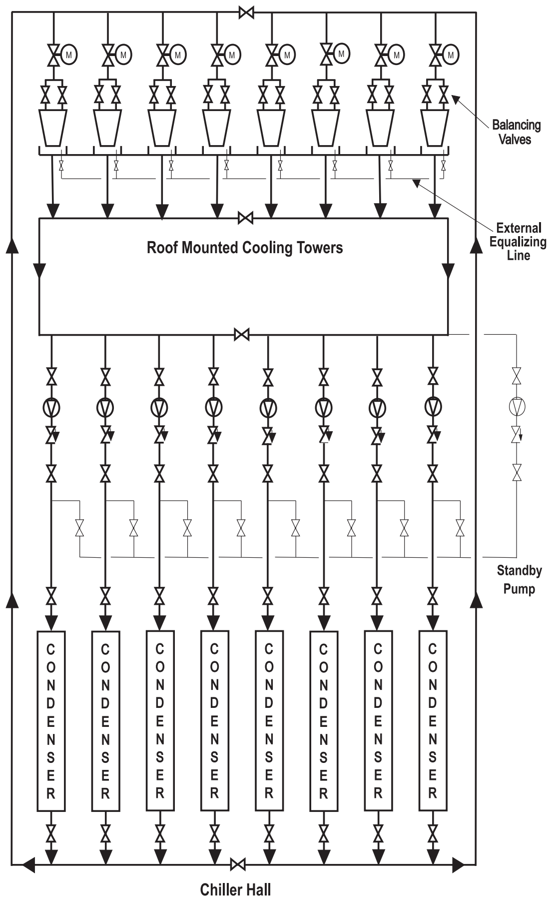


Figure 7-14. Pumps dedicated to specific condensers.

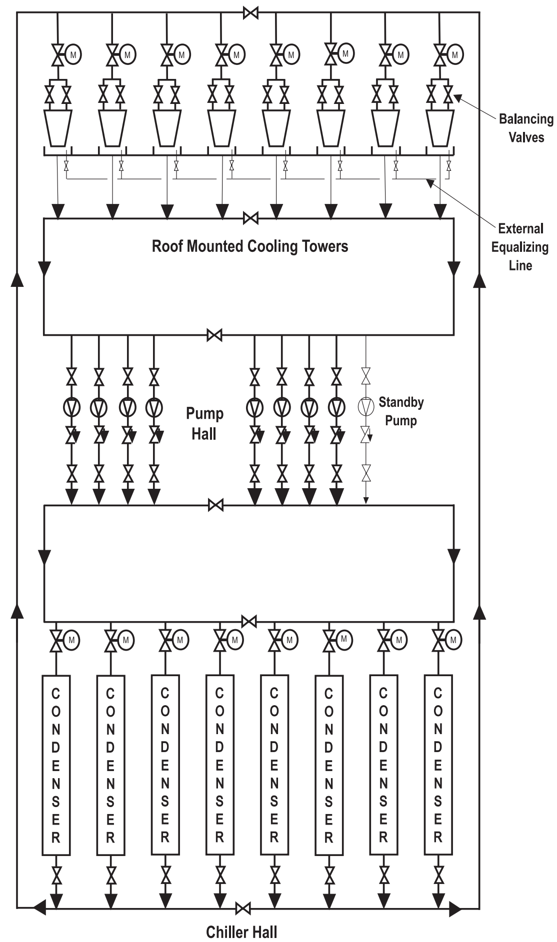


Figure 7-15. Condenser pumps with header.

reduced appreciably below design flow before tower performance is seriously impaired.

Variable-speed drives can be useful on towers, but under Middle Eastern conditions there are very few hours where partial speed is needed. For those periods it would be useful to have VSDs on some cooling tower cells, but not all.

Cooling tower basins

For multi-cell towers, common in large district cooling plants, the cells should be connected together with a header on both the supply and return sides with isolation valves to separate the sections. This design approach enables future expansion of cooling tower capacity when buildout is phased in to match the system load. To minimize cost, butterfly valves are typically used on the cell supply lines. These valves can be used for balancing, although "high-performance" butterfly valves would serve this function better than "standard" butterfly valves. The supply valves should be fitted with electric motor actuators so they can be opened and closed automatically when the cell is operated.

For multiple cooling towers, or cooling tower cells, that are fed by a common condenser-water header, the flow rate of cool water drawn from the basin of each tower/cell will never be exactly the same as the flow rate of the warm water fed into the tower inlet. To prevent basins from overflowing or running dry, the flow into each tower should be balanced as well as possible and an equalizer line should be installed to interconnect the towers/cells.

The function of the equalizer line is to allow flow by gravity from one basin to the next to maintain equal basin water level. Since the head created by differences in water levels between basins is the only motive force that creates flow through the equalizer line, it is critical that the equalizer line is sized large enough that pressure drop in the line is minimal. The equalizer line should be sized to handle 15% of the design flow rate for each cell, with the pressure loss through the equalizer piping at this flow rate not exceeding the water level difference between normal operating water level and tower overflow. The recommended approach is to install equalizer lines external to the tower. To facilitate maintenance on a cell while the others are in operation, each branch of the equalizer line to a basin should have a manual isolation valve.

7.6.4 Condenser-water piping arrangement

In large district cooling plants, pumps can be connected to condensers in two arrangements:. One is to have one pump for each condenser as shown in Figure 7-14, and the other is to connect the pumps to a header and then to the condensers as shown in Figure 7-15.

In both arrangements, as a chiller comes online another pump is started. The advantages of arranging the pumps in a header are that any pump can supply any chiller and a backup pump can be provided, usually at less cost than when one pump is dedicated to a specific condenser. The header arrangement is particularly advantageous when the towers and pumps are located remotely from the chillers. Additionally, with a header system it can be possible to reduce the number of pumps; for example, one pump could serve two tower cells. However, each pump would require variable-speed drives and the condensers would require flow control valves to maintain a constant differential pressure across the condenser. On a practical side, the pumps may become so large that the number of suppliers might be so small that bidding may not be competitive. In addition, the motor efficiency and horsepower may not be acceptable.

7.7 Water Treatment

As water quality varies from region to region, there is no one recommended water treatment program. The intent of this chapter is provide guidelines for the design of a successful water treatment program which will

- minimize deposition,
- minimize corrosion and
- effectively control microbiological activity.

Achieving these goals will lead to maximized plant life, efficiency of operation and safe operating waterside conditions. Unless there is a depth of in-house experience in the district cooling company, a qualified and experienced water service provider should be consulted. This water service provider should be ISO-certified, use environmentally acceptable chemicals and have experience in operating water treatment programs at the utility level in the area where the plant is constructed.

The topics addressed in this chapter include

- chilled-water systems,
- condenser-water systems,
- water supply,
- treatment approaches,
- dosing and control,
- Legionella,
- zero liquid discharge and
- service standards.

7.7.1 Water supply

Water is required for the distribution network (primarily the initial filling and, infrequently, makeup) and for condenser cooling. Generally, potable water from municipal water mains is used in the distribution network, although it is possible to use softened ground water.

District cooling systems can use a variety of options for cooling the chiller condensers, but generally water-cooled systems using cooling towers are used. A variety of sources can be used for makeup water for cooling towers, including:

- potable water,
- ground water (may be brackish),
- treated sewage effluent (TSE),
- seawater used for tower makeup directly and
- seawater or brackish water treated using reverse osmosis or other desalination technologies.

Seawater can also be used in a "once-through" arrangement, where seawater is passes directly through chiller condensers for heat rejection and cooling towers are not used.

With water supplies becoming scarcer worldwide, especially in arid areas like the Middle East, district cooling operators are obliged to consider all supplies that are available. When considering alternative supplies it is worthwhile to consult with a water services provider who has working experience of the particular sources being considered.

Potable water

Potable water is commonly used in non-arid areas and is the preferred source for tower makeup. Standard materials can be used: copper for chiller condenser tubes and galvanized or coated steel for cooling towers. However, potable water is not readily available in the Middle East and in some locales its use in cooling towers is prohibited. This has driven district cooling companies to search for alternate sources for cooling tower makeup.

Treated sewage effluent

Treated sewage effluent (TSE) is an important option to consider. Given that the developments served by district cooling also generate wastewater, it is useful to evaluate integration of wastewater treatment and district cooling as discussed in Chapter 4. Alternatively, it may be possible to obtain TSE from existing wastewater treatment systems.

There are a number of challenges with using treated sewage effluent, including availability and timing. Treated sewage effluent may not be available at the time and in the quantities needed by the district cooling plant. The potential TSE quantity usually is based on a mixed-use development that includes office, retail and residential. Since offices generate less wastewater than residential buildings, for example, if office space is developed first, then there could be an imbalance since the available TSE is not sufficient for cooling tower makeup.

A second challenge is competition with other uses for TSE, which in the Middle East is primarily irrigation. If the development plans to use TSE for irrigation then it is possible that no TSE would be available for cooling towers, or the quantity might be so small that it isn't worth pursuing, or the excess might not be available until the later construction phases.

In addition, TSE quality is not predictable and can create problems in the tower and condenser system. Recent experience has found that significant levels of algae grow in TSE storage tanks, which therefore require more frequent cleaning and increased levels of chlorination. Chlorine is aggressive to some metals, including stainless steel fasteners used in cooling towers. Also, sulfates present in TSE are aggressive toward copper, which is commonly used in chiller condensers. If the TSE quality is poor, special tube materials like super-ferritic stainless or titanium may be required.

With good quality water, i.e., low in dissolved minerals, cooling tower cycles of concentration can be increased. Experience with TSE indicates that cycles of concentration must be reduced to about 2.5, which results in more water consumption because more water is blown down.

Seawater in a once-through arrangement

It is possible to circulate seawater straight through the chiller condensers so that no cooling towers are required. In areas where cooling towers cannot be sited, once-through cooling may be the only option. Using once-through seawater offers formidable challenges:

1. The volumes of water required for once-through cooling are immense compared to cooling tower makeup, resulting in significant piping costs. Distance to the sea is a key consideration.

2. The seawater available in most Middle East locations is quite warm, particularly where the sea is shallow. Peak seawater temperatures can reach as high as 38 C (100 F), which approaches the upper limit for condenser cooling with standard packaged chillers.

3. Environmental studies must be undertaken to obtain permission from environmental authorities. Since the water is heated, diffusion modeling is required to confirm environmental regulations for temperature are met. hydrodynamic studies may also be required to confirm that the warm discharge is not recirculated back into the intake.

4. Piping and condenser-tube materials must be capable of withstanding the aggressive nature of seawater. For piping, this means using non-ferrous materials such as glass-reinforced plastic (GRP) and high-density polyethylene (HDPE). For the condensers, this means using special tube materials (such as titanium, super-ferritic stainless or copper-nickel alloys), specially clad tube sheets and internally coated water boxes.

5. Biological activity must be controlled. The sea is a living fluid that changes seasonally and can experience blooms of algae or sea creatures such as microbial mollusks. Typically, seawater must be chlorinated to kill the biological growth and to maintain cleanliness in the piping and condensers. The required water treatment can lead to environmental concerns. The conventional treatment chemical is sodium hypochlorite (bleach), usually generated from seawater on site. Also, seawter velocity should be maintained above 1.8 m/s (6 ft/s) inside the chiller condenser tubes to avoid fouling buildup.

6. A final concern is control of suspended biological material and silt/sand particles that may result from turbulent seas or land reclamation activities. The plant must have intake design, filtration equipment and material selections to accommodate anticipated seawater intake material loads, and land reclamation activities may need to be monitored by the district cooling utility to ensure acceptable loading levels are not exceeded.

Seawater as tower makeup

Use of seawater in cooling towers requires far less water than once-through seawater cooling, and concerns about rejecting hot water into the sea are reduced, provided the water is discharged after the tower basin. However, the cooling tower blowdown will likely be warmer than the sea during off-peak periods when the sea is cool and the dew point is relatively high. Therefore, thermal diffusion studies may still be required by the environmental authorities.

Since seawater is used, all the precautions mentioned above about material selection must be considered, as well as using corrosion-resistant cooling tower materials such as polyvinyl chloride (PVC).

In addition to using oxidizing biocides (sodium hypochlorite), additional chemicals will be required, including non-oxidizing biocides and dispersants. Also, an anti-scalant may be required, as some dissolved solids may reach their saturation limit due to evaporation of seawater.

Seawater treated using reverse osmosis or other desalination technologies

Potable water is commonly produced by desalinating brackish groundwater or seawater. This technique can also be used by district cooling companies. Since "normal" materials can be used in condensers and cooling towers, the plant cost is reduced, but the savings are offset by the cost of the desalination plant. The two major categories of desalination technologies are reverse osmosis and distillation.

Reverse osmosis uses semi-permeable membranes and does not require heating the water. Although it is commonly used in the Middle East, reverse osmosis poses several challenges when raw seawater is used, and the operator must be careful that the pre-treatment is functioning properly.

- Membranes are easily fouled by organic material. The Gulf is biologically active and subject to frequent and regular periods when algae blooms. These periods often occur during summer months, but they are quite unpredictable. Chlorine chemicals such as sodium hypochlorite are commonly used to kill biological matter, but chlorine attacks reverse osmosis membranes. Although chlorine-resistant membranes are coming onto the market, they can only tolerate chlorine for short periods of time.
- Dredging for land reclamation projects generates high silt levels which is also a source of problems for the membranes. Reverse osmosis plant operators are always paying close attention to the silt levels, even to the level of colloidal matter. The suspended particles must be removed, which usually results in large settling ponds. If the operator is not careful, mistakes can ruin a number of expensive membranes.

Distillation desalination can take several forms:

- multi-stage flash (MSF) distillation
- multi-effect distillation (MED)
- vacuum vapor compression

Since heat is required, most distillation plants operate in conjunction with power plants or some other source of low-grade and low-cost waste heat.

Naturally, desalination plant operators look for water that is not subject to algae blooms or high silt loadings. Taking water from brackish aquifers is one source – if the authorities will allow it. Alternatively, water can be taken from "protected" sources rather than from open intakes. Protected sources can be vertically drilled beach wells or horizontally drilled intake fields similar in concept to septic tank drainage fields, but in reverse. Both options serve as the first level of treatment to reduce biological contamination and suspended solids.

7.7.2 Treatment approaches

Any water treatment program must address the problems of deposition, corrosion and microbiological activity throughout the entire system. In the paragraphs that follow, treatment approaches will be discussed for both chilled and condenser-water systems.

Chilled water

In the chilled-water portions of the plant and in the distribution network, the problems encountered include

- corrosion in the chiller tubes,
- deposition in the chiller tubes,
- microbiological activity and
- corrosion in the system pipe network.

Treatment approach

Following are the recommended treatment approaches in a district cooling plant where pipes can be flushed:

- Pipes should be cleaned in sections using a non-acid cleaning agent in conjunction with a temporary pump and filter system. The water used for cleaning should therefore be retained in the system. This will conserve water.
- To lift debris off the lower section of the pipes, the water velocity should be a minimum of 1.5 m/s (5 ft/s) during this process. If necessary, the pipes should be cleaned in sections to ensure that this velocity is maintained. In unusual situations it may be necessary to mechanically clean pipe sections.
- Water should be recirculated for 24-48 hours while the filters remove debris from the system. It should be noted that this process can be made more effective by keeping dirt out the pipeline in the first place. This means carefully handling and installing pipe works during the construction stage.
- Water should be treated with a nitrite or molybdate product (or a combination of these) to finally passivate the metal. There are reports of success with organic corrosion inhibitors, but these are still regarded as less effective approaches.
- Pipeline passivation should be a continuous process immediately before commissioning. If there is a delay in commissioning the plant, resulting in standby conditions, then the system should be treated with twice the amount of corrosion inhibitor or recirculated daily for at least one hour.
- A biocide such as isothiazalone should be added to prevent microbiological activity. If molybdate is used, biocide may not be necessary.
- Finally it may be necessary to drain parts of the system from time to time to remove settled solids. In this case, local regulations may affect how the treated water can be disposed. The water treatment specialist usually can help in determining the proper course of action.

Unlike the piping in the district cooling plant, which is mostly smaller sized and often vertically oriented, chilled-water distribution piping is mostly large and primarily horizontal. This situation presents specific cleaning and disposal problems. Low-lying areas in the system may harbor debris, and flow velocities may be difficult to achieve. In this case flushing probably will not be effective and some other form of mechanical cleaning ("pigging") will be necessary. Depending on the conditions and circumstances, a bare-type pig could be used to remove construction debris and dirt or a wire brush or scraper pig could be used if the pipe internal surfaces need to be cleaned.

Dosing and control

Chilled-water quality is best monitored by testing the system water for chemical residual and dosing the appropriate amount of treatment to the system.

Two suitably sized dosing pumps should be connected to a bypass to the system. These should be fed from dosing tanks (with containment dikes or bunds), with one tank containing corrosion inhibitor and the other biocide. Manual control using a limit timer should be used.

A pot doser should be used as a standby mechanism.

Condenser water

On the condenser-water side the problems can include

- corrosion in tube sheet and end cap (waterbox),
- corrosion in copper tubing,
- deposition in tubes,
- corrosion in system pipe work,
- deposition in cooling tower fill (fouling),
- corrosion in cooling tower materials and
- microbiological activity.

While most of the above problems can be controlled by effective pre-cleaning and maintenance treatment, the problem of corrosion in the tube sheet and end cap starts long before the chiller arrives on site. In the factory, the chiller is hydrotested and then drained prior to shipping. This hydrotesting initiates the corrosion process. Subsequent treatment is not enough to clean and passivate this metal and often spectacular corrosion is seen in the form of tubercules (nodules of rust) at the first annual inspection.

This is particularly so on the condenser-water side where the level of chemical treatment is not sufficient to passivate the metal, and the oxygenated, suspended-solids-laden water drives the corrosion process further. This problem is further worsened if low flow results in stagnant conditions in the water box.

Two general solutions are to have the tube sheet and water box coated with epoxy by the manufacturer or at the hydrotest stage use a corrosion inhibitor to prevent water box rusting. In any event, the tube sheet should be inspected on delivery to allow any remedial work to be done before the chiller is installed.

Treatment approach

Since energy efficiency is of vital importance to district cooling operators, emphasis should be given to every means possible for keeping heat exchanger surface areas clean.

Pre-cleaning the condenser-water system is less arduous than the chilled-water distribution system, but it is just as important. A significant factor in keeping the condenser-water system clean is the cooling tower basin design. The basin should be configured with a weir design, whereby debris in the system water is likely to settle in the basin before passing over the weir into the return to the condenser pumps. There are a variety of options in these designs and the cooling tower supplier can advise on this. Here are the key elements to consider:

- Before starting the cleaning process, the cooling tower basin should be cleaned manually to remove debris. While doing this, care should be taken not to damage any system coating.
- On filling with water, the system should be cleaned using a non-acid cleaning chemical ensuring that all parts of the system are cleaned. It may be necessary to carry out a two-stage cleaning process whereby the condenser section of the chiller is cleaned after the cooling tower section and pipes. This process should be run for 24 to 48 hours prior to opening the blowdown system to remove cleaning chemicals. It will be necessary to ensure that blowdown quality complies with local disposal standards.
- The system should then be treated with a scale/corrosion inhibitor as recommended by the water service provider. The product's use should meet disposal standards as set by the local authorities. Initially, the product should be dosed at the passivation level as recommended by the supplier, and then reduced to the maintenance level.
- Microbiological control in the system should be achieved using oxidizing biocides dosed preferably on a continuous or semi-continuous basis using redox control. A biodispersant also should be incorporated into the program to aid the effectiveness of the biocide. A permitted non-oxidizing biocide should be used on an occasional basis.

Dosing and control

The water within the cooling tower system should be controlled via a programmable logic controller (PLC). Following are key recommendations for dosing and control:

- The blowdown system should controlled for conductivity to manage the dissolved solids at the optimum level.
- Dosing of scale and corrosion inhibitor chemical should be carried out proportionally. This can be achieved by a contact head water meter or even by level control in the cooling tower basin.
- Dosing of biocide and biodispersant should be controlled by timer if semi-continuous dosing is used. Otherwise control of the oxidizing biocide should be

by redox control.

- Suitably sized pumps should be used for scale/corrosion inhibitor, oxidizing biocide and biodispersant.
- Suitably sized chemical dosing tanks in opaque polyethylene should be used. Tanks should be calibrated externally to observe product level, and the tanks should also be bunded (diked) to contain any chemical leaks.

The above should be installed in a bypass system, which should be valved to allow isolation. A water sampling point should also be included. It is preferable to skid-mount this equipment and install it in an easily accessible area to allow recharging of chemicals, changing of corrosion coupons and other maintenance work.

Legionella control

There is much justified concern about the dissemination of Legionnaire's disease by cooling towers. Many authorities and professional bodies have produced common sense guidelines to controlling the risk, including

- ASHRAE guideline 12-2000, "Minimizing the risk of Legionellosis associated with building water systems";
- the UK Health & Safety Commission, "The control of Legionella bacteria in water systems" (this publication is known as L8); and
- Eurovent 9/5, "Recommended code of practice to keep your cooling system efficient and safe."

In essence, these guidelines advise system operators to

- assess the risk and take reasonable measures to reduce it (use a complete water treatment program, including suitable biocides);
- ensure that the cooling tower is correctly maintained;
- sterilize the system regularly (2 x per year); and
- monitor water quality, including microbiological activity, and keep records.

The risk of Legionella growth is ever-present, but vigilance and common-sense action will reduce the risk to a minimum. It is recommended that the relevant sections in the above-referenced guidelines be studied and incorporated into the district cooling operator's maintenance program.

7.7.3 Zero liquid discharge

When applied to cooling towers, zero liquid discharge (ZLD) is a process where blowdown is recycled. For example, blowdown would be treated in a reverse osmosis plant and the product water then reused for tower makeup. Economics and legislation drive this process depending on location.

The economics of this are system-specific and should be considered on a case-by-case basis. The obvious advantage is that it saves makeup water and can increase the effective cycles of concentration as the product water may be low in dissolved solids. The disadvantage is that it does have an operating cost, and disposal of reject water may need a special application such as thermal evaporation. Following are key factors to consider:

- Availability and price of alternative water supplies. If water is cheap and plentiful, ZLD becomes uneconomic. If it is expensive or the supply is restricted, then ZLD may be an option.
- Plant size. The plant must be large enough to justify the capital expenditure or rental terms.
- Available space. There must be sufficient plant area to install the RO plant.
- Disposal of reject. Often there are regulatory limitations on disposal, and evaporation may necessary. Options for evaporation include thermal (increasing initial cost and operating cost) or evaporation ponds (increasing initial costs and space requirements).

7.7.4 Service standards

In working with a water-quality service company, it is essential the district cooling operator set the agenda for service and the key success parameters. It is recommended that the service company

- be ISO 9001- and ISO 14001-registered;
- provide a copy of the company's environmental policy;

Condenser Water
• pH
• conductivity
• calcium/total hardness
• chloride
• M alkalinity
• iron
• calcium balance
• inhibitor level (provided by company)
• dip slide total count
Chilled Water
• pH
• conductivity
• inhibitor level (provided by company)
• iron

Table 7-10. Recommended monthly tests.

System	Test	Frequency	Standards
Condenser water	Carbon steel/ copper	1 per month 1 per 3 months	3 mils/yr maximum 0.1 mils/yr and no pitting
Chilled water	Carbon steel/ copper	1 per 3 months 1 per 3 months	1 mils/yr maximum 0.1 mils/yr and no pitting

Table 7-11. Corrosion-coupon standards.

- supervise and report on the pre-cleaning process as well as commissioning of all equipment;
- be prepared to commit to a minimum of 12 visits per year, during which the tests listed in Table 7-10 should be carried out and reported in writing;
- formally train site personnel in simple monitoring tests and problem-solving techniques;
- check records produced by site personnel;
- conduct twice yearly tests for Legionella (it would also be wise to carry out independent tests on Legionella);
- carry out corrosion coupon readings with the standards shown in Table 7-11;
- conduct deposit analysis as required; and
- implement quarterly review meetings to highlight problems and set timetable for improvements.

7.8 Balance of Plant

Balance of plant means components other than the major mechanical and electrical equipment. This section addresses the following topics:

- piping design for condenser water
- sidestream filters
- cooling tower basin sweepers
- transformer room cooling
- equipment access
- noise and vibration

7.8.1 Piping design for condenser water

The two choices for piping material are welded steel or glass-reinforced plastic (GRP). GRP is also known as fiber-glass-reinforced plastic (FRP). Although steel is tougher and more familiar to many mechanical contractors, GRP merits consideration because it is lighter and easier to install and is resistant to corrosion. If the condenser water pH is monitored and controlled in applications using steel pipe, corrosion should not be a problem, but using GRP offers a corrosion-free solution.

The supporting requirements for GRP are significantly different than for steel. Concentrated loads must be avoided, thus saddles should be used to spread the weight from clevis or roller hangers over a greater area; for larger pipe, the distances between supports should be shortened to achieve the same level of support. GRP is susceptible to ultraviolet damage and sunlight-induced biological growth, so outside GRP piping must be painted or covered. To avoid potential water hammer issues, water velocity should be kept below 3 m/s (10 ft/s) and the friction coefficients appropriate for piping and fittings should be used. Using lower velocities can reduce the flow imbalances induced by non-symmetrical piping arrangements. Using lower velocities also results in lower pressure drops and, in turn, less pumping power.

7.8.2 Sidestream filters

Water treatment programs can control dissolved solids, but cannot remove suspended solids. Air contains solid contaminants, such as sand, dust, soot, insects and debris, which are all scrubbed into the condenser water at the cooling towers. These contaminants will increase the chemical demand and fouling factor, reduce the cooling system efficiency, shorten the equipment lifespan and increase energy costs. This is of particular concern in the Middle East, where the level of sand and dust in the air can be significantly higher than other locales.

There are several mechanical filtration systems available to effectively remove suspended solid contaminants. There are also two basic approaches to cooling tower water filtration, full-flow filtration and sidestream filtration. With full-flow filtration, the filtration equipment is installed in the primary flow path, and the entire system flow is strained continuously. With sidestream filtration, only a portion of the water is pumped continuously from the cooling tower sump by means of a bypass filtration system and returned back to the cooling tower sump. Sidestream filtration is not as effective as full-flow filtration, but full-flow filtration is not cost-effective for the very high condenser-water flow rates of large district cooling systems.

Sand media filters and cyclone separators are commonly used as a sidestream filtration. Sand filters are the more effective filtration method, but require a larger footprint and consume backwash water during their automatic backwash cleaning cycle. Cyclone separators are a less effective filtration method but have a smaller footprint and require no backwash. Cyclone separators can also be used as a full-flow filtration.

Typically, sidestream sand filters are sized to continuously filter the cooling tower basin water inventory at a rate equivalent to about 3% to 5% of the total circulation flow rate through tower. In contrast, cyclone separators are typically sized to circulate about 10% to 15 % of system flow. Both systems can be used with sweeper jets in the basin to keep the basin floor cleaned and minimize manual cleanings. However, if the sweeper jet option is selected, it is important to get expert advice on its implementation and operation at the design stage.

In general, the designer's decision whether to select sand filters or cyclone separators is based on a variety of factors, with primary considerations, including

- space availability,
- cost considerations,
- sizes and characteristics of particles requiring filtration and
- acceptable level of maintenance requirements.

The experience of district cooling plant operators in the Middle East has suggested that sidestream filters in the chilled-water system have limited utility after the commissioning and initial operating phases. However, most experience has been with systems using indirect customer connections. When customers are directly

Performance Characteristic	Cyclone Separator	Sand Filter
Particulate removal ability on sidestream application	98% efficient in removing 45 micron and larger particulates with specific gravity of 1.6 or greater (removes particulates that sink in water).	95% efficient in removing 10 micron and larger particulates (will remove heavier particulates as well as particles that float in the water).
Removal of particles lighter than water (floating particulates)	Very low efficiency of removal. Light particles will tend to pass right through.	High efficiency in removing lighter/ floating particulate.
Susceptibility to fouling by oil or grease	Presence of oil or grease does not affect performance.	Oil and grease will foul media.
Positive media filtration	Does not use centrifugal forces to remove particles.	Silica sand forms 10-micron pockets that trap particles in the media bed.
Centrifugal forces	Uses centrifugal forces to cause particulate to spin out of suspension.	None; uses positive media filtration.
Pressure drop across unit	Pressure drop across separator is constant at specific flow rate. Pressure drop across separator unit will not increase as purge chamber becomes full of debris. Separator will just pass debris rather than removing.	Pressure drop across sand filter will increase as media bed becomes full of debris. When differential across vessel reaches 16-psi differential, the pressure switch will initiate backwash.
Full-flow application	Best application for cyclone separator as pressure drop across unit is constant.	Normally not recommended for sand filter, as pressure drop across vessel increases as unit becomes dirty.
Backwash cycle	No backwash; purge only.	Sand filter backwashes for 3 minutes at its designed flow rate.
Backwash frequency	Does not apply.	Backwash is generally once every 24 hours. When differential across filter vessel reaches 1.1 bar (16 psi) differential, filter will go into backwash mode. If pressure switch does not activate backwash, then 24-hour time clock will.
Purge cycle	Separator can be manually or automatically purged to drain. Time needed to clean lower purge chamber is 10-15 seconds. Water loss is minimal.	Does not purge.
Drain size required	Minimal quantity purged. In general, size the sanitary drain to equate to the size of the purge valve; for example, 1” for 1”.	Needs to be sized to accommodate 3 minutes of backwash at design flow rate. If drain available is not big enough, consider using holding tank.
Purge or backwash water recovery	Bag filter can be plumbed into separator purge outlet, with outlet of filter typically plumbed to suction side of the pump. Advantage is zero water loss. Disadvantage is regular bag cleaning.	Bag filter can be plumbed into backwash outlet. Need to size bag filter to accommodate size of backwash. Advantage is zero water loss. Disadvantage is regular bag cleaning – even higher maintenance.
Frequency of filter media replacement	If used, backwash water recovery bags will last 6-12 months.	Silica sand used should last 5-6 years. Sand may need replacing earlier if oil-fouled or biologically fouled. If used, backwash water recovery bags will last 6-12 months.
Required maintenance	Lower maintenance due to fewer moving parts. If skid packages chosen, pump seals, pump motors and auto-purge valves may need replacement over time.	Potentially higher maintenance with sand filter skid. In addition to pump seals, pump motors and media pack needing replacement, the valves, linkage, timers, valve actuator and pressure switch may need replacement over time.
Footprint of skid plus flexibility of design	Footprints of skid systems with flow rates 9.5 l/s (150 gpm) and higher, the separator tends to be significantly smaller in size. Also, the separator can be configured from a vertical profile to a 22-1/2 degree profile where there is height limitation	Sand filter skid packages with flow rates of 9.5 l/s (150 gpm) and higher tend to be larger and heavier (due in part to weight of filter pack). As an example, a 63.1 l/s (1000 gpm) sand filter system could be 5-6 times the size of a similar separator.

Table 7-12. Performance characteristics of sand filters vs. cyclone separators.

connected to the district cooling distribution system, sidestream filters may be useful. Since the district cooling company has little or no control over the customers' piping, contamination from the customers' sides is a concern and sidestream filters may be appropriate.

7.8.3 Cooling tower basin sweepers

Although cooling tower basin sweepers have been used successfully in many North American and European installations, experience has shown they offer little benefit in the Middle East, where the primary "contaminant" is the extremely fine sand that so often blows through the area. Much of this fine sand is only stirred up by basin sweepers and requires manual removal from the basin. Also, manual labor costs are much lower in the Middle East than in North America and Europe, making manual basin cleaning more cost-effective.

7.8.4 Transformer room cooling

Although transformers are efficient, they do give off heat -- as much as 0.8% of the transformer rating. This heat must be dissipated in some fashion. If the transformers are located outdoors, then they are cooled using natural convection. However, when the transformers are located inside rooms, the heat must be removed mechanically. Ventilation cooling and air conditioning are the two mechanical options available for cooling transformer rooms.

After the transformer heat gain is determined, ventilation cooling air flow can be calculated for various levels of temperature rise. Since transformers are derated at higher ambient temperatures, it is important to understand the tradeoff between the volumes of air circulated (size of air-handling units) and the possible derating of the transformers. Additionally, the large volumes of air that have to be moved require large openings, and if noise emission is a potential issue, these openings will require sound attenuation. Additionally, since dry-type transformers are less efficient with dust on them, it is important to thoroughly filter the outside air.

Air conditioning can be supplied using chilled water from the district cooling plant. Equipment sizes will be much smaller compared to the ventilation fans, and it will be easier to mitigate noise problems; however, the tons used to cool the transformer rooms will not be available to sell to district cooling customers, so the life-cycle cost of using air conditioning will be significantly greater than using ventilation cooling.

7.8.5 Equipment access

Designers know to provide clear space to pull and replace evaporator and condenser tubes, but similar care should be provided for other equipment like pumps, air-handling units, motor control centers, etc. As examples, the design engineer should consider how pump cases will be removed from large horizontally split case pumps and how chiller motors and compressors will be removed if and when that becomes necessary.

It is generally difficult to justify the costs of 3-degree movement bridge cranes. Instead, 2-degree movement monorails often provide the most appropriate facility for maintaining and moving heavy loads, provided the space is clear to get the component from the operating position to the floor for subsequent replacement or repair. Therefore, it is important to keep the hoisting points above equipment components clear. Lighting is important for maintenance, but lights (or cable trays) should not be placed in the way of the hoists. Likewise, piping to the chillers also must not encroach into the access removal areas or prohibit component removal.

During design, it is also important to anticipate the need for removing components from the cooling tower.

Lifts (elevators) facilitate movement of the tools, equipment and supplies required for maintenance and can be considered an element in the plant health and safety program.

7.8.6 Noise and vibration

Since district cooling plants are often sited in densely populated areas of high-value real estate, understanding and controlling sources of noise and vibration are fundamental tasks for the district cooling plant design. Increasingly common is integration of the district cooling plant with other building uses, so controlling noise and vibration is critical to maintaining positive public relations with the other "tenants."

The appropriate strategy depends on the specific plant configuration, proximity to neighbors, site conditions and local codes or ordinances. To set the proper framework from which to assess noise and vibration, the district cooling company should engage an experienced acoustics consultant to document background noise levels and to recommend control strategies.

The acoustics consultant commonly will have data for the various noise sources; however, the analysis will be improved if actual sound data is available for the equipment proposed for the plant. The potential sources of noise and vibration include

- chiller compressors and motors;
- chilled-water pumps & motors;
- condenser-water pumps and motors;
- noise generated from water flowing through piping, especially from cooling towers where towers are located above other "tenant" spaces;
- cooling tower fans;
- cooling tower water falling through fill materials;
- auxiliary mechanical equipment;
- control valves;
- main electrical power transformers; and
- emergency power generators.

The acoustics consultant will establish sound level criteria and propose strategies for reducing noise to meet the criteria. These strategies might include

- high-density wall and floor construction,
- sound reduction at all wall and floor penetrations,
- sound-rated door and frame assemblies,
- sound-attenuated ductwork penetrations,
- sound-attenuated piping penetrations,
- acoustically efficient selection of mechanical equipment and methods of installation
- mechanical piping and ductwork insulation with sound transmission barriers and/or
- equipment inertia bases.

7.9 Electrical Systems

Proper electrical design has always been important in district cooling plants, and as equipment sizes and voltages increase, it becomes even more critical that design is comprehensive and thorough. Because of the critical nature of electrical design and hazards, the design engineer rather than the contractor should be responsible for electrical design. If the contractor desires to change the design, those changes or deviations should be reviewed, evaluated and approved by the design engineer.

Engineers should perform such critical studies as the

- short-circuit study,
- protective device coordination study and
- arc flash hazard study.

7.9.1 Short-circuit study

Short-circuit studies determine the magnitude of currents flowing throughout the power system at various time intervals after a "fault" occurs and at various locations in the plant. The output of the study

- identifies whether the system and equipment can withstand the available fault current;
- specifies the ratings of the equipment; and
- describes conductor construction, lengths, and reactance to resistance (X/R) ratios, transformer impedances, ratings, wiring connections and short-circuit protective device ratings.

Normally the study would confirm that over-current protective devices are capable of interrupting the maximum-available fault currents, and since this depends on the utility impedance values, it is important to start discussions with the electric authority very early in the design process.

7.9.2 Protective device coordination study

The main objectives of the protective device coordination study are to prevent injury to personnel, minimize damage to system components and limit the extent and duration of service interruption due to equipment failure or human error. The results of the coordination study will determine settings for protective devices to trip in the desired sequence during a fault condition. This tripping sequence, in turn, isolates the fault area from the remaining portions of the power system, thus minimizing plant outages.

Short-circuit studies determine withstand ratings (the fault current level which a device can safely handle for a defined time without failing) for electrical equipment. If rule-of-thumb values are used with the idea that the contractor will to perform the final calculations, it is possible the electrical equipment, which tend to be long-lead items anyway, will be delayed even longer as the contractor and owner settle why the contractor's offering must be different from the design engineer's rules of thumb. To avoid this confrontation, the design should be completed by the design engineer.

7.9.3 Arc flash hazard study

The main objectives of the arc flash hazard study are to determine the necessary flash-protection boundary distances and incident energy to determine the minimum personal protective equipment (PPE) requirement. The results of the arc flash study can be used to reduce the PPE requirement, since adjustments to reduce the arc fault conditions will result in reduced PPE requirements. It is expected that the outcome of this study, when implemented, will result in most Category 4 PPE requirements being decreased to Category 1 or 2.

For further information on arc flash studies please see the Appendix C.

8. Controls, Instrumentation and Metering

8.1 Introduction

District cooling instrumentation and control systems (DCICSs) can be complex and distributed in nature due to the number of locations that must be controlled and the necessity to interface equipment from various vendors at each location. DCICSs vary greatly from one provider to another. Even the equipment owned by a single provider can vary greatly from site to site.

> A standardized terminology is essential for discussion of district cooling Instrumentation and control systems (DCICSs).

A standard terminology must be developed to begin any "best practices" discussion. This chapter begins by presenting a few models that introduce this terminology in a graphical format. Then a sample district cooling instrumentation and control system is introduced, using a "real-world" example to further clarify the models previously presented. The remainder of the chapter poses some best practice guidelines for each of the components contained in the models and the example.

Some of the concepts presented may not apply to every district cooling provider's system. For example, the sample system described in this chapter is comprised of a network of various types of plants communicating with two separate command centers. It should be understood that some district cooling providers may not require this level of automation. Their network architecture may not include any command centers at all, electing to control and monitor their plants locally instead of centrally.

The models, sample system and concepts presented here are meant to be generic in nature and are not intended to refer to any specific provider or equipment manufacturer.

8.2 Definitions

The following terms and abbreviations are used throughout this chapter.

BAS	building automation system
DCICS	district cooling instrumentation and controls system. Pronounced D-KICKS
DCS	distributed control system
DDC	direct digital controller
EEMS	expert energy management systems
EEPROM	electrically erasable programmable read only memory
HDA	historical data acquisition
HMI	human-machine interface
I&C	instrumentation and controls
I/O	input/output
mADC	milliamps DC
OIT	operator interface terminal
OLE	object linking embedding. A technology that supports the linking and embedding of objects from one application, seamlessly, into another application.
OPC	OLE for process control. A standard that specifies communication of real-time plant data between devices from different manufacturers.
PC	personal computer
PLC	programmable logic controller
Provider	district cooling provider
RTTMS	real-time thermal modeling and simulation
SCADA	supervisory control and data acquisition
SOP	standard operating procedure
UPS	uninterruptible power supply
VDC	voltage DC
VFD	variable-frequency drive

8.3 Overview

8.3.1 Typical DCICS functions

Depending on the provider, a typical district cooling instrumentation and control system may perform any or all of the following functions:

- Control and monitor process conditions at the district cooling provider's various plants automatically, with little or no user intervention.
- Provide a common user interface for the provider's personnel, allowing them to monitor and control their plants either locally within the plant or from command centers located strategically throughout the provider's district.
- Automatically gather accurate energy metering data and store this data in a format and location that is readily accessible by the provider's accounting systems for billing purposes.
- Automatically gather and store other types of data for maintenance and energy efficiency optimization purposes.
- Alarm when process conditions traverse outside of established normal operating ranges or when equipment failure is detected both locally at the affected plant and remotely as mandated by the provider's standard operating procedures (SOPs).
- Provide indication of certain process parameters local to where the parameters are being measured.
- Allow any device that is usually controlled by the DCICS to be overridden and controlled at the site where the device is installed.
- Provide a common data I/O interface for real-time data exchange with external applications such as expert energy management systems (EEMS) and real-time thermal modeling and simulation (RTTMS) systems.

A DCICS provides control and monitoring of plant equipment and alarms for unacceptable conditions, as well as data for maintenance, troubleshooting, accounting and billing purposes.

8.3.2 General design factors

There are some general factors that must be considered before undertaking any DCICS design effort. These factors will greatly influence the overall design and deployment of the system:

- How will the provider operate and maintain the system? Will control and monitoring functions be performed locally at the plant level, remotely at strategically positioned command centers, or a combination of both?
- If remotely, is the communication infrastructure in place in the provider's district to support the large amount of inter-plant networking that is required with this approach?
- Will the plants be manned or unmanned? How will equipment be sequenced on and off – manually, automatically or semi-automatically?
- How will energy metering data be gathered? Manually or automatically by the DCICS? Will submetering of the individual tenants be performed or will the provider simply meter their customers' buildings and/or complexes as whole units?
- How will data be "forwarded" to the provider's accounting systems? Electronically, or transcribed manually?
- Will the DCICS be required to interface to any third party packages such as energy efficiency optimization programs or maintenance scheduling programs?

8.3.3 DCICS performance evaluation

The following are key metrics to use in evaluating the performance of a DCICS:

- The system's ability to control and monitor the plant, distribution, energy transfer and storage systems in the most efficient and cost-effective manner to satisfy their customers' chilled-water demand.
- Stability of the system. The system should be available for provider use 24 hours a day, 365 days per year with minimal or no downtime. Frequent or random "crashes" are not acceptable.
- Reliability of the system.
- Accuracy and availability of the data generated by the system.
- Ability of the system to monitor energy generation, demand and consumption and to act on that data in an effort to increase the district cooling provider's overall efficiency.
- Ease of use for the provider's operational personnel.
- Ease of development and serviceability.
- Supportability of the system by multiple vendors, as opposed to being tied to one vendor for the life of the system.
- Ease of disaster recovery.
- Ability to interface to the different types of equipment that can be found in typical plant, distribution, energy transfer and storage systems.
- Initial and ongoing operating costs of the system.
- Ability to grow as the provider's chilled-water infrastructure grows, including integrating new equipment without affecting existing operations.

A well-designed DCICS will be easy-to-use, stable, reliable, accurate, supportable, expandable and well-integrated with the provider's other systems.

8.4 Physical Model

Figure 8-1 models the physical nature of a typical district cooling instrumentation and control system. The purpose of this model is to introduce a standard terminology that is used throughout this chapter.

A brief description of the various entities that make up the DCICS physical model can be found in the following sections. A typical DCICS may contain any number of these entities.

8.4.1 Sites

A typical DCICS site may physically contain the following types of installations:

- plant(s)
- command center(s)

8.4.2 Plants

For the purposes of this chapter, a plant is defined as a collection of equipment, piping and infrastructure that produces, stores, distributes or transfers cooling energy. Examples of plants include, but are not limited to

- chilled-water production plants,
- thermal energy storage plants,
- thermal energy transfer stations and
- pumping stations.

Plants can be manned or unmanned.

8.4.3 Local plant I&C system

Each plant will typically be controlled by one local plant's instrumentation and controls (I&C) system. Each local plant's I&C system will contain

- local plant controller(s),
- local operator interface terminal(s) and/or
- operations workstation(s).

Local plant controllers

Local plant controllers are the "heart" of the local

A local plant I&C system monitors and controls equipment in a plant that resides at a site. A site may contain many plants, and a DCICS may encompass many sites.

plant's I&C system. They interface directly to the plant's equipment, monitoring and collecting critical plant data, while at the same time automatically executing the algorithms that control the plant's overall operation.

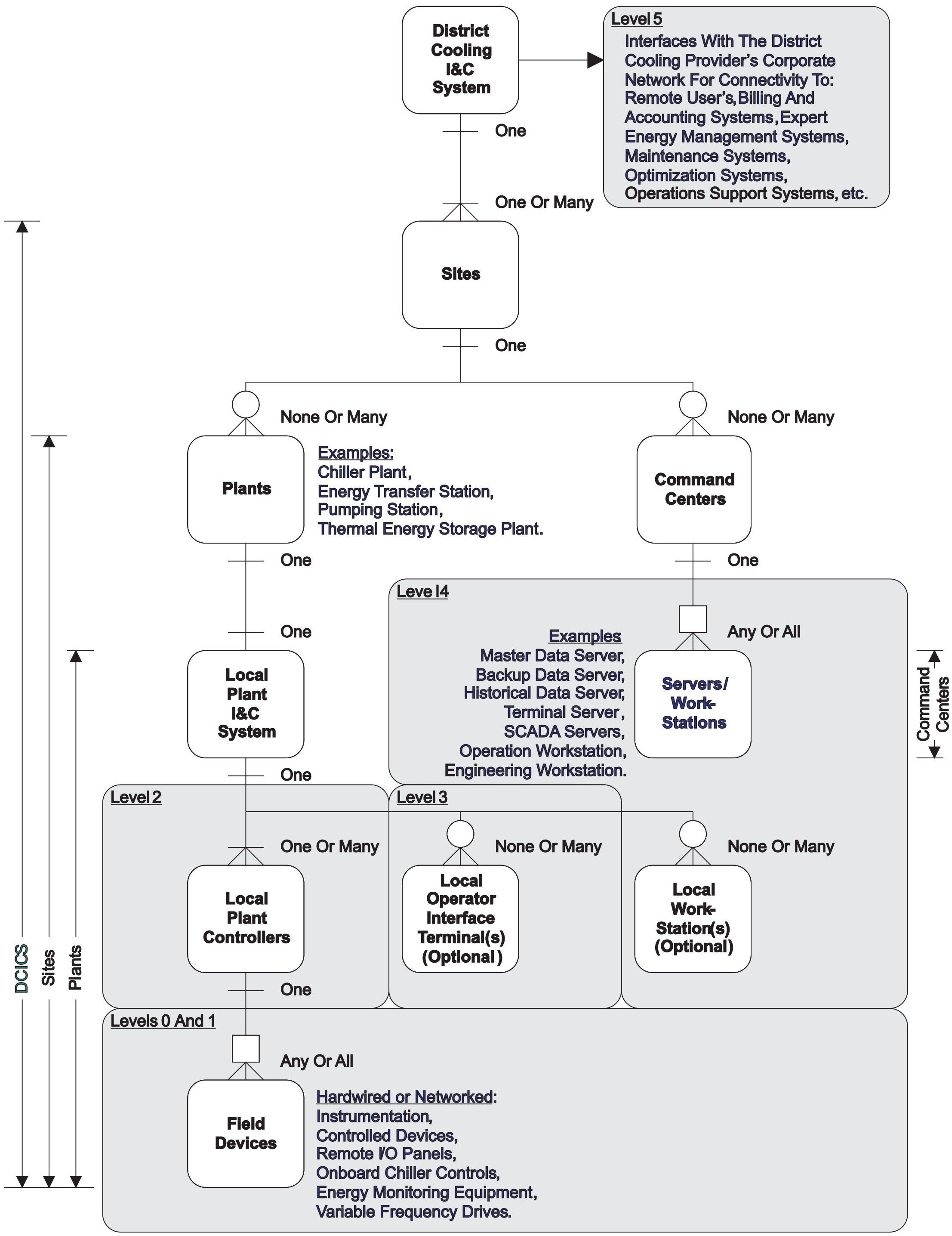


Figure 8-1. DCICS physical model.

Field devices

Each local plant controller will have numerous field devices connected to it. These field devices are either inputs into the DCICS used for monitoring conditions and equipment at the plant or outputs from the DCICS used to control the plant's equipment. Field devices are typically connected to the local plant controllers in one of two ways:

- hard-wired signals, directly into the controllers' I/O racks
- proprietary, high-speed industrial communication networks

> Absorption cooling is not very common in the Middle East due to significant performance degradation at high condensing temperatures, high heat rejection requirements and lack of suitably inexpensive heat sources.

Local operator interface terminals

Local operator interface terminals (OITs) typically communicate at the local controller network level, connecting directly to the individual plant controllers. The purpose of the local OITs is to allow personnel to interface with the DCICS locally at the plant level. OITs are typically mounted on local control panels that are generally installed in the vicinity of the controlled equipment or systems. For providers who do not utilize a command center approach, as discussed below, the local OITs function as the primary user interface into the DCICS.

Local workstations

Local workstations provide an alternate user interface into the DCICS for providers who utilize a command center approach. They can offer more functionality than local OITs and are typically installed remotely from the command center that services the plant (such as in a supervisor's office or in an enclosure on the plant floor). Unlike local OITs (that in a well-designed DCICS communicate to the plant controllers directly), local workstations communicate to the plant controllers indirectly, through data servers in the corresponding command center(s), and are thus dependent on the command center equipment for their operation.

8.4.4 Command centers

District cooling providers that elect to operate their plants remotely will do so from what are referred to as command centers. The command center provides a centralized point of operation for the DCICS. A provider may have one central command center or may elect to install several local command centers throughout their district at strategic locations. A command center may also be dedicated to a specific plant, such as in the case of a local plant control room.

In its simplest form, a command center will consist of a single computer performing all of operator interface, data logging and reporting functions required for the plant(s) that it serves.

> Command centers may be as simple as a single computer in a control room in a chiller plant or as complex as an array of servers and workstations in a corporate data center.

In more complex configurations, command centers may consist of several server class computers, workstations, displays, printers and other peripherals all working together to provide the required services.

The number, type and purpose of each component in a command center will vary greatly from one implementation to another. The terminology that each manufacturer of command center equipment uses for each component also varies greatly. The following sections utilize a standard terminology to categorize some of the more commonly used components. Not all categories listed will be required in every implementation, and some implementations may require categories other than those listed.

Data server

The data server is a computer that communicates directly to the local plant controller(s). In a very simple configuration the data server may be the only computer in the command center. In this type of configuration, the data server polls all of the plant controllers that are in its purview for data and serves this data up to other applications that are running on the data server.

In more complex configurations, the data server may be one part of a redundant array of data servers, polling all of the plant controllers in its purview and serving the resultant data up to other applications running on that data server and to other data servers and workstations that are part of the DCICS. In this configuration, all of the applications running on the other servers and workstations get their data indirectly from the plant controllers via the data server.

Historical server

The historical server's role is to periodically collect data from the data server, to store that data to a mass storage device (i.e., hard drive) and to serve this data up to the other equipment and systems that require it. A typical historical server will collect, among other things, customer metering data, process variables, alarms and operator-initiated events.

Historical servers collect real-time data from the data server(s) and store this data to a mass storage device in a format that is accessible by many applications.

In a very simple configuration, the historical server software may run on the only computer in the command center: the data server.

In more complex configurations, the historical server may part of a redundant array of historical servers, periodically polling the data server(s) for data and storing this data to mass storage device(s) that are accessible to the other equipment and systems that require it.

Users of the data collected and stored by the historical server include other DCICS applications as well as many types of Level 5 systems (i.e., accounting, maintenance, billing systems).

Command center workstations

Local workstations were introduced during the discussion of the different plant components earlier in this chapter. Command center workstations serve the same function as local workstations except they are installed in command centers. Both types of workstations provide windows into the DCICS for the provider's personnel.

Another type of workstation that is typically found in a command center, but not locally at the plant, is an engineering workstation. An engineering workstation allows properly trained personnel to troubleshoot and modify the different objects (displays, graphical objects, programming objects, reports, etc.) and programs that perform the DCICS functions.

Regardless of whether a command center workstation is used for operational or engineering purposes, it is typically an office-grade machine that has software installed on it that allows it to communicate to the data server, the historical server and any other server required to perform its stated purpose. Additionally, an engineering workstation will have development versions of that same software, as well as other programming/configuration tools installed on it.

Workstations are the main operator interfaces into the DCICS and get their data from the data server(s).

Terminal server

For district cooling providers who wish to give users in their organization remote access to their DCICS from computers that do NOT have any special software installed on them, a terminal server may be required. A terminal server is a machine that hosts applications and serves them up to remote users without the need for the remote users to have any special software installed. The applications are installed and run on the terminal server, not the remote users' machines. The remote user simply logs in to the terminal server (typically using a standard web browser) and starts the application as if it was being run from the user's local hard drive.

Other servers and workstations

Depending on the hardware and software selected to implement the command center, other servers and workstations may be required. One example may be a gateway server that bridges between the DCICS and an expert energy management system (EEMS) installed on the provider's corporate network. Another example may be a domain controller, which handles the authentication of users and security policies in some operating systems. The number and types of other servers and workstations that may be required vary with the scale and scope of the DCICS.

8.5 Logical Model

Due to the distributed nature of a typical district cooling instrumentation and control system, it is easier to visualize its various components logically as opposed to physically. Figure 8-2 maps the physical components that make up a typical DCICS onto a logical model.

8.5.1 Level 0

Level 0 equipment is installed in the field and directly monitors or controls the production, storage, distribution or transfer of the cooling energy and its media. Level 0 devices do not utilize a network to connect to the DCICS controller(s) directly; instead, they are connected via hard-wiring through a Level 1 device.

Examples of Level 0 equipment include sensors and transmitters that monitor process variables such as temperature, flow, pressure, electrical current, electrical voltage and contact closures. Other examples of Level 0 equipment that control equipment in the field are motor starters for constant-speed pumps and fans, solenoids for isolation valves and transducers for modulating control valves.

Typically, Level 0 devices are configured and calibrated via switches, potentiometers, and/or jumpers located directly on the devices. Due to their hard-wired nature, there is typically a limited amount of information that can be obtained from Level 0 devices.

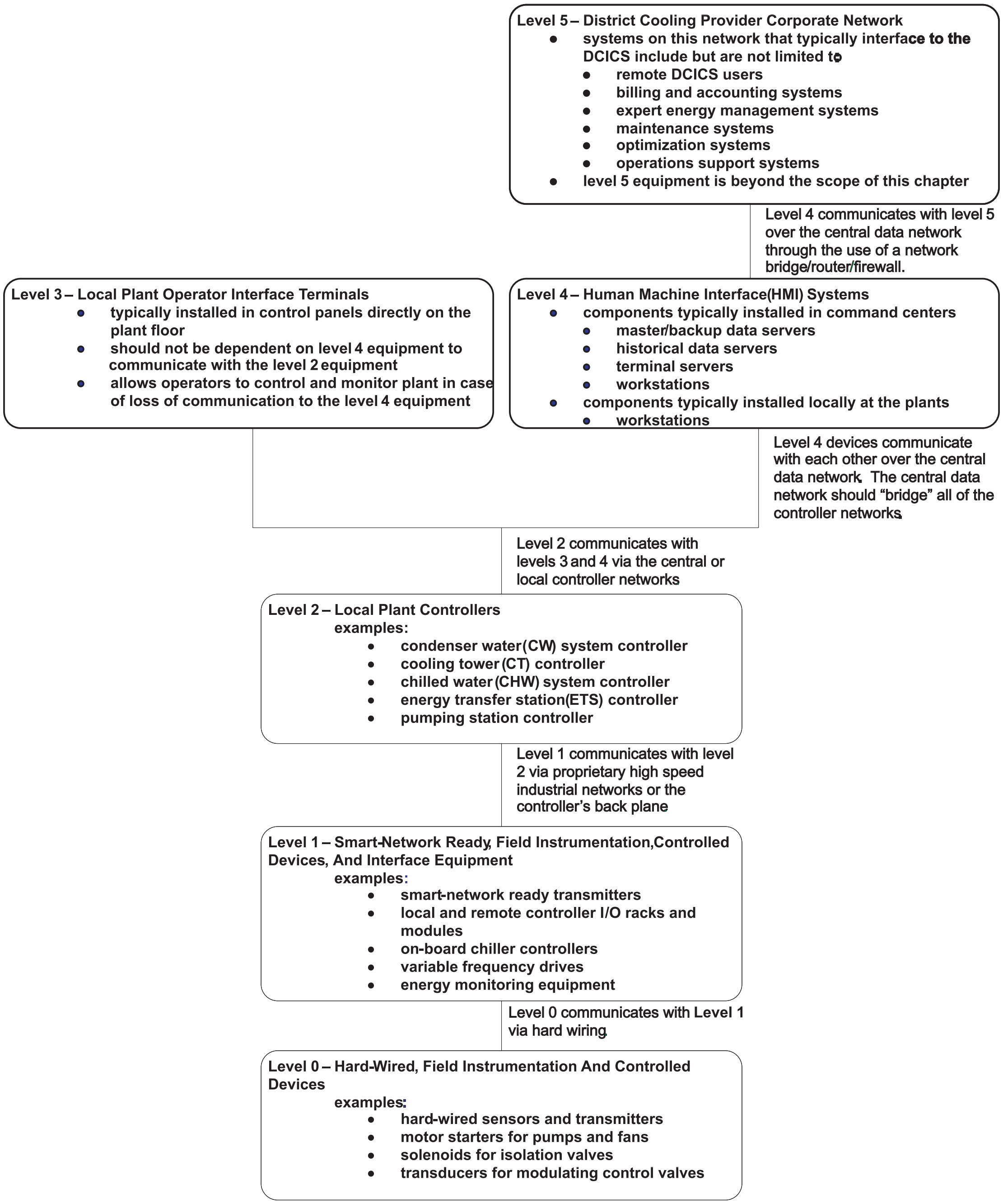


Figure 8-2. DCICS logical model.

> Level 0 devices monitor and control the equipment and process conditions in a plant.

Certain Level 0 devices utilize communication protocols that are superimposed on the hard-wired I/O signals (i.e., HART protocol). These types of devices would still be classified as Level 0 devices since the physical connection to the DCICS controller(s) is via hard-wiring, not a communication network.

8.5.2 Level 1

Level 1 devices connect directly to their associated controller via proprietary high-speed industrial networks or directly to the controller's internal communications bus, not by hard-wiring, as is the case with Level 0 devices.

Level 1 devices are "smart" devices that are typically configured and calibrated through the use of special configuration software over the same network that connects them to their associated controllers. In addition to the process variable(s) that they monitor, many other variables such as tag names, ranges, malfunction reports and configuration details can be read from Level 1 devices by the controllers that are connected to them. This type of information would not be available using an equivalent Level 0 device.

Examples of Level 1 equipment include "smart-network-ready" transmitters, local and remote I/O racks and modules, some variable-frequency drives and most energy meters.

Some Level 1 devices, such as "smart-network-ready" pressure transmitters, are standalone and do not require any Level 0 devices to perform their stated function. Other types of Level 1 devices, such as chilled-water energy meters, require that hard-wired Level 0 instruments (temperature and flow transmitters) be connected to them to perform their energy calculations. The sole purpose of yet other types of Level 1 devices, such as local and remote I/O racks and modules, is to connect Level 0 devices to their associated controller. Regardless of a device's function, if it is connected to the DCICS controller over any sort of high-speed industrial network or through the controller's internal communications bus, it should be considered a Level 1 device.

Level 1 devices connect to the local plant controller(s) over an industrial high-speed network.

Following are descriptions of some of the typical types of Level 1 devices:

Local I/O modules – Hard-wired Level 0 devices are connected to their associated controllers via local I/O modules. These modules are installed in the same rack as the controller and communicate with the controller over its internal communications bus.

Remote I/O racks and modules – Remote I/O racks and modules serve the same function as local I/O modules in that they are the termination point for any Level 0 devices that need to interface with the controller. However, unlike local I/O modules, remote I/O modules are installed in remote I/O racks, not the controller rack. The remote I/O racks are, in turn, connected to the controller over a proprietary high-speed industrial network.

Onboard chiller controllers – The chiller manufacturer typically supplies the onboard chiller controllers with the individual chillers. These standalone controllers monitor and control essential chiller operations, such as modulation of chiller capacity and interlocking of the chiller safety circuitry. Chiller controllers will typically communicate with the DCICS over high-speed industrial networks. Real-time Information, such as chiller operating data and alarm/diagnostic information, can be obtained from the onboard chiller controller over this high-speed network.

Variable-frequency drives – Variable-frequency drives (VFDs), which are also called variable-speed drives (VSDs), are devices that control the various types of motor-driven devices that are found in a typical plant (compressors, fans, and pumps). The proper use of VFDs is one of the best ways to increase plant energy efficiency.

VFDs are typically connected to the DCICS via a high-speed industrial network due to the large number of control and monitoring points that are available from them. However, some providers continue the practice of using hard-wiring to connect critical control points, such as start/stop, speed control and running status. In this scenario, where critical points are hard-wired, the high-speed network is still typically connected, but the data gathered over it is used for monitoring purposes only.

Energy monitoring equipment – Energy monitoring equipment, as the name implies, is used to monitor the energy (both electrical and thermal) produced and/or consumed. A typical energy meter will consist of the meter itself, several hard-wired Level 0 devices (such as temperature sensors/transmitters, flow sensors/transmitters, current transducers, voltage transducers) and a high-speed industrial network data connection to the meter's associated controller. The network connection is required due to the large amount of metering data that is available from a typical energy meter. Hard-wiring of all of these signals will not be practical in most circumstances. These devices are critical to the district cooling provider's business since they are typically used for billing purposes and evaluating plant operating efficiencies.

Field instrumentation – Most manufacturers of field instrumentation (temperature, flow and pressure transmitters, etc.) provide communication options for their equipment which allow them to communicate to their associated controllers over a high-speed industrial network, as opposed to hard-wiring them. If field instrumentation is provided with a communication option, then it would be categorized as a Level 1 device, not a Level 0.

8.5.3 Level 2

Level 2 is reserved for the local plant controllers. Controllers come in many shapes and sizes and are available from a multitude of vendors. As mentioned during the discussion of the physicalm, the controllers are the "heart" of the local plant I&C system, controlling and monitoring the plant's overall operation.

Basically there are three categories of controllers available on the market:

- programmable logic controllers (PLC)
- distributed control systems (DCS)
- direct digital controllers (DDC)

There are two basic types of controllers that are in use in chilled-water plants today: PLCs and DCSs. Each type has its own strengths and weaknesses.

Direct digital controllers (DDC) are ideally suited for commercial building automation Systems (BAS), but are not usually a good fit for the industrial nature of a modern DCICS. As such, they will not be discussed in this chapter.

To compare the other two categories of controllers (PLCs and DCSs), it is helpful to understand the history behind their design, development and deployment.

- PLCs were originally designed to control discrete types of systems. Most of their inputs and outputs were discrete (or binary) in nature. Since little computing power was needed to process binary data, PLCs tended to operate very quickly, making them ideal for machine control where speed is of the essence.
- DCSs, on the other hand, were originally designed to control processes. The majority of their inputs and outputs were analog in nature, measuring process variables such as temperatures, pressures, flows, pH and conductivity. Complex algorithms were built into the operating systems of the original DCSs to handle these types of signals and, as such, they tended to operate more slowly than PLCs, which in most cases was acceptable for the types of systems they were controlling.

Since the early 1990s everything about computers has increased at almost exponential rates (processor power and speed, memory sizes and speeds, storage capacity, etc.), while at the same time the costs of computers and computing components have decreased at nearly the same rate. This has caused the line between PLCs and DCSs to blur to the point where the two are almost indistinguishable from each other from the point of view of their capabilities. Today's PLCs can handle huge numbers of analog points and have the instruction sets necessary to process those points for most applications. Conversely, modern DCSs are usually fast enough to handle most "discrete intensive" machine applications.

Of course there are still some tasks where a PLC will out-perform a DCS and vice versa. Any discussion attempting to compare the two types of systems would invariably lead to both positive and negative arguments for each. For the purposes of this chapter, it is assumed that either type of system is adequate to control *any* provider's DCICS. It should also be pointed out that with the technology available today, it is possible (and even likely) that some providers will elect to install hybrid PLC/DCS systems.

Table 8-1 summarizes some of the pros and cons of each type of system. The purpose of the table is not to recommend one type of system over another, but to assist the district cooling provider in selecting which type of system to implement for its DCICS. However, more often than not, this selection will be made based on less technical criteria, such as previously installed systems, familiarity with a particular system and the availability of local vendor support.

8.5.4 Level 3

Local operator interface terminals (OIT) reside at Level 3 in the logical model. These terminals are installed locally at the provider's various plants, typically in control panels mounted directly on the plant floor. The main purpose of these OITs is to allow the provider's personnel to control and monitor the equipment locally at the plant.

For providers who do not utilize Level 4 equipment, the local OITs serve as the only interface to the plant's equipment. For provider's who do utilize Level 4 equipment, the local OITs often serve as secondary interfaces into the DCICS that are used only if the link to the Level 4 equipment is severed.

The local OITs are often connected directly to the Level 2 controllers and do not rely on any Level 4 equipment (e.g. Level 4 networks hubs, switches or routers) to communicate with the controllers. This is key to ensuring that the plant can still be monitored and controlled even if the Level 4 equipment is taken off line for any reason.

Level 4 equipment allows personnel to interface to the DCICS locally at the plants or remotely from other locations such as in command centers.

The choice of local OITs will often be based on what equipment is being used at Level 2 (i.e., the controllers) because they are so tightly coupled with those controllers.

Local OITs in a DCICS environment typically have much less functionality than their Level 4 counterparts and will have little or no permanent data storage capabilities.

8.5.5 Level 4

Level 4 in the logical model is the domain of the human-machine interface (HMI) equipment. Equipment at this level is unique in that some of it may reside in the

Controller Type	Pros	Cons
Programmable Logic Controller (PLC)	• Easily integrated with third-party hardware. • Easily integrated with third-party user interface systems (Levels 3 and 4). • Programming languages are very flexible and easy to troubleshoot, provided the programs are written according to a pre-approved standard. • The ability to have multiple manufacturers' PLCs seamlessly integrated to each other and to a single-user interface. • There are thousands of integrators worldwide who can support and service PLCs. If a provider's relationship with a particular PLC integrator sours, ongoing support for their DCICS is usually easy to find.	• Because the programming languages are very flexible, PLC programs can be difficult to troubleshoot and maintain if the programs are not written according to a pre-approved standard. • The controller and user interface systems are usually not as tightly integrated as with a DCS, which may increase application development time.
Distributed Control System (DCS)	• The controllers (Level 2) and user interfaces (Levels 3 & 4) are designed as one system. One "front-end" is used to program both the controllers and the user interfaces. This usually means faster application development time. • A DCS typically has advanced algorithms built in that makes complicated processing of analog points easier than PLCs. However, most DCICSs will never need to take advantage of these types of algorithms. • Because the controllers and user interfaces are designed as one system they will typically have advanced self-diagnostic capabilities.	• A DCS is proprietary in nature. Once a DCS is selected, the provider is usually married to that manufacturer's controller, I/O and user interface equipment and software. • It is necessary to use the DCS's user interface. Connecting to third-party HMI systems may be cumbersome and even impossible. • If none of the built-in algorithms meet the requirements of the system, the programming languages are usually not powerful enough to create your own algorithms. • DCS manufacturers tend to limit the number of companies who support their equipment to a select few per region. Finding ongoing support for their DCS may prove difficult if the relationship between the provider and the company who originally installed the DCS is severed for any reason.

Table 8-1. PLC vs. DCS – pros and cons.

provider's command center(s), while other components may be located on the plant floor(s).

A well-designed DCICS will interface as seamlessly as possible to many types of third-party applications running on Level 5 equipment.

Examples of Level 4 equipment that reside in command centers include master/backup data servers, historical data servers, terminals servers, operations workstations and engineering workstations. Note that command centers may be local to the individual sites (such as in a control room in a chilled-water production plant) or may be located remotely at strategic locations throughout the provider's district. Typically, the only Level 4 equipment that resides on the individual plant floors themselves is operations workstations.

It should be noted that if a DCS system is used at Level 2, then the distinction between Level 3 and Level 4 equipment is often non-existent. A DCS generally deploys only one type of user interface and it is tightly integrated into the DCS. In fact, manufacturers of DCS systems may argue that there is no distinction at all between Levels 2, 3 and 4. However, for the purposes of this chapter and the sake of consistency across platforms, these levels will remain as previously defined.

8.5.6 Level 5

Level 5 systems are installed on the provider's corporate network and interface with the DCICS. Examples include

- links to remote DCICS users;
- billing and accounting systems;
- maintenance systems;
- optimization systems, such as real-time modeling and simulation software;
- expert energy management systems; and
- operations support systems.

Level 5 equipment is beyond the scope of this chapter.

The points that are monitored and controlled should be planned carefully in order to avoid under- or over instrumentation in the plant.

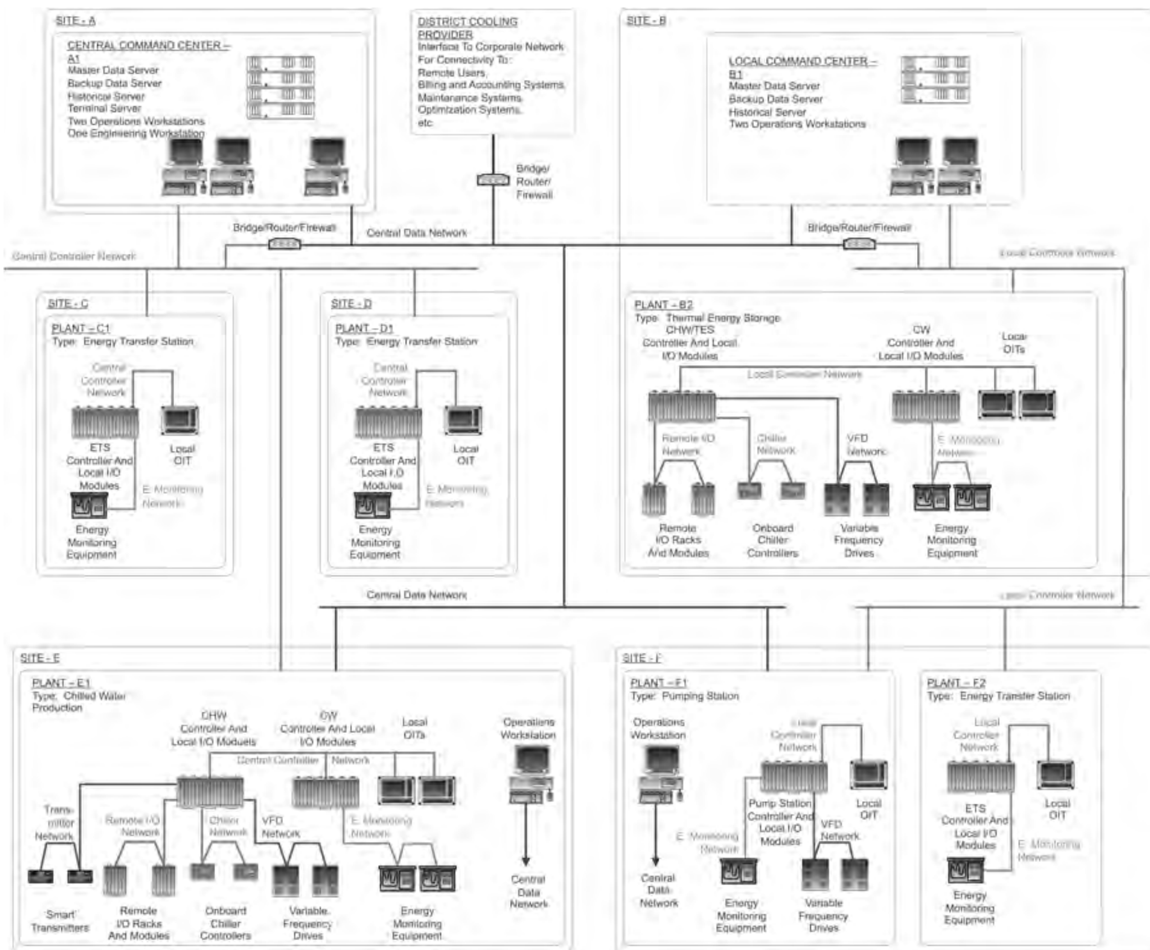


Figure 8-3. Sample DCICS system.

8.6 Sample DCICS

Figure 8-3 illustrates a sample DCICS. The purpose of this figure is to further clarify the models previously introduced in this chapter. It is not intended to represent any specific provider's system or to imply the use of any specific manufacturer's equipment. To simplify the figure, Level 0 equipment is not depicted.

8.7 Level 0 – Best Practices

The sections that follow present some guidelines for specifying and installing Level 0 equipment.

8.7.1 Point justification

The following process variables are monitored and controlled by Level 0 instruments in a typical district cooling instrumentation and control system plant:

- temperature
- liquid/steam flow
- liquid/steam pressure
- outside-air humidity
- water-quality conditions (conductivity, resistivity, pH)

It is important to specify the proper instrumentation to effectively monitor and control a plant's operation. An under-instrumented plant will be difficult to operate, maintain and troubleshoot. An over-instrumented plant will be expensive, confusing to operate and will not necessarily lead to a "better" control system. Both situations should be avoided.

Careful analysis should be conducted of the plant's operating requirements. In order for a point to be considered, it must be needed to

- effectively control the plant's operation based on a pre-approved sequence of operations;
- gather information about the plant's operation for accounting or administration purposes (i.e., for customer billing or efficiency calculations);
- notify plant operations that the plant is not operating properly or that a problem has occurred or is about to occur; and
- drive external Level 5 applications like optimization

applications and operations support systems.

8.7.2 Criteria for device selection

Before selecting an instrument, its purpose must be considered. For example, if a temperature transmitter is being used for customer metering it will require a higher accuracy than if it were used solely for troubleshooting purposes.

Once the purpose of the instrument is ascertained, the specification of the proper instrument for the task can be made. Table 8-2 outlines the different types of sensors that are available for some process variables that are typically found in a plant and some best practice specifications that should be considered when specifying each type of instrument.

8.7.3 Redundant Level 0 equipment

Where the monitoring of a certain process variable is critical to the plant's overall operation, redundant Level 0 instrumentation may be required. The controller that the instrumentation is connected to would determine which transmitter to use and should alarm if the values being read from the transmitters differ from each other

Process Variable	Sensor Types	Best Practice Specifications	
Temperature	• RTDs – resistive temperature detector (preferred) • Thermistors	1. End-to-end accuracy:	Liquid: Critical: +/- 0.56 C (+/- 1 F) Non-critical: +/- 0.56 C (+/- 1 F) Air (dry bulb): +/- 1.11 C (+/- 2 F)
		2. Resolution:	+/- 0.56 C (+/- 1 F)
		3. Process connections:	Liquid: Use thermo wells that pene trate the pipe they are installed in by the lesser of half the pipe diameter or six inches. Air: Provide protection from direct sun light and the building's exhaust when installed out doors for more accurate readings.
		4. Sensor range:	RTD: -260 C (-436 F) to 650 C (1202 F) Thermistor: -136 C (-212 F) to 150 C (302 F)
		5. Transmitter range:	4-20 mADC (preferred), 0-20 mADC, 0-5 VDC, 1-5 VDC, 0-10 VDC, 2-10 VDC, or -10-10 VDC signal proportional to a specified range within the overall sensor's range.
		6. Transmitter type:	2-wire (preferred)
		7. Cost:	RTD: Moderate Thermistor: Low
		8. Stability:	RTD: High Thermistor: Moderate
		9. Sensitivity:	RTD: Moderate Thermistor: High
		10. Linear:	RTD: Yes Thermistor: No
		11. Number of sensor wires:	3 or 4 wires are acceptable
		12. Transmitter mounting:	Integral to sensor or located remotely on a pipe, instrument stand, wall or panel are all acceptable. Should be easy to access for maintenance and calibration purposes. If there is a local display, it should be at eye level and easily read. Note that some controllers can accept RTD and thermistor inputs directly without the need for a separate transmitter.
Liquid Flow	• Inline magnetic meter (preferred) • Ultrasonic meter • Insertion magnetic meter • Vortex meter	1. End-to-end accuracy:	In-line magnetic meter: Highest +/- 1% full-scale typical Ultrasonic meter, vortex meter: High +/- 2% full-scale typical Insertion magnetic meter, insertion

Table 8-2. Level O best practice specifications. *Continued*

Process Variable	Sensor Types	Best Practice Specifications	
Liquid Flow (continued)	• Insertion turbine • Insertion paddle • Orifice		turbine: Medium Insertion paddle, orifice: Low
		2. Resolution:	0.063 l/s (1 gpm)
		3. Process connections:	Adhere strictly to manufacturer's requirements for straight runs of pipe upstream and downstream of meter.
		4. Turndown ratio:	Inline magnetic meter: 1000:1 typical Ultrasonic meter: 1000:1 typical Insertion magnetic meter: 50:1 typical Vortex meter: 30:1 typical Insertion turbine: 30:1 typical Insertion paddle: 10:1 typical Orifice: 5:1 typical
		5. First cost:	Inline magnetic meter: High Ultrasonic meter: High Insertion magnetic meter: Medium Vortex meter: High Insertion turbine: Medium Insertion paddle: Low Orifice: Medium
		6. Ongoing maintenance cost:	Inline magnetic meter: Lowest Ultrasonic meter: Low Insertion magnetic meter: Low Vortex meter: Medium Insertion turbine: High Insertion paddle: High Orifice: Medium
		7. Transmitter range:	4-20 mADC (preferred), 0-20 mADC, 0-5 VDC, 1-5 VDC, 0-10 VDC, 2-10 VDC, or -10-10 VDC signal proportional to specified range within the overall sensor's range.
		8. Transmitter type:	Integral to sensor or located remotely on a pipe, instrument stand, wall or panel are all acceptable. Should be easy to access for maintenance and calibration purposes. If there is a local display, it should be at eye level and easily read.
		9. Transmitter mounting:	Integral to sensor or located remotely on a pipe, instrument stand, wall or panel are all acceptable. Should be easy to access for maintenance and calibration purposes. If there is a local display, it should be at eye level and easily read.
		10. Other considerations:	Ultrasonic meters may provide false readings if air or other particles pass through them. Orifice meters require a pressure drop to operate, which increases energy consumption and are not recommended for use in a typical DCICS. Paddle, turbine and vortex meters typically require more maintenance then magnetic and ultrasonic meters and are also not recommended.

Table 8-2. Level O best practice specifications.

Continued

Process Variable	Sensor Types	Best Practice Specifications	
Liquid Pressure	• Capacitance • Piezoresistive (either type is acceptable for most DCICS applications)	1. End-to-end accuracy:	+/- 1% full-scale typical
		2. Resolution:	6.9 mbar (0.1 psi)
		3. Maximum operating pressure:	Sensor-specific. Must be greater than the normal operating pressure that the instrument will experience when installed.
		4. Normal operating pressure:	Application-specific – should be specified during detailed DCICS design. Must be less than the maximum operating pressure that the instrument is designed for.
		5. Burst pressure	Sensor specific. Must be greater than the maximum operating pressure that the instrument is designed for.
		6. Process connections:	Typically provided through capillary tubing. Isolation valves should be used at all capillary pressure taps into the main process piping so that the instrument can be isolated for maintenance purposes. Three-valve isolation/equalization manifolds should be used on all differential pressure applications. Provisions should be provided for blow down of the capillary tubing in situations where fouling may occur
		7. Transmitter range:	4-20 mADC (preferred), 0-20 mADC, 0-5 VDC, 1-5 VDC, 0-10 VDC, 2-10 VDC, or -10-10 VDC signal proportional to a specified pressure range.
		8. Transmitter type:	2-wire (preferred)
		9. Transmitter mounting:	Typically, integral to sensor. Capillary tubes should be routed so that the sensor/transmitter assembly is easy to access for maintenance and calibration purposes and the tubes themselves are safe from damage. If there is a local display, it should be at eye level and easily read.
Outside-Air Humidity	• Bulk polymer relative humidity • Thin-film capacitance relative humidity (either type is acceptable for most DCICS applications)	1. End-to-end accuracy:	+/- 5% relative humidity typical
		2. Resolution:	0.1 % relative humidity
		3. Measurement range:	0.0 to 100.0 % relative humidity
		4. Use:	In a typical chilled-water production plant, the outside-air wet-bulb temperature is needed for efficient plant operation. There are wet-bulb temperature sensors available that monitor wet bulb directly, but are more expensive and require more frequent calibration then RH sensors. It is recommended that RH sensors be used and that the controller that the humidity instrumentation is connected to calculates the wet-bulb temperature from the RH and dry-bulb temperatures using industry standard calculations.
		5. Transmitter range:	4-20 mADC (preferred), 0-20 mADC, 0-5 VDC, 1-5 VDC, 0-10 VDC, 2-10 VDC, or -10-10 VDC signal proportional to 0.0 to 100.0 % RH.

Table 8-2. Level O best practice specifications.

Continued

Process Variable	Sensor Types	Best Practice Specifications	
Outside-Air Humidity (continued)		6. Transmitter type:	2-wire (preferred)
		7. Installation considerations:	Install along with an outside-air dry-bulb temperature transmitter. Most manufacturers make a combination RH/dry-bulb temperature instrument just for this purpose. Both sensors should be protected from direct sunlight and the building's exhaust. For large installations it is often advantageous to install multiple sensors/transmitters at strategic locations around the installation and the controller can determine which one to use.
Water-Quality Conditions	• Conductivity • Resistivity • pH	1. End-to-end accuracy: 2. Resolution:	+/- 1% full-scale typical Conductivity: 0.01 µS/cm Resistivity: 0.01 mega-ohms per centimeter (MΩ-cm) pH: 0.01 pH
		3. Maximum ranges:	Conductivity: 0.00 to 100.00 µS/cm Resistivity: 0.00 to 100.00 MΩ-cm pH: 0.00 to 14.00 pH
		4. Process connections:	These types of probes require frequent maintenance and calibration. As such, they should be installed in the line they are monitoring by the use of ball valve assemblies that allow the probes to be removed from the process without shutting the process down. In addition, most pH probes have the requirement that they are never allowed to be "dry." Special consideration must be paid to this fact during detailed design.
		5. Transmitter range:	4-20 mADC (preferred), 0-20 mADC, 0-5VDC, 1-5 VDC, 0-10 VDC, 2-10 VDC, or -10-10 VDC signal proportional to a specified range within the maximum range of the probe type being used.
		6. Transmitter type:	4-wire (24 VDC power preferred)
		7. Transmitter mounting:	Typically, remotely from the probe. Pipe, instrument stand, wall and panel are all acceptable means of mounting the transmitter. Should be easy to access for maintenance and calibration purposes. If a local display is used, it should be at eye level and easily read. The cabling from the transmitter to the probe must be of sufficient length and routed so that the probe can be removed from the process piping (via the ball valve assembly mentioned above).

Table 8-2. Level O best practice specifications.

by more then a predetermined amount.

Redundant instruments have the added advantage of ease of maintenance and calibration because one instrument can be temporarily taken out of service while the plant continues to run using the other instrument.

When a particular process variable or controlled device is critical to the plant's overall operation, it is advisable to install redundant field instruments for that point.

The obvious disadvantage to Level 0 instrumentation redundancy is cost. For this reason, careful thought should be given during design as to which instruments (if any) should be installed redundantly. A general rule of thumb is to install redundant instruments if failure of a particular instrument would cause the entire plant to shut down. If the answer is yes, then redundant instruments should be considered, but are not mandatory. Redundant Level 0 instrumentation should be handled on a case-by-case basis and should only be utilized in the most critical situations because it will increase initial costs and ongoing maintenance costs.

8.7.4 Local instrumentation

When a particular process variable must be monitored locally at the process and remotely by the district cooling instrumentation and control system, one approach is to install transmitters with local displays, rather than installing separate local gauges to monitor the same point. An obvious drawback to this approach is that if power to a transmitter with a local display is lost, and there is no local gauge, then there would be no way to monitor the process variable in question, either locally or from the DCICS. Therefore it is typically best practice to use local gauges for critical process variables that must be monitored locally even if transmitter power is lost or if the DCICS is down.

If a particular process variable only needs to be monitored locally at the process, then local gauges are the obvious choice.

Regardless of how the local reading is obtained – from a local display on a transmitter or from a standard local gauge – the reading should be easily obtained without obstruction or the need for a ladder.

8.7.5 Localized overrides for each controlled component

When a field device is controlled by one of the plant's controllers, it is good practice to provide a means of operating that device, locally at the device, bypassing the DCICS altogether. This ensures the plant can still be operated in the event of a failure of the DCICS that would otherwise leave the plant inoperable. Different types of controlled devices will require different methods of local control, as summarized below.

- Constant-speed pumps/fans: hand-off-auto (HOA) switches.
- Variable-speed pumps/fans: hand-off-auto (HOA) switches for start/stop control; local/remote (L/R) switches for speed control selection; potentiometers for local speed control.
- Electrically actuated two position (open/closed) valves: open-close-remote (OCR) switches.
- Electrically actuated modulating control valves: local-off-remote (LOR) switches for position control mode selection, potentiometers for local position control.
- Pneumatically actuated valves: pneumatic auto/manual loading stations.
- Chillers: local onboard chiller control panels with push buttons, pilot lights, selector switches, and/or operator interface terminals.
- Air compressors: local onboard compressor control panels with push buttons, pilot lights, selector switches, and/or operator interface terminals.

8.7.6 Good installation practices

A number of good installation practices were discussed in detail in section 8.7.2 for each type of instrument found in a typical plant.

Any device that is controlled by the DCICS should be capable of being manually overridden at the device, so the plant can continue to be operated even if the local controller is down.

In general, a well-designed DCICS will allow Level 0 field instrumentation to be easily serviced, maintained and calibrated by properly trained personnel while minimally affecting the overall operation of the plant. Extensive use of thermo wells, isolation valves and insertion instrument ball-valve assemblies should be employed so that instrumentation can be removed and serviced while the plant is running.

All instrumentation wires, cables, and tubing should be properly labeled following a pre-approved labeling scheme.

Local codes for conductor sizes, colors and insulation should be adhered to.

All field instruments should be tagged for easy identification. Tagging should include the instrument's asset tag number along with a brief description of the instrument's purpose.

Test ports should be specified at all major equipment for testing pressures and temperatures.

8.8 Level 1 – Best Practices

The sections that follow present guidelines for specifying and installing Level 1 equipment.

8.8.1 Level 1 field instrumentation

The following process variables are monitored and controlled by Level 1 instruments in a typical district cooling instrumentation and control system:

- temperature
- liquid flow
- liquid pressure
- outside-air humidity
- water-quality conditions (conductivity, resistivity, pH)

These same process variables can also be monitored by Level 0 transmitters (see section 8.7). Some criteria to consider when deciding to specify a Level 0 or a Level 1 field instrument are covered in section 8.9.2.

The same best practice considerations that apply to Level 0 field instrumentation apply to their Level 1 counterparts as well (see section 8.7). In addition, the network that connects the Level 1 field instruments to their respective controllers must also be specified, designed and installed properly. Section 8.8.8 contains some best practices that should be followed when specifying, designing and installing Level 1 networks.

8.8.2 I/O modules and racks

Level 0 equipment connects to its respective controller(s) via I/O modules. I/O modules are installed in two locations with respect to their controllers:

- Local I/O modules are installed in the same rack as their controllers and communicate with the controller over the controller's internal communication bus.
- Remote I/O modules are installed in an I/O rack remotely from their controllers and communicate with the controller over a high-speed industrial network.

Since a loss of a remote I/O network may affect many instruments simultaneously, special thought must be put into the design and deployment of these networks. Refer to section 8.8.8 for items to consider when specifying, designing and installing any Level 1 network.

For analog signals, the most important design criterion to consider is the resolution of the analog to digital (A/D) and the digital to analog (D/A) converters that are employed in their circuitry. This resolution should be high enough as to introduce negligible error into the end-to-end accuracies of Level 0 devices to which they are connected. Most modern analog I/O modules utilize at least 12-bit converters, which is usually more than adequate for most DCICS applications. As microchip technology continues to improve, more and more manufacturers are switching to 16-bit converters, which even further improves the end-to-end accuracy of the entire circuit. A minimum of 12 bits is recommended, but 16 bits is preferred when available.

The selection of I/O modules and racks is determined by the type of controller(s) and the Level 0 equipment to which they will be connected.

When redundant Level 0 equipment is utilized, thought must be put into whether or not to utilize redundant I/O modules and/or racks as well. It may not be acceptable to wire the redundant Level 0 devices into the same I/O module or even the same I/O rack, since doing so reintroduces a single point of failure (the I/O module and/or rack) into the system for the Level 0 devices.

8.8.3 Onboard chiller controllers

Most modern chillers are provided with stand-alone onboard controllers that monitor and control the essential operation of the chiller. These controllers will typically have network connectivity of some sort built in and can also accept hard-wired control signals.

Whether the DCICS will interface to the onboard chiller controller(s) over its network or via hard-wiring, or a combination of both, is dependent on the designer's confidence in the networking capabilities of the onboard chiller controller(s) and the robustness of the network's design and implementation. Network confidence should be based on reliability, throughput and security. Not all of the networks that are supported by chiller manufacturers are suitable for control purposes.

If the designer has little or no confidence in the network's capabilities, then hard-wiring should be used for all controlled points, and the network would be used for monitoring only those points that are non-essential to the plant's overall operation. Conversely, if the designer has a high level of confidence in the chiller's networking capabilities, then it is acceptable to perform both monitoring and control functions over the network, provided the best practice guidelines in section 8.8.8 are followed when specifying, designing and installing the network.

Whether the DCICS will interface to the onboard chiller controllers over its network or via hard-wiring, or a combination of both, is dependent on the designer's confidence in the network's ability to effectively handle control functions.

At a minimum, the following points should be accessible from the onboard chiller controller(s) via hard-wiring and/or over the network:

- chiller start/stop command
- chiller running status
- general alarm status (alternately, individual alarms may be available)
- supply-temperature setpoint
- electrical voltage, current and energy
- evaporator refrigerant temperature
- evaporator refrigerant pressure
- evaporator chilled-water proof of flow status
- condenser refrigerant temperature
- condenser refrigerant pressure
- condenser-water proof of flow status
- compressor discharge refrigerant temperature
- guide vane position

8.8.4 Variable-frequency drives

Most modern industrial VFDs
- can be equipped with a network option for control and monitoring purposes,
- can be controlled and monitored via hard-wiring or
- can be used with a combination of both strategies.

How the district cooling instrumentation and control system will interface to the VFDs is dependent on the designer's confidence in the networking capabilities of the VFDs and the robustness of the network's design and implementation. Again, network confidence should be based on reliability, throughput, and security. If the designer has little or no confidence in the network's capabilities, then hard-wiring should be used for all controlled points, and the network would be used for monitoring only those points that are non-essential to the plant's overall operation. Conversely, if the designer has a high level of confidence in the VFDs networking capabilities, then it is acceptable to perform both monitoring and control functions over the network, provided the best practice guidelines in section 8.8.8 are followed when specifying, designing and installing the network.

At a minimum, the following points should be accessible from a typical DCICS VFD via hard-wiring and/or over the network:
- start/stop command
- running status
- fault status
- speed command
- speed feedback
- voltage, current, and electrical power data
- disconnect status
- bypass/normal status
- local/remote status
- hand-off-auto status

> The networking options available from most industrial VFD manufacturers are usually robust enough for control functions.

8.8.5 Energy monitoring equipment

Both thermal and electrical energy production and/or consumption are monitored in a typical DCICS. Energy meters are used to monitor this energy data for accounting or administrative purposes (i.e., for billing, plant efficiency calculations and other purposes).

Table 8-3 outlines the two types of energy meters that are found in a typical DCICS plant and some best practice considerations that should be taken into account when specifying each type of instrument.

8.8.6 Metering and submetering

The decision to meter entire buildings or submeter the individual building tenants is application specific and should be handled on a case-by-case basis.

Regardless of whether metering and/or submetering is utilized, it is usually carried out by ETS controller(s) and energy meters that are installed in the customer's buildings but are owned, operated and maintained by the

Process Variable	Sensor Types	Best Practice Specifications	
Thermal Energy	Temperature: RTDs, thermistors, sensor/transmitter assemblies (RTDs preferred) Liquid Flow: all types listed as acceptable in section 8.7.2. (inline magnetic meter preferred)	1. End-to-end accuracy:	+/- 5% full-scale typical
		2. Resolution:	Consumed/produced energy: 1 ton-hour Instantaneous energy: 0.1 ton Flow: 0.063 l/s (1 gpm) Temperature: 0.056 C (0.1 F)
		3. Process connections:	Two temperature sensors or sensor/transmitter assemblies, one for supply and the other for return. See the process variable temperature section 8.7.2 for process connection details. One flow sensor/transmitter. See the process variable-liquid flow section 8.7.2 for process connection details.
		4. Transmitter connectivity to DCICS:	It is recommended that energy meters used in a typical DCICS connect to the plant controllers via a high-speed industrial network, not hard-wiring, making them Level 1 devices. This is due to the large amount of data that is available from most modern energy meters.

Table 8-3. Energy meter best practice specifications.

Continued

Process Variable	Sensor Types	Best Practice Specifications	
Thermal Energy (continued)		5. Local displays:	Every energy meter installed in a DCICS application should have a local display that allows the provider's personnel to take readings, locally at the meter, in the event the link to the controller is severed for any reason.
		6. Transmitter mounting:	Pipe, instrument stand, wall or panel are all acceptable means of mounting the transmitter. There should be easy access for maintenance and calibration purposes. The local display should be at eye level and easily read.
		7. Monitoring for billing purposes:	If an energy meter is being used for billing purposes, it should be capable of calculating and storing metering data internally, independent of the controller it is connected to, so that if the link to the controller is lost for any reason, the metering data will not be lost. This is good practice even in non-revenue type meters.
Electrical Energy	Current and voltage transformers	1. End-to-end accuracy:	+/- 5% full-scale typical
		2. Resolution:	Energy: 1.0 kWh Real power: 0.1 kW Reactive power: 0.1 kVAR VA: 0.1 VA Power factor: 0.1 Voltage: 0.1 volts Current: 0.1 amps
		3. Process connections:	One current transformer (CT) per phase. One voltage transformer (PT) per phase. Should be installed in a motor control center (MCC).
		4. Transmitter connectivity to DCICS:	It is recommended that energy meters used in a typical DCICS connect to the plant controllers via a high-speed industrial network, not hard-wiring, making them Level 1 devices. This is due to the large amount of data that are available from most modern energy meters. There are other types of energy meters that provide an analog output (i.e., 4 20 mADC) that is proportional to the instantaneous electrical power (kW) being measured or a pulse output that indicates the amount of electrical energy (kWh) that has been consumed/produced since the last pulse. These types of meters are not recommended in a typical DCICS application.
		5. Local displays:	Every energy meter installed in a DCICS application should have a local display that allows the provider's personnel to take readings, locally at the meter, in the event the link to the controller is severed for any reason.
		6. Transmitter mounting:	Typically, electrical energy meters are installed through a door in the switchgear lineup for the circuits they are monitoring. There should be easy

Table 8-3. Energy meter best practice specifications. *Continued*

Process Variable	Sensor Types	Best Practice Specifications	
Electrical Energy (continued)			access for maintenance and calibration purposes. The local display should be at eye level and easily read.
		7. Monitoring for billing purposes:	If an energy meter is being used for billing purposes it should be capable of calculating and storing metering data internally, independent of the controller it is connected to, so that if the link to the controller is lost for any reason, the metering data will not be lost.

Table 8-3. Energy meter best practice specifications.

district cooling provider. A well-designed and implemented ETS will allow for submetering of individual customers as well as for metering of entire buildings.

Some providers may elect to utilize Level 5 real-time thermal modeling and simulation (RTTMS) systems that are capable of performing "virtual metering" as a backup to their normal mode of physical metering. These applications are beyond the scope of this chapter, but should be considered during the design of any large-scale district cooling instrumentation and control system.

A well-designed ETS controller and associated energy monitoring equipment will support metering of entire buildings and submetering of individual tenants in those buildings.

8.8.7 Redundant Level 1 field instrumentation

When a certain process variable is critical to the plant's overall operation, and that process variable is monitored by a Level 1 field instrument, redundant Level 1 instrumentation may be required. The controller that the instrumentation is connected to would determine which instrument to use and should alarm if the values being read from the transmitters differ from each other by more than a pre-determined amount.

Redundant instruments have the added advantage of ease of maintenance and calibration because one instrument can be temporarily taken out of service while the plant continues to run using the other instrument.

The obvious disadvantage to Level 1 field instrumentation redundancy is cost. For this reason careful thought is required during design regarding which instruments (if any) should be installed redundantly.

8.8.8 Level 1 network best practice considerations

Level 1 networks are, in some respects, the most critical networks in a DCICS because the low-level monitoring and control of the plants occurs over these networks. For this reason, the proper specification, design and installation of Level 1 networks is critical.

A well-designed Level 1 network will not allow for a single point of failure, where the failure of a single device on the network causes all of the devices on the network to lose communication with their controller(s). This includes, but is not limited to, network interface devices, bridges, routers and hubs.

Level 1 network cable routing also must be considered. The network cable should be routed in such a way that a break in any segment of the network should minimally compromise the controller's ability to communicate to the rest of the equipment on the network. In some situations this may mean installing redundant cabling and network infrastructure devices. When redundant cabling is used, the two redundant networks should be physically routed in different paths to decrease the likelihood of the same event taking out both networks. Redundant network cables should never be run in the same conduit or along side of each other in separate conduits over long distances.

8.8.9 Level 1 data considerations

During the detailed design phase of a DCICS, it is important to consult the manufacturer of any planned Level 1 equipment to ensure that all of the data required by the application will be available over the high-speed industrial network that will connect it to the associated controller. The data format accuracy when read over the network and its refresh rate over the network are also important requirements to consider and should be specified on a case-by-case basis.

8.9 Levels 0 & 1 – Choosing Points to Monitor and Control

This section presents some illustrations that depict what points should be monitored and controlled for different equipment segments that can be found in the various types of plants owned and operated by a typical provider.

The examples that follow illustrate both Level 0 and Level 1 instrumentation implemented together. Table 8-4 provides a key to the instrument tagging symbols used and explains how Level 0 and Level 1 devices are depicted in the examples. Table 8-5 describes how to interpret the function identifiers that are shown in the examples. A discussion is provided after the examples regarding the criteria that should considered when deciding to whether to specify Level 0 or Level 1 field instrumentation or a combination of both.

When process variables that are read over a Level 1 network are used in control loops, it is important that the data refresh rate on the network be fast enough to maintain effective system operations.

8.9.1 Example equipment segments

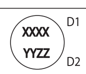
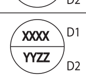
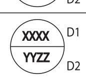
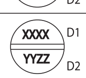
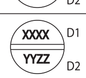
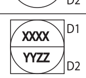
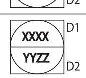
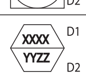
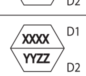
Primary-secondary systems

Figure 8-4 illustrates the recommended instrumentation for a primary-secondary system. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, the instrumentation should be in place to perform the following functions:

- Monitor the differential pressure across the customer load at the furthest possible hydraulic point(s) from the secondary pumps (PDIT-1000). Depending on the physical layout and the communication infrastructure available in the district cooling provider's district, this may be miles away from the plant at an energy transfer station that the plant supplies (see section 8.9.1/Heat exchangers) or it may be in the plant itself.
- Control the speed of the running secondary pumps based on this differential pressure.
- Stage the secondary pumps based on this differential pressure (customer demand).
- Monitor the supply flow (FIT-1001) and temperature (TIT-1001), the return temperature (TIT-2001) and the chilled-water energy (JIT-1001) being delivered to all of the customers on the loop. Note that individual customers are typically metered at the energy transfer stations, not at the chiller plants. Submetering of individual users at each customer site is also an alternative that may be considered and should be accounted for in the design and implementation of the DCICS.
- Stage primary pumps based on chiller status.
- Stage chillers based on chiller load (IIT-1380, see section 8.9.1/Chiller evaporators), supply temperature (TIT-1001), supply flow (FIT-1001), and/or direction of chilled-water flow (deficit vs. supply) in the decoupling line (FIT-3000).
- Monitor the temperature being supplied from all of the chillers (TIT-1000).
- Monitor the temperature being returned to all of the chillers (TIT-2000).
- Monitor the temperature (TIT-3000) and bi-directional flow (FIT-3000) in the decoupling line.

The purpose of the bi-directional flow meter in the

	Instrument that is installed in the field, in free space.
	Instrument that is install in the field in a utility panel, and is accessible from the front of the panel.
	Instrument that is installed in the field in a utility panel, and is NOT accessible from the front of the panel.
	Instrument that is installed in the field in a control panel that is accessible from the front of the control panel.
	Instrument that is installed in the field in a control panel that is NOT accessible from the front of the control panel.
	DCICS hardwired input, output, or function that is accessible by the user via the Level 2 and/or Level 3 user interfaces. When connected to a field device it indicates that the field device is a level 0 device.
	DCICS hardwired input, output, or function that is NOT accessible by the user. When connected to a field device it indicates that the field device is a level 0 device.
	DCICS input, output or function, acquired through a communication link, that is accessible by the user via the Level 2 and/or Level 3 user interfaces. When connected to a field device it indicates that the field device is a level 1 device.
	DCICS input, output or function, acquired by a communication link, that is NOT accessible by the user. When connected to a field device it indicates that the field device is a level 1 device.

XXXX = Function identifier (see Table 8-5) ZZ = Equipment number
YY = P&ID number (or system identifier) D1 and D2 = Text fields used to further explain the purpose of the point.

Table 8-4. Key to instrument tagging symbols.

	FIRST-LETTER (4)		SUCCEEDING-LETTER (3)		
	MEASURED OR INITIATING VARIABLE	MODIFIER	READOUT OR PASSIVE FUNCTION	OUTPUT FUNCTION	MODIFIER
A	Analysis		Alarm		
B	Burner. Combustion		User's Choice	Button	Blue
C	Conductivity			Control	Closed
D	Density (Mass) Or Specific Gravity	Differential Specific Gravity			
E	Voltage		Sensor (Primary Element)		
F	Flow Rate	Ratio (Fraction)			Forward
G	User's Choice		Gauge-Local Viewing Device		Green
H	Hand				High
I	Current (Electrical)		Indicate		
J	Power	Scan			
K	Time. Time Schedule	Time Rate Of Change		Control Station	
L	Level		Light		Low
M	Moisture Or Humidity				Middle. Intermediate
N	User's Choice				
O	User's Choice		Orifice. Restriction		Open
P	Pressure		Point. (Test) Connection		
Q	Quantity	Integrate. Totalize			
R	Radiation	Regulating	Record		Red. Reverse. Remote
S	Speed. Frequency	Safety		Switch	
T	Temperature			Transmit	
U	muitivariable		Multifunction	Multifunction	Multifunction
V	Vibration. Viscosity			Valve Damper"	Louver
W	Weight. Force		well		White
X	Run. Energize Actuate	X Axis Actuate			
Y	Status. Event. State Of Presence	Y Axis Of Presence		Relay. Compute Convert	Yellow
Z	Position. Dimension	Z Axis		Driver. Actuator Unclassified Final Control Element	

Table 8-5. Function identifier key.

decoupling line (FIT-3000) is to detect surplus or deficit flow conditions. Decoupling line flow in the supply to return direction indicates a surplus flow condition. Decoupling line flow in the return to supply direction indicates a deficit flow condition. This same information can be obtained by trained personnel in other ways, thus eliminating the need for the decoupling line flow meter (FIT-3000). Some alternate methods include

- observing the chiller supply (TIT-1000), return (TIT-2000) and decoupling line (TIT-3000) temperatures and
- adding up all of the individual chiller flows (FIT-1370, see section 8.9.1/Chiller evaporators) and comparing the result to the flow to be delivered to the customers (FIT-1001).

Due to the large size of the supply line in a typical district energy primary-secondary system, it may not always be feasible to install an independent customer-supply flow transmitter (FIT-1001) at the plant. An alternative involves eliminating the customer-supply flow transmitter and adding up all of individual chiller flows (FIT 1370, see section 8.9.1/Chiller evaporators) and using the resultant sum as an indication of total flow to the plant's customers. Also, it is important to provide ways to determine how much flow is present in the decoupling line and the direction in which it is flowing. This means that if the customer-supply flow transmitter (FIT-1001) is eliminated, then the decoupling line flow meter (FIT-3000) must usually be provided (the decoupling line is usually smaller than the supply line).

If the customer-supply flow transmitter (FIT 1001) is eliminated, and the provider still wishes to have an independent customer-supply energy meter at the plant (JIT-1001), then the plant controller must provide the customer-supply energy meter (JIT-1001) with a flow value proportional to the value that it calculates from

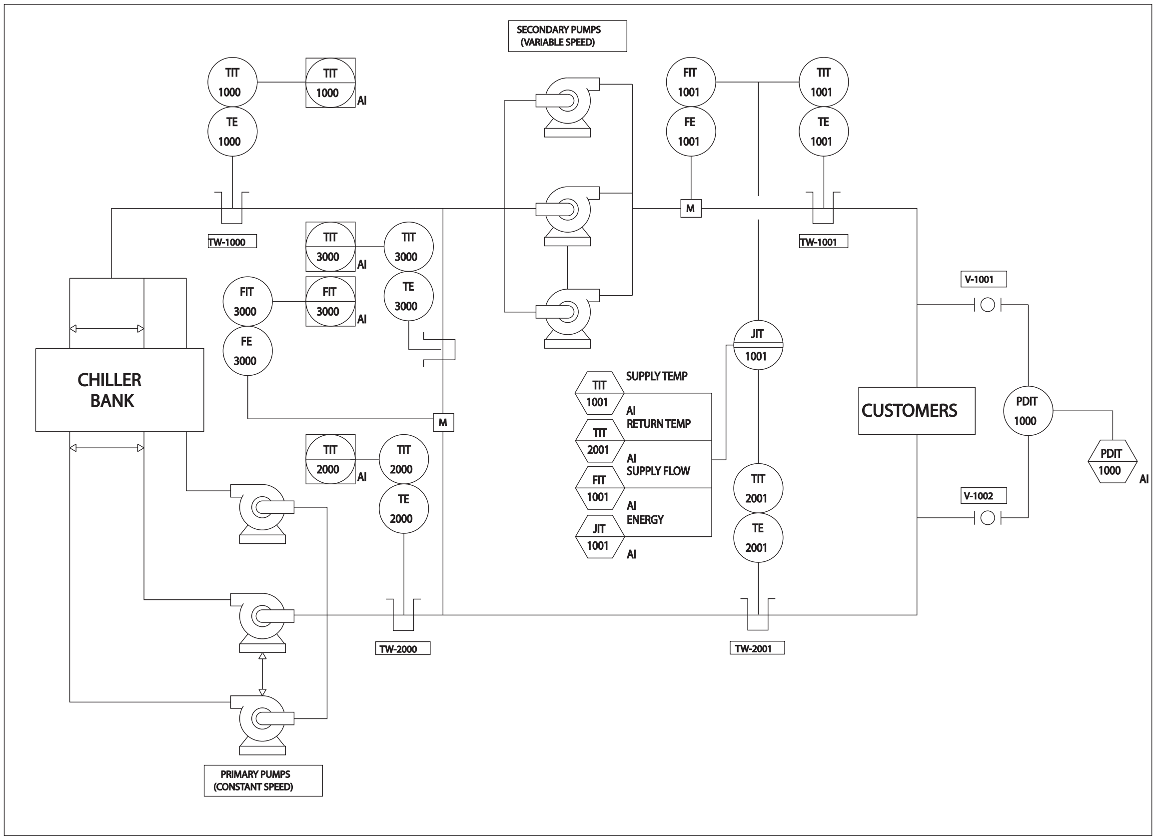


Figure 8-4. Primary-secondary system.

the individual chiller flows and the flow in the decoupling line.

In addition to eliminating the independent customer-supply flow transmitter (FIT-1001), the independent customer-supply energy meter (JIT-1001) can also be eliminated. If it is eliminated, then the individual chiller energy meters (JIT 1370, see section 8.9.1/Chiller evaporators) would be used to determine the total chilled-water energy that the plant is delivering to its customers. Also, any flow present in the decoupling line would need to be accounted for and figured into the overall plant efficiency calculations.

Due to the large size of the supply line in a typical district energy primary-secondary system, it may not always be feasible to install an independent customer-supply flow transmitter at the plant.

Variable primary systems

Figure 8-5 illustrates the recommended instrumentation for a variable-primary system. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, the instrumentation should be in place to perform the following functions:

- Monitor the differential pressure across the customer load at the furthest possible hydraulic point(s) from the distribution pumps (PDIT-1000). Depending on the physical layout and the communication infrastructure available in the cooling provider's district, this may be miles away from the plant at an energy transfer station that the plant supplies (see section 8.9.1/Heat exchangers) or it may be in the plant itself.
- Control the speed of the distribution pumps to maintain a minimum customer differential pressure (PDIT-1000).
- Stage the distribution pumps based on customer demand (PDIT-1000).
- Stage chillers based on chiller load (IIT-1380, see section 8.9.1/Chiller evaporators), supply temperature (TIT-1000) and/or supply flow (FIT-1000).
- Monitor the differential pressure across the chiller bank (PDIT-3000).
- Automatically modulate the bypass control valve (CV/PY-3000), based on the chiller bank differential pressure (PDIT-3000) to maintain a minimum flow through the chillers. Normally this valve should be closed and should only modulate open under very low customer demand conditions.
- Allow operators to manually control the bypass

control valve locally at the valve, bypassing the DCICS altogether (HS-3000).

- Monitor the remote status of the bypass control valve's local-off-remote (LOR) switch (HS-3000).
- Monitor the position of the bypass control valve (ZT-3000).
- Monitor the supply flow (FIT-1000) and temperature (TIT-1000), the return temperature (TIT-2000) and the chilled-water energy (JIT-1000) being delivered to all of the customers from the plant. Note that individual customers are typically metered at the energy transfer stations, not at the chiller plants. Submetering of individual users at each customer site is also an alternative that may be considered.

Instead of using the differential pressure across the chiller bank to control the bypass valve, the individual chiller flows may be used (FIT-1370, see section 8.9.1/Chiller evaporators), thus eliminating the need for the chiller bank differential pressure transmitter (PDIT-3000).

Due to the large size of the supply line in a typical district energy variable primary system, it may not always be feasible to install an independent customer-supply flow transmitter (FIT-1000) at the plant. An alternative involves eliminating the customer-supply flow transmitter and adding up all individual chiller flows (FIT 3001 through FIT-3003) and using the resultant sum as an indication of total flow to the plant's customers. However, this scheme only works if the bypass control valve (CV 3000) remains closed. If the bypass valve does open, a way of determining how much flow is present in the bypass line must be provided. This may involve installing a flow meter in the bypass line (the bypass line size is typically much smaller than the supply line size) or using a delta P type of valve in the bypass line and calculating bypass flow based on the valve's position.

Regardless of how it is calculated, if the customer-supply flow transmitter (FIT 1000) is eliminated, and the provider still wishes to have an independent customer-supply energy meter at the plant (JIT-1000), then the plant controller must provide the customer-supply energy meter (JIT-1000) with a flow value proportional to the value that it calculates.

In addition to eliminating the independent customer-supply flow transmitter (FIT-1000), the independent customer-supply energy meter (JIT-1000) can also be eliminated. If it is eliminated, then the individual chiller energy meters would be used to determine the total chilled-water energy that the plant is delivering to its customers. Note that any flow present in the bypass line would need to be accounted for and figured into the overall plant efficiency calculations.

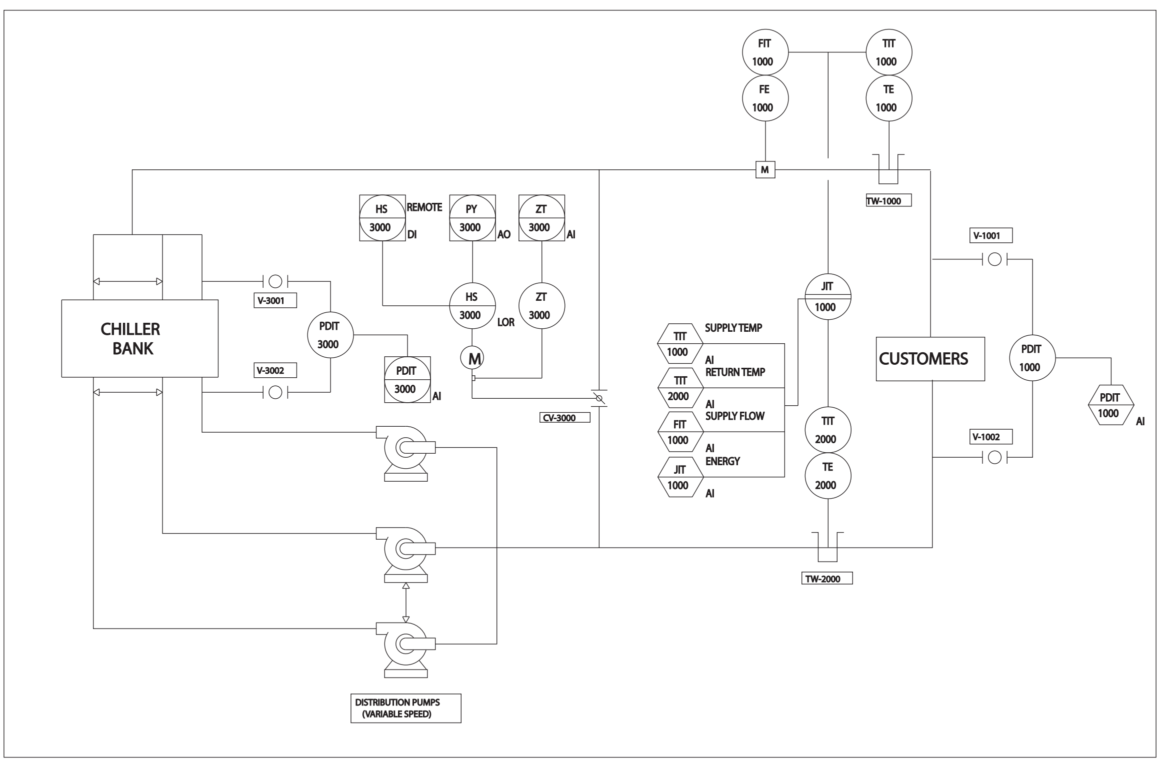


Figure 8-5. Variable primary system instrumentation.

Chiller evaporators

Figure 8-6 illustrates the recommended instrumentation for the supply and return piping to a single chiller evaporator. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, instrumentation should be in place to perform the following functions:

- Automatically isolate the evaporator's supply from the chilled-water supply piping with a modulating control valve (CV-1370).
- Monitor the actual position of the evaporator supply isolation valve (ZT-1370).
- Allow operators to manually control the evaporator supply isolation valve via a local-off-remote (LOR) switched located locally at the valve, bypassing the DCICS altogether (HS-1370).
- Monitor the remote status of the evaporator supply isolation valve's LOR switch (HS-1370).
- Manually isolate the evaporator's return from the chilled-water return piping with a hand-operated valve (V-1371). Note that some providers may elect to automate this valve as well as the supply valve. However, there would be no reason to make this a modulating type of valve if it was automated. A simple isolation valve would suffice.
- Monitor the flow (FIT-1370) and temperature (TIT-1370) of chilled water leaving the evaporator, the temperature (TIT-1371) of the chilled water entering the evaporator and the chilled-water energy (JIT-1370) being produced by the evaporator.
- Communicate with the chiller's on board controller to obtain the following minimum information:
  - running status (XI-1380)
  - general trouble status (XA-1380)
  - electrical voltage (EIT-1380)
  - electrical current (IIT-1380)
  - electrical energy being consumed by the chiller (JIT-1380)
  - evaporator refrigerant temperature (TIT-1380)
  - evaporator refrigerant pressure (PIT-1380)
  - evaporator chilled-water flow switch status (FSL-1380)
  - Guide vane position
- Use the same communication link to remotely start/stop the chiller (XS-1380) and to reset its supply-temperature setpoint (TC-1380).
- Locally monitor the chilled-water supply (PI-1323) and return (PI-1320) pressures as close to the evaporator as possible.

A modulating evaporator supply valve is not a requirement since these valves are typically set to either full-closed when the chiller is not in use or some other position (usually full-open) when the chiller is in use. Rarely are these valves actually modulated. Therefore, in this example, the modulating evaporator supply valve could be replaced with a simple isolation (full-open/close) type of valve. Another alternative would be to not automate these valves at all and require the provider's personnel to manually open these valves prior to starting the chiller. However, the modulating valve does provide some degree of flexibility in the system's operation, especially in variable primary systems.

The discussion above is based on the assumption that the local plant controller communicates to the onboard chiller controllers via a high-speed industrial network for both control and monitoring purposes. It is still common practice in the industry to hard-wire control signals and to use the high-speed industrial network

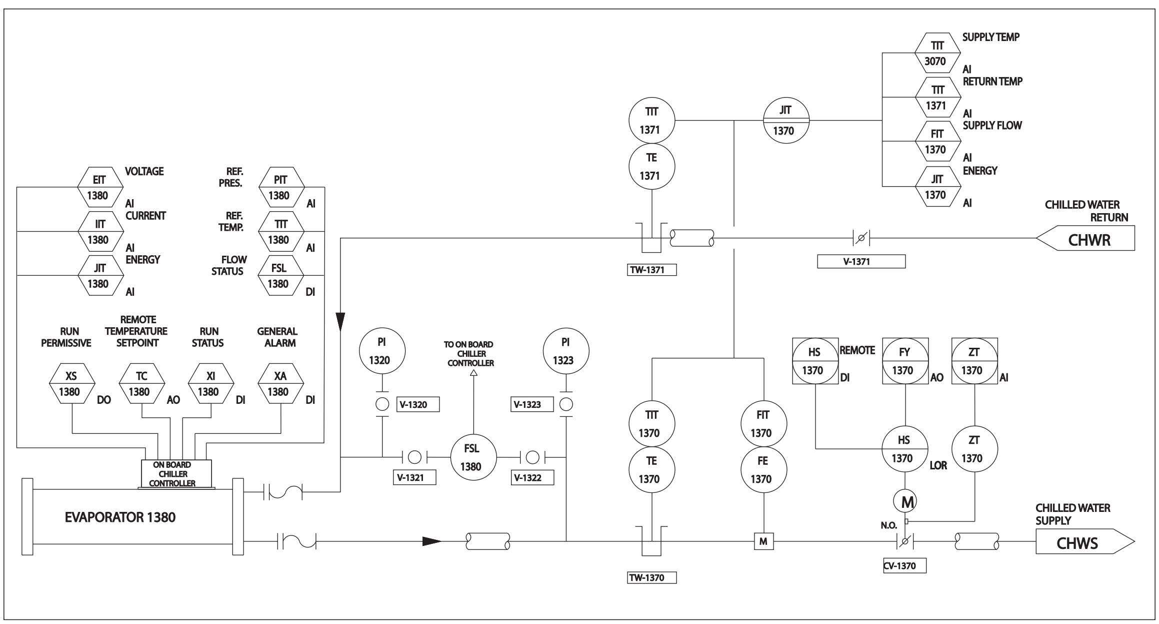


Figure 8-6. Chiller evaporator supply and return instrumentation.

for monitoring purposes only. However, with the increased reliability available in modern high-speed industrial networks, either approach (hard-wired or networked) is acceptable provided the network is robust and fail-safe.

If a provider requires that the evaporator supply and return pressures be monitored remotely as well as locally, indicating transmitters can be used and the local pressure gauges (PI-1320, PI-1323) can be removed.

Condenser-water systems

Figure 8-7 illustrates the recommended instrumentation for a condenser-water system. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, instrumentation should be in place to perform the following functions:

- Monitor the condenser-water supply (TIT-8010) and return temperatures (TIT 8011).
- Control the cooling tower fans and valves to maintain the condenser-water supply temperature (TIT-8010) to setpoint.
- Stage the cooling towers to meet the demands of controlling condenser-water supply temperature (TIT-8010) to setpoint.
- Monitor the outside-air temperature (TIT-8000) and relative humidity (MIT-8000). Calculate the outside-air wet bulb (MIY-8000) from these values.
- Stage the condenser-water pumps on and off based on the number of chillers running or the current flow requirements of the condenser-water loop.
- Maintain the cooling tower basin Level (LIT-9010, see section 8.9.1/Cooling towers) by controlling the makeup flow to the towers (AV-8020).
- Monitor the full-open/full-close status of the condenser-water makeup isolation valve (ZSO-8020/ZSC-8020).
- Allow operators to manually control the condenser-water makeup isolation valve locally at the valve, bypassing the DCICS altogether (HS-8020).
- Monitor the remote position of the condenser-water makeup isolation valve's open-close-remote (OCR) switch (HS-8020).
- Communicate with the chemical treatment system's onboard controller to obtain the following minimum information:
  - condenser water conductivity (AIT-8030)
  - condenser water pH (AIT-8031)
  - general alarm status (XA-8030)
- Use the same communication link to command the chemical treatment system to manually open/close the blowdown valve (AV-8030). Normally the chemcal treatment system's onboard controller will automaically control this valve based on condenser-water conductivity (AIT-8030).
- Monitor the condenser-water makeup flow (FIT-8020) and the blow down flow (FIT 8030). Totalize these values to calculate the total amount of water

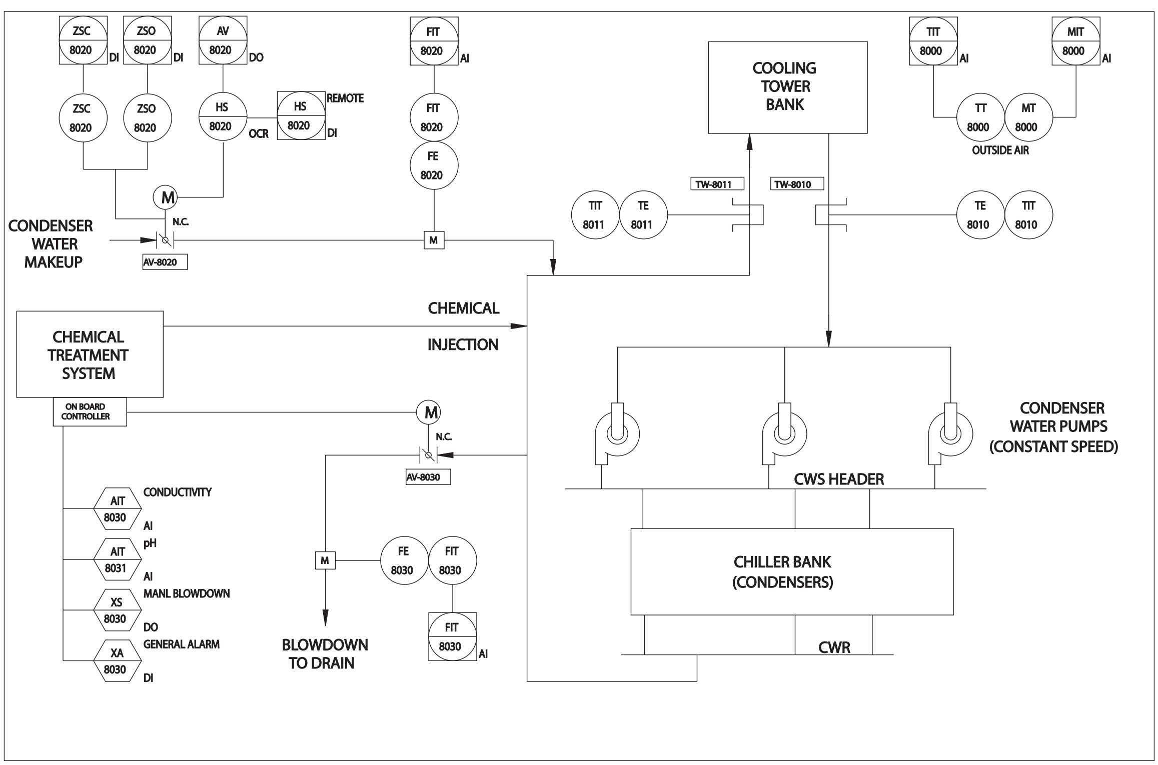


Figure 8-7. Condenser-water system instrumentation.

delivered to the plant (FIQ-8020) and the total amount of water sewered by the plant (FIQ 8030).

The proper selection of the condenser-water supply-temperature setpoint is the key to saving energy in the condenser-water loop. A setpoint that is too low will require more energy to maintain the setpoint while providing little or no impact to chiller efficiency. Conversely, a setpoint that is set too high will result in inefficiencies in the chiller's operation and may even cause it to trip off. The setpoint should be set to a value that is within the recommended range specified by the chiller manufacturer.

Using the calculated outside-air wet bulb (MIY-8000) to reset the condenser-water supply temperature within an acceptable range will also provide potential energy savings if implemented properly. A well-designed and implemented district cooling instrumentation and control system will support condenser-water supply-temperature reset.

Some water authorities offer credit allowances to their customers for water that is delivered to their customer's plants but is not sewered. In the case of a chilled-water production plant, this volume of water represents the water that is evaporated from the cooling towers. To qualify for the credit allowance some form of water usage documentation is usually required. A well-designed DCICS will allow the provider to take advantage of these credits when they are available. To calculate the amount of water evaporated from the cooling towers, the blowdown flow total (FIQ 8030) is subtracted from the makeup flow total (FIQ 8020).

Another way to decrease the operating cost of a chilled-water production plant is to research alternate sources of makeup water. Depending on the location of the plant this may be in the form of well water and/or condensate captured from other equipment.

Strategic selection and location of the chiller plant equipment (i.e., cooling towers, chillers) instrumentation and valves will allow providers in certain temperate climates to utilize free cooling during the colder months of the year.

A well-designed and implemented DCICS will be able to support one or more of the following methods of free cooling:

- refrigerant migration
- strainer cycle
- plate-and-frame heat exchanger

Cooling towers

Figure 8-8 illustrates the recommended instrumentation for a typical cooling tower. For clarity, the following

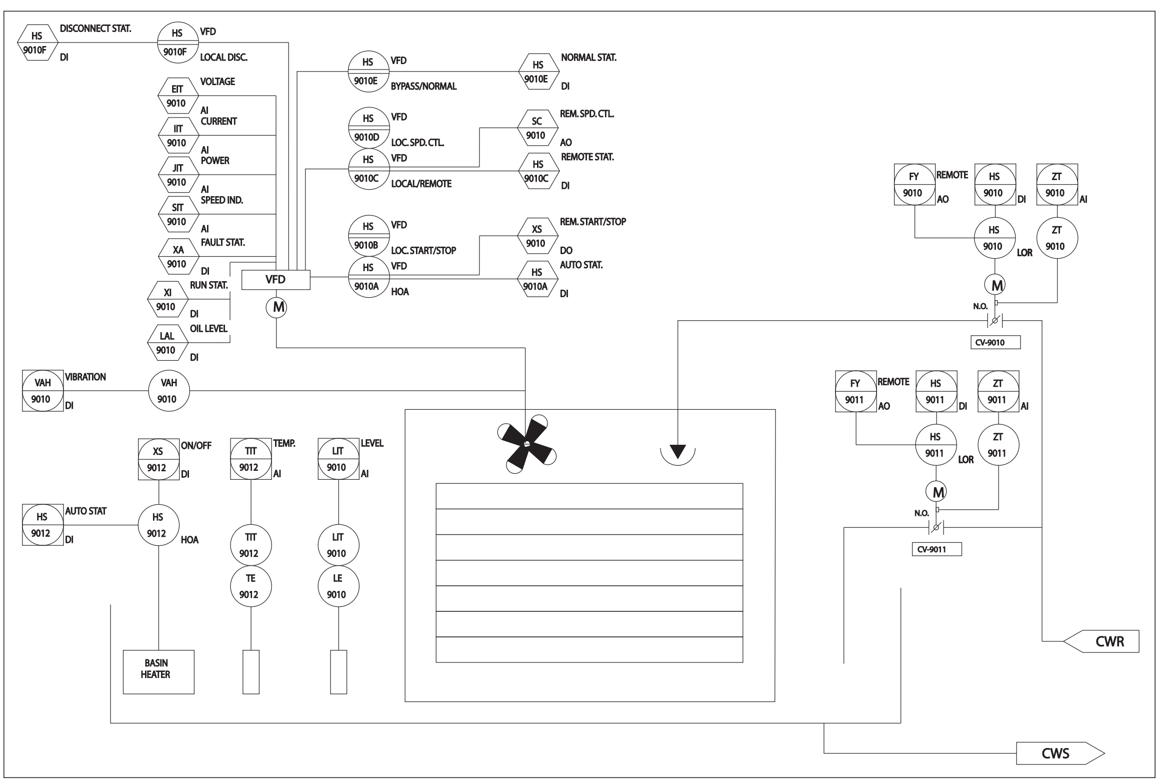


Figure 8-8. Cooling tower instrumentation.

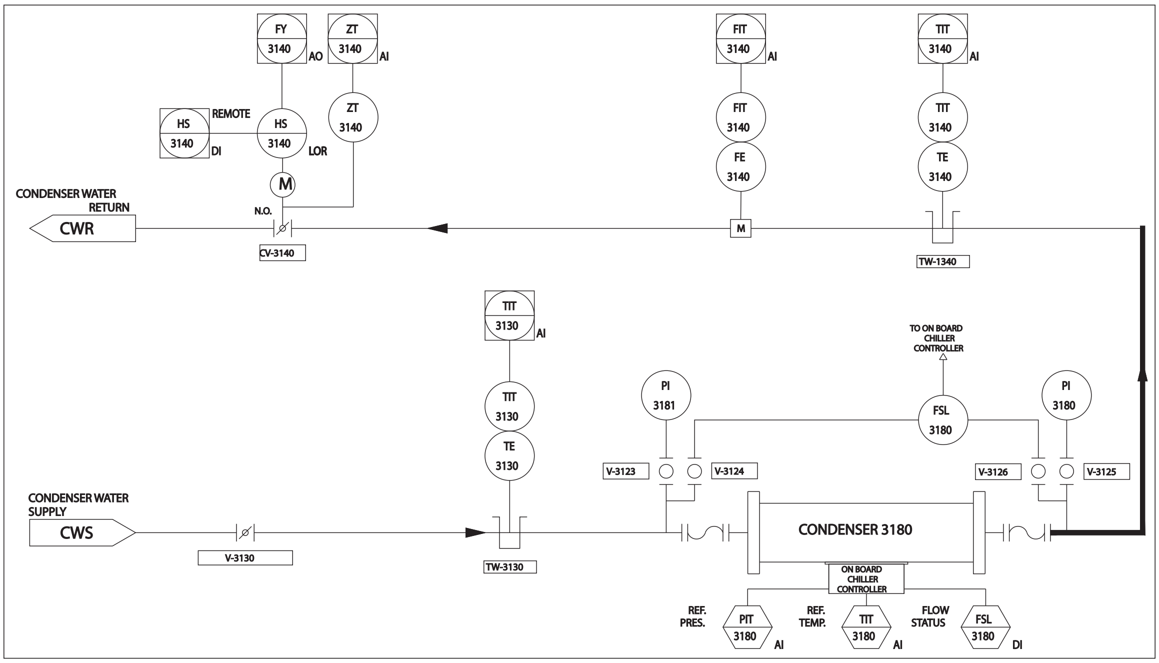


Figure 8-9. Chiller condenser supply and return instrumentation.

discussion refers to the tag names depicted in the figure.

At a minimum, the instrumentation should be in place to perform the following functions:

- Automatically modulate the cooling tower's supply valve (FY-9010) and bypass valve (FY-9011) to maintain condenser-water supply temperature to setpoint.
- Monitor the actual positions of the cooling tower's supply valve (ZT-9010) and bypass valve (ZT-9011).
- Allow operators to manually control the cooling tower's supply and bypass valves, locally at the valves, bypassing the DCICS altogether (HS-9010 and HS 9011, respectively).
- Monitor the remote status of the cooling tower's supply and bypass valves' local-off-remote (LOR) switches (HS-9010 and HS-9011, respectively).
- Stage the cooling tower fan as needed to maintain the condenser-water supply temperature to setpoint.
- Communicate with the cooling tower fan's VFD to facilitate the following minimum functionality:
  - Automatically start/stop the fan from the DCICS (XS-9010).
  - Monitor the fan's running status (XI-9010).
  - Monitor the fan's VFD fault status (XA-9010).
  - Automatically modulate the fan's speed from the DCICS (SC-9010) to maintain condenser-water supply temperature to setpoint.
  - Monitor the actual fan speed (SIT-9010).
  - Monitor the electrical voltage (EIT-9010), current (IIT-9010), and power (JIT-9010) being consumed by the fan.
- Monitor fan vibration sensor and oil level (VAH-9010, LAL-9010). Stop the fan if a high-vibration or a low oil-level situation exists.
- Monitor the temperature of the condenser water in the cooling tower's basin (TIT 9012) and turn the basin heater (XS-9012) off and on to maintain that temperature to setpoint.
- Allow operators to manually turn the basin heater off and on locally at the basin, bypassing the DCICS altogether (HS-9012).
- Monitor the auto status of the basin heater's hand-off-auto (HOA) switch (HS 9012).
- Monitor and maintain the level of the condenser water in the cooling tower's basin (LIT-9010) to setpoint by opening and closing the condenser-water makeup valve (AV-8020, see section 8.9.1/Condenser-water systems).

An alternative to monitoring the electrical energy being consumed by a plant's individual motors is to monitor the electrical energy at one or two locations, in the switchgear that feeds all of the motors, thus eliminating the energy meters at each motor.

It may be acceptable to some providers to install low-temperature and high/low-level switches instead of transmitters in the cooling tower basins.

Centrifugal chiller condensers

Figure 8-9 illustrates the recommended instrumentation for the supply and return piping to a single centrifugal chiller condenser. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, the instrumentation should be in place to perform the following functions:

- Automatically isolate the condenser's return from the condenser-water return piping with a modulating control valve (CV-3140).
- Monitor the actual position of the condenser-water return control valve (ZT 3140).
- Allow operators to manually control the condenser-water return control valve locally at the valve, bypassing the DCICS altogether (HS-3140).
- Monitor the remote status of the condenser-water return control valve's local-off-remote (LOR) switch (HS-3140).
- Monitor the presence of flow through the condenser (FSL-3180).
- Monitor the condenser head (refrigerant) pressure (PIT-3180).
- Control the condenser head pressure (PIT-3180) to setpoint by modulating the condenser-water return control valve (CV 3140) when the chiller is running.
- Monitor the condenser refrigerant temperature (TIT-3180).
- Monitor the flow (FIT-3140) and temperature (TIT-3140) of condenser water leaving the condenser and the temperature (TIT-3130) of the condenser water entering the condenser.
- Locally monitor the condenser-water supply (PI-3181) and return (PI-3180) pressures as close to the condenser as possible.

If a provider requires that the condenser supply and return pressures be monitored remotely as well as locally, indicating transmitters can be used and the local pressure gauges (PI-3180, PI-3181) can be removed.

Constant-speed pumps

Figure 8-10 below illustrates the recommended instrumentation for a constant speed pump. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, the instrumentation should be in place to perform the following functions:

- Automatically isolate the pump's supply with an isolation valve (AV/XS-1380).
- Monitor the full-open/full-close status of the pump's supply isolation valve (ZSO 1380/ZSC-1380).
- Allow operators to manually control the pump's isolation valve locally at the pump, bypassing the DCICS altogether (HS-1380).
- Monitor the remote status of the pump's open-close-remote (OCR) switch (HS 1380).
- Manually isolate the pump's discharge with an isolation valve (V-1389). Note that some providers may elect to automate this valve as well.
- Automatically start/stop the pump from the DCICS (XS-1341).
- Monitor the voltage (EIT-1341), current (IIT-1341) and power (JIT-1341) being consumed by the pump.
- Allow operators to manually start/stop the pump locally, bypassing the DCICS altogether (HS-1341).
- Monitor the auto status of the pump's hand-off-auto (HOA) switch (HS-1341).
- Monitor the status of the pump's local disconnect switch (HS-1342).
- Monitor the differential pressure across the pump (PDIT-1341).
- Locally monitor the pump's supply (PI-1341) and discharge (PI-1342) pressures as close to the pump as possible.

If a provider requires that the pump supply and discharge pressures be monitored remotely as well as locally, indicating transmitters can be used and the local pressure gauges (PI-1341, PI-1342) can be removed. In this scenario, the differential pressure transmitter

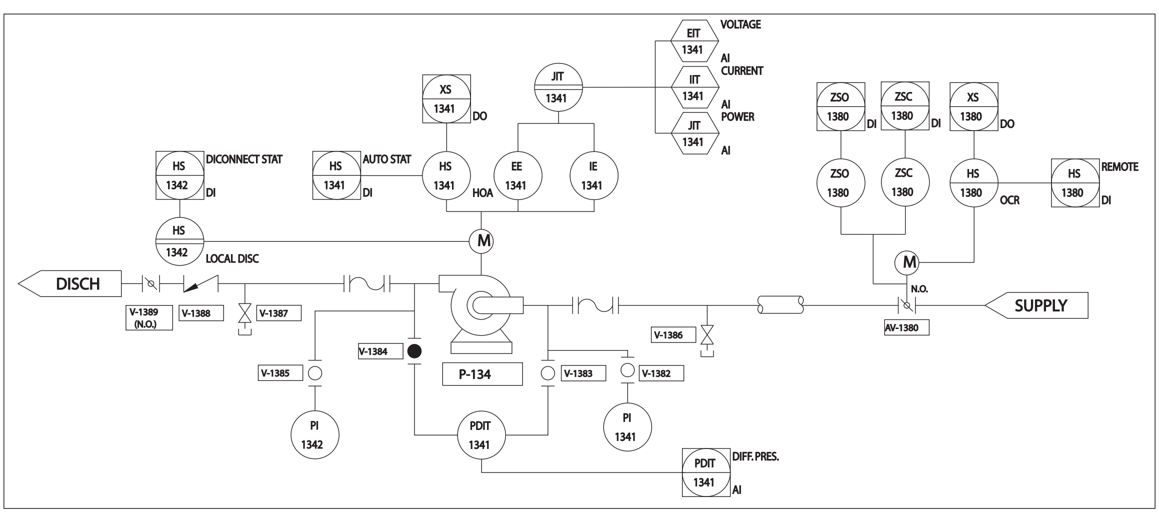


Figure 8-10. Constant-speed pump instrumentation.

(PDIT-1341) could also be removed and the DCICS could calculate the differential pressure from PI-1341 and PI-1342.

Variable-speed pumps

Figure 8-11 illustrates the recommended instrumentation for a single variable speed pump. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, the instrumentation should be in place to perform the following functions:

- Automatically isolate the pump's supply with an isolation valve (AV/XS-3020). Note that depending on where the pump is installed, the automated isolation valve may actually be on the pump's discharge; however, the following discussions assume an automated supply isolation valve and a manual discharge isolation valve.
- Monitor the full-open/full-close status of the pump's supply isolation valve (ZS 3020/ZSC-3020).
- Allow operators to manually control the pump's supply isolation valve locally at the valve, bypassing the DCICS altogether (HS-3020).
- Monitor the remote status of the pump's supply isolation valve's open-close-remote (OCR) switch (HS-3020).
- Manually isolate the pump's discharge (V-3021). Note that some providers may elect to automate this valve as well.
- Communicate with the pump's VFD to facilitate the following minimum functionality:
  - Automatically start/stop the pump from the DCICS (XS-3020).
  - Monitor the pump's running status (XI-3020).
  - Monitor the VFD's fault status (XA-3020).
  - Automatically control the pump's speed from the DCICS (SC-3020).
  - Monitor the actual pump's speed (SIT-3020).
  - Monitor the electrical voltage (EIT-3020), current (IIT-3020), and power (JIT-3020) being consumed by the pump.
- Allow operators to start/stop the pump locally, bypassing the DCICS altogether (HS-3020A/B).
- Monitor the auto status of the pump's hand-off-auto switch (HS-3020A).
- Allow operators to control the speed of the pump locally, bypassing the DCICS altogether (HS-3020C/D).
- Monitor the remote status of the pump's local-remote speed control switch (HS 3020C).
- Monitor the normal status of the VFD's bypass/normal switch (HS-3020E).
- Monitor the status of the pump's local disconnect switch (HS-3020F).

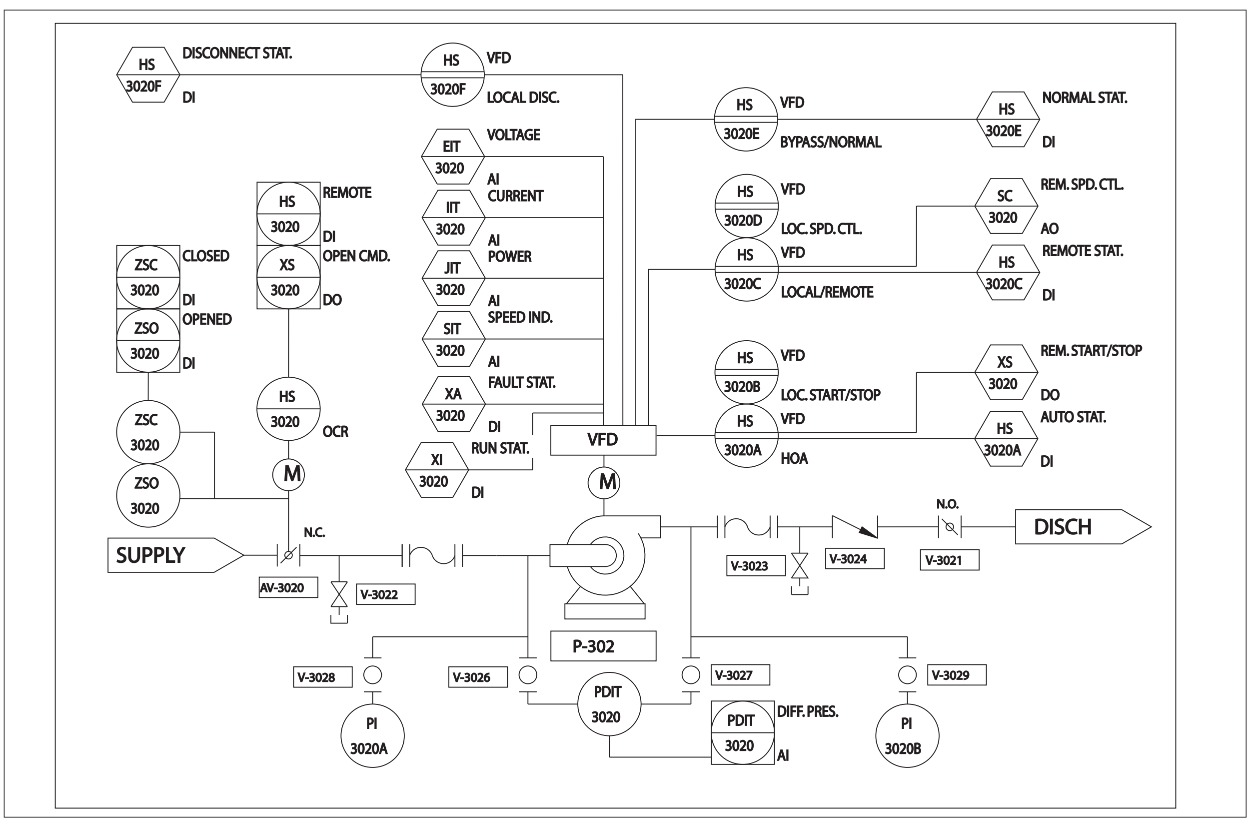


Figure 8-11. Variable-speed pump instrumentation.

This example uses a communication link to the VFD, not hard-wiring, making it a Level 1 device. Because of the wealth of information that is available from industry standard VFDs, this is usually the more cost-effective approach. The slight increase in cost of a 'network ready' VFD is more than offset by the installation cost of hard-wiring all of these signals. Some providers may elect to implement a hybrid approach, where all of the control signals (start/stop, speed control) are hard-wired, but a communication link is used to gather all of the other information. Still other providers may only hard-wire the control signals and not collect the other data at all.

Heat exchangers

Figure 8-12 illustrates the recommended instrumentation for a single heat exchanger utilized in a typical energy transfer station (ETS) application. For clarity, the following discussion refers to the tag names depicted in the figure.

At a minimum, the instrumentation should be in place to perform the following functions:

- Monitor the heat exchanger's customer-side supply temperature (TIT-2000).
- Automatically modulate the heat exchanger's provider-side return valve (FY 3000) to maintain the heat exchanger's customer-side supply temperature to setpoint.
- Monitor the actual position of the heat exchanger's provider-side return valve (ZT-3000).
- Allow operators to manually control the heat exchanger's provider-side return valve, locally at the valve, bypassing the DCICS altogether (HS-3000).
- Monitor the remote status of the heat exchanger's provider-side return valve's local-off-remote (LOR) switch (HS-3000).
- Monitor the provider-side supply flow (FIT-1000) and temperature (TIT-1000), the return temperature (TIT-3000) and the chilled-water energy (JIT-1000) being delivered to the heat exchanger by the provider.
- Monitor the heat exchanger's customer-side return temperature (TIT-4000).
- Monitor the approach temperature of the heat exchanger to trend heat exchanger performance.
- Locally monitor the pressures at each of the heat exchanger's ports (PI-1000, PI 2000, PI-3000 and PI-4000).
- Monitor the differential pressure across the provider's side of the heat exchanger (PDIT-1000). Ensure that this signal is communicated back to the controller in the plant(s) that supplies chilled water to this heat exchanger. The speeds of the distribution pumps in the plants should be controlled to main-

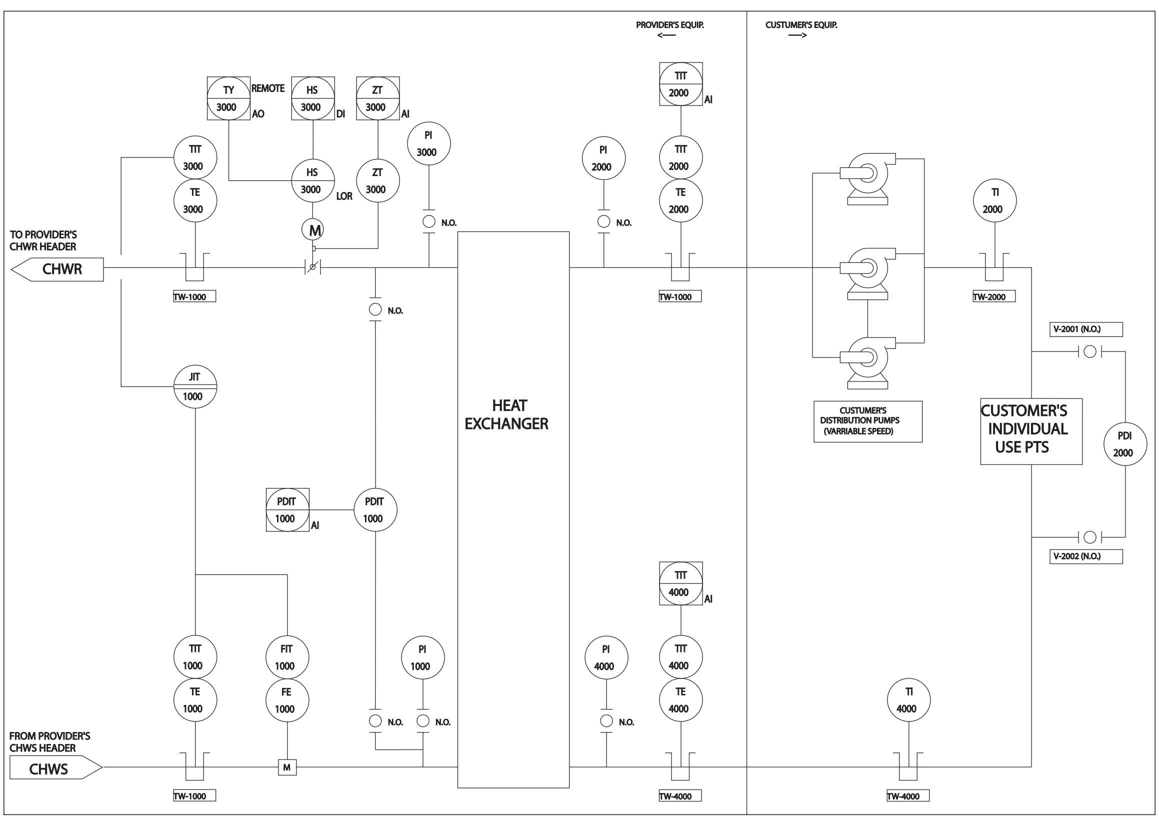


Figure 8-12. Heat exchanger instrumentation.

tain this differential pressure to setpoint (see sections 8.9.1/Primary-secondary systems and 8.9.1/Variable primary systems). This pressure can also be used to determine fouling of the heat exchanger.

- This example assumes that the customer-side equipment will be controlled by the customer's control system, not the DCICS. However, there may be rare situations where the provider will be called upon to control this equipment. Typically, the customer-side distribution pumps are staged on and off, and their speeds are modulated to control differential pressure across the customer's use points to setpoint. It may also be beneficial to monitor the actual positions of the customer's individual cooling coil control valves and to reset the differential pressure setpoint to more closely track current customer requirements. Actual space temperatures could also be used for this purpose. In any case, most customers will elect to control the equipment on their side of the heat exchangers with their own control system. As a result, this discussion is not applicable to the DCICS.

8.9.2 Level 0 vs. Level 1 – field instrumentation

The illustrations provided above are just examples and are not intended to stipulate that, if a particular field device is depicted as a Level 0 or a Level 1 device in the example, that it must be so specified in practice. The choice of whether to specify Level 0 or Level 1 field instrumentation, or a combination of both, is application-specific and should be handled on a case-by-case basis.

Table 8-6 lists some criteria that should be considered when making this decision.

Following are advantages to using Level 1 over Level 0 field instrumentation:

- Reduced installation costs (provided there are a large number of instruments and they are not located close together or to the controller they are connected to).
- Typically, Level 1 instruments provide more data to the DCICS than Level 0 instruments.
- A well-designed DCICS will allow properly trained personnel to "drill down" from higher networks to Level 1 networks to connect to a particula rfield instrument that may be having a problem, thus providing the ability to remotely troubleshoot the system.

The main disadvantage of using Level 1 over Level 0 field instrumentation is cost increases resulting from the fact that Level 1 instrumentation is typically more expensive then Level 0 instrumentation, and that programming and configuration costs are also usually higher. However, these costs are more than offset by savings in installation costs when there are a large number of instruments and they are located far way from each other and from the controller to which they are to be connected.

Due to the additional data that they provide, their inherent troubleshooting features, and the potential installation savings that can be realized by using them, the trend in the industry is to specify Level 1 field instruments whenever it is cost effective to do so.

8.10 Level 2 – Best Practices

The sections that follow present some guidelines for local Level 2 plant controllers. Local plant controllers provide the actual control and monitoring functions at the plant level by interfacing to Level 0, 1, 3 and 4 equipment.

8.10.1 Types of controllers

The different types of controllers that are typically used in a district cooling instrumentation and control system and the advantages and disadvantages of each type are discussed in section 8.5.3. To summarize, programmable logic controllers (PLCs) and distributed control systems (DCSs) are acceptable for most DCICS applications.

If the following is true…	**then select field instrumentation of this type:**	
	Level 0	**Level 1**
The field instrumentation count is small and the instruments are located in the same vicinity as the controller to which they will be connected (such as in the case of an ETS).	√	
The field instrumentation count is large or the instruments are distributed throughout the plant far away from the controller to which they will be connected (such as in the case of a large chilled-water production plant).		√
The field instrumentation provides more then one or two variables that must be accessed by the controller to which they will be connected, where hard-wiring all of these variables would be cost-prohibitive (such as in the case of energy meters and VFDs).		√

Table 8-6. Level 0 vs. Level 1 field instrumentation – selection criteria.

> The decision to use Level 0 or Level 1 field instrumentation is dependent on instrument count, instrumentation location with respect its controller and the amount of data available from the instrumentation.

Proprietary direct digital controllers (DDC) are better suited for commercial applications and are usually not used in a DCICS.

8.10.2 Selection criteria

The controller(s) selected should support at least one of the following pictorial programming languages:

- Function block diagrams
- Ladder logic diagrams
- Sequential function charts

High-level, general purpose languages, such as C, C++, Pascal, Fortran and Visual BASIC, while very powerful, should be avoided due to their complexity.

Regardless of the programming language selected, its instruction set must be robust enough to build the complex logic, math, sequencing, timing, counting, and other algorithms that are required in a typical DCICS application. Some of the control functions that are seen in different types of plants are discussed in section 8.14. The ability to create, modify, upload, download and save controller programs using an engineering workstation is recommended. Once stored in a controller, the programs and their associated data should be protected by battery and/or EEPROM, which prevents accidental loss in the event of a power failure.

The ability to make online changes to the controller's logic while the plant continues to operate should be required by all DCICS controllers.

The programming environment used by the controllers must support a broad range of debugging and troubleshooting tools including cross-referencing, advanced search-and-replace features, and data table lookups. Online program monitoring and tracing that graphically presents the different states and values of the program's instructions and the data they are operating on must be supported.

The controller selected must be able to process a large number of I/O points reliably and quickly. The I/O modules that the points are wired into should be configured through software (not DIP switches or jumpers) whenever possible. These configurations should be stored and downloaded with the controller's program.

> Key criteria to consider when selecting local plant controllers include available programming languages; the power of their instruction sets; their editing, debugging and documentation features; and their ability to perform engineering functions online.

> The programs that run on the local plant controllers should be able to be created, modified, uploaded, downloaded and saved from a Level 4 engineering workstation.

It is essential that the controller have a large internal variable capacity to perform the complex tasks typically required by a district cooling instrumentation and control system application.

Since the controller must communicate to many types of external devices (Level 1, 3 and 4 equipment), it must support a variety of communication protocols and media.

Most controllers are installed in harsh environments and must be capable of operating in those conditions. Following are typical environmental:

- Operating temperature: 0 C - 60 C (32 C - 140 F), typical
- Operating relative humidity: 5% RH - 95% RH (non-condensing), typical
- Others to consider:
  - vibration
  - shock
  - radiated RF immunity

8.10.3 Distributed controllers

For large plants it may be beneficial to design the plant's control system using distributed controllers as opposed to using one controller for the entire plant. That way, if a particular controller must be taken offline for any reason, only those devices that are controlled by that controller must be operated manually in order to keep the plant running, instead of all of the devices in the plant, as is the case if a single controller is used.

For example, controllers could be distributed in a large chilled-water production plant as follows:

- Controller 1 – Cooling tower controller
- Controller 2 – Condenser water loop controller
- Controller 3 – Chilled water loop controller
- Controller 4 – Balance of plant controller (HVAC, electrical energy monitoring, chemical feed system monitoring and control, etc.)

8.10.4 Controller redundancy

For critical plants, redundant controllers should be used. Most manufacturers of PLC systems and DCSs offer redundant controller options. Redundant controllers eliminate a single point of failure, allow one controller to be serviced while the other controller continues to

Local plant controllers should have large I/O and internal memory capacities and be able to process their inputs and outputs and scan their programs many times a second.

operate the plant, and can eliminate the need to install many distributed controllers (see previous section).

One of the key design factors to consider when deploying redundant controllers is setpoint synchronization. If an operator makes a setpoint to the master controller, it must be copied to the backup controller, or unpredictable operation may occur when the controllers are switched.

Redundant controllers will also typically require additional programming and a mechanism must be put in place at the Level 4 data servers in order for them to switch to the current master controller for their data.

8.10.5 Critical data integrity

Some of the data gathered by a DCICS is critical to the provider's business (i.e., billing and efficiency data). The financial impact to the provider if this data is lost can be disastrous. For this reason, critical data should be collected and stored locally at the controller to which the metering instrumentation is connected, so that if the connection to the historical data server is lost, the data will not be. When the connection is restored, the data that was stored while the connection was down can then be forwarded.

Since there is no way of anticipating how long the connection between a plant controller and its historical data server will be down, controllers that collect and store critical data should be equipped with flash cards, read-writeable CD/DVDs or some other removable non-volatile storage media. The plant controller should periodically backup critical data to this media. Procedures should be in place for restoring data in the event that a controller needs to be replaced.

Redundant controllers should be installed in critical plants.

A good rule of thumb is that controllers that perform metering functions should store their metering data internally as follows:

- current daily totals
- last 30-day totals
- current monthly totals
- last 12-month totals
- current yearly totals
- last 10-year totals

8.10.6 Time-of-day synchronization between controllers

All of the controller real-time clocks in a highly distributed DCICS application should be synchronized to a single source. This is very helpful in determining the sequence of events that occur during major system upsets. If the real-time clocks are not synchronized between plants, it may be impossible to determine what the root cause of the upset was.

Critical metering data should be collected and stored 'at the lowest possible' point. This is typically at the controller to which the metering instrumentation is connected (i.e., an ETS controller).

Time synchronization may be as simple as tying all of the controllers to a central time controller that periodically updates all of the remote controllers to its internal clock or as complex as connecting all of the controllers to IRIG-B satellite signals.

8.10.7 Controller power requirements

Since controllers provide all of the low-level control and monitoring functions for the plants in which they are installed, the power feeding these controllers (and their I/O racks and modules as well) should be backed up by emergency generators and/or uninterruptible power supplies (UPS).

Emergency generators require the use of an automatic transfer switch (ATS) to automatically toggle between normal power and the emergency power being produced by the generator(s) that is started when normal power is lost. The automatic starting of an emergency generator and the activation of the ATS takes time (<30 seconds typically). A UPS is needed to keep the controller energized for the short amount of time required to start the generator and transfer to emergency power. The UPS should be sized to keep the controller energized during this short power transitional period.

Emergency generators and/or uninterruptible power supplies should be installed for all critical controllers.

There may also be situations where an emergency generator is not available at a particular plant. In these situations a UPS is required and should be sized to keep the controllers energized for a much longer period of time. The length of time is dependent on the individual provider's requirements.

The UPS should

- be industrial grade;
- have power conditioning and filtering capabilities;
- have the capability to shield control equipment

from voltage transients, line noise, spikes, surges and fluctuations;
- have the ability to annunciate its status to the DCICS by way of hard-wired I/O or communications; and
- be equipped with automatic maintenance bypass capabilities to ensure continued power to the load-side equipment in the event of battery failure or battery replacement maintenance.

> Level 3 OITs allow personnel to monitor and control plants locally at the plants. They should not be dependent on any Level 4 equipment to communicate with their associated plant controllers.

8.11 Level 3 – Best Practices

The sections that follow present some guidelines for the local Level 3 operator interface terminals (OITs).

Local OITs are installed directly on the plant floors close to the equipment they control and monitor. When a district cooling provider does not use Level 4 equipment, the local OITs provide the only means for personnel to interface to the DCICS and serve as secondary interfaces in the event that the link to the Level 4 equipment is lost.

8.11.1 Connecting local OITs to local controllers

Local Level 3 OITs should be coupled as tightly to the local plant controller(s) as possible and should not rely on Level 4 equipment (servers, hubs, switches, routers, etc.) to communicate to those controller(s). This ensures that the plant can continue to operate in the event of a loss of connectivity to the Level 4 equipment.

8.11.2 Displaying metering data on local OITs

If a controller is collecting metering data (i.e., an ETS controller), the local OIT(s) connected to that controller should display the metering data in a tabular format so that readings can be taken manually in the event of an extended down time with the Level 4 equipment.

A well-designed DCICS should permit manual readings to be entered into the historical data such that automatic and manual readings can be queried together to generate concise usage reports.

8.11.3 Environment

Local OITs are typically installed in harsh environments, directly on the plant floors, near the equipment that they control and monitor. The local OITs and the enclosures in which they are mounted must be rated for these types of environments. The use of standard office-grade, user-input devices, such as mice and keyboards, is not acceptable in most situations. Instead, the OITs should be provided with waterproof membrane-style keyboards and pointing devices. Touch-screen technology is also recommended whenever possible.

8.11.4 Local OIT power requirements

The local OITs should be backed up by the same emergency generators and/or uninterruptible power supplies (UPS) that back up their associated controllers.

8.12 Level 4 – Best Practices

The terminologies, hardware and software used by different suppliers of Level 4 equipment vary greatly. The sections that follow present best practice tips for the design and deployment of the Level 4 equipment depicted in the sample DCICS that was introduced in section 8.6. Although the terminology and components may vary from one supplier to another, the principles presented here can be applied across the board to Level 4 equipment from any supplier.

> Data servers are perhaps the most critical Level 4 component. They should be highly fault-tolerant and should be installed in redundant pairs

Level 4 equipment is typically comprised of server-class computers, similar to those found in data centers around the world; personal computers, such as desktops, towers and laptops; network infrastructure equipment, like hubs, switches, routers and firewalls; and the necessary software to allow these devices to perform their specified functions. Table 8-7 provides best practice tips for the computer hardware and software aspects only. Best practice tips for network infrastructure equipment are discussed in section 8.13.

8.13 Networking Best Practice Considerations

8.13.1 DCICS network categories

The networks that facilitate communications between the different district cooling instrumentation and control system components can be categorized as shown in Table 8-8.

Level 1 networks are used to interface Level 1 equipment to their associated Level 2 controller(s). These networks are usually self-contained within a single plant, are high-speed and are secure by nature. Section 8.8.8 provides some best practices to consider when designing and deploying Level 1 networks.

Level 2+ controller networks are used to connect Level 2 controllers together and to connect Level 2 controllers

Level 4 Component	Topic	Best Practice Tips
Data Server(s)	Hardware	The role of the data server implies its criticality. If its hardware is improperly specified, it can become a single point of failure that prevents personnel from interfacing with their equipment and can result in loss of data. A well-designed data server will ● be a server class machine, running a server-class operating system; ● have large amounts of random access memory (RAM); ● have multiple processors (if the operating system and application software can exploit them); ● incorporate hard-drive fault tolerance (minimum RAID Level 1); ● have redundant power supplies; ● have redundant cooling fans; and ● have a minimum of two network interface cards (NIC): ■ one to communicate with its associated controllers over the controller network. ■ one to communicate with the balance of the Level 4 equipment over the data network. ■ one to communicate with the balance of the Level 4 equipment over the data network.
	Redundancy	To further decrease the likelihood of a data server becoming a single point of failure, multiple data servers should be installed in redundant and highly available configurations. In these types of configurations, at least two data servers are used. One is designated as the master and the other(s) is designated as the backup(s). Normally, all of the other Level 4 servers and workstations communicate with the master data server for their data. However, if the master data server should fail, all of the other Level 4 servers and workstations should automatically switch to the backup data server for their data. Fallback to the master data server upon its recovery can be automatic or manual, depending on the district cooling provider's preference. How historical data collection is handled when redundant data servers are used is also a key design concept to consider. Normally, only the master data server should log historical data to the historical server, not the backup(s). This prevents duplicate data from being written. When the backup data server detects that the master data server is down, it must automatically pick up the data logging responsibilities and begin to log historical data to the historical server. When the master data server is restored, normal data logging should resume automatically. Every record written to the historical server should be date- and time-stamped and should be flagged with the name of the data server that logged the record.
	Historical data – "store and feed forward"	If the data server that is currently logging to the historical server is operating properly, but loses its connection to the historical server, it should begin to store data to its local hard drive. This is why fault-tolerant RAID drives are recommended for data servers. When the connection to the historical server is restored, the data that was logged locally on the data server should be automatically copied to the historical server. When it is confirmed that the data has been copied successfully to the historical server, it should be removed from the data server so that duplicate records do not exist in the system.
	Power	All data server(s) should be powered by an uninterruptible power supply (UPS) that is in turn backed up by an emergency generator.
	Software	The software that runs on a typical data server varies greatly from one supplier to another, and any attempt to specify best practices for it is beyond the scope of this chapter. However, some typical software applications that run on data servers are listed below: ● I/O drivers – programs that communicate to the Level 2 controllers and serve the data accessed up to other applications that are running on the data server. OPC servers are the most common type. ● real-time process-variable database management applications (scanning, scaling, alarming, etc). ● visualization software – graphical user interface screens ● alarm handling software

Table 8-7. Level 4 componentry best practice tips. *Continued*

Level 4 Component	Topic	Best Practice Tips
Data Server(s) (continued)		• historical data collection software • historical data trend display software • reporting software
Historical Server	Hardware	The criticality of the historical server depends on the "value" that the provider places on the data being collected and stored. The following criteria should be addressed when determining the "value" of the data: • Why is the data being collected and stored? For maintenance and troubleshooting? To determine plant efficiencies? For customer invoicing? • What is the required data collection rate? • How long must the data be retained? A historical server that is collecting and storing "critical" data should • be a server-class machine, running a server-class operating system; • have large amounts of random access memory (RAM); • have multiple processors [if the operating system and historical data acquisition (HDA) software can exploit them]; • incorporate hard-drive fault tolerance (minimum RAID Level 1); • have ample hard drive space to store the large amount of data that is required by a typical DCICS; • have redundant power supplies; • have redundant cooling fans; and • have a minimum of two network interface cards (NIC), with both connected to the associated data network for communication fault tolerance and increased bandwidth.
	Redundancy	As long as the following criteria are met, historical server redundancy is not required: • Fault tolerant hardware is specified for the historical server (see above). • Redundant data servers are deployed, and they log data to the historical server as described above. • The data servers utilize a "store-and-feed-forward" data collection approach when logging to the historical server (see data server section above), ensuring that data will not be lost if the connection to the historical server is lost for any reason. • The data being logged to the historical server is backed up periodically and taken off site.
	Power	All historical server(s) should be powered by an uninterruptible power supply (UPS) that is in turn backed up by an emergency generator.
	Software	The storage file format built into most historical data acquisition (HDA) applications is proprietary and can vary from supplier to supplier. However, most modern HDA software packages support interfacing to third-party, non proprietary relational database server applications as well. This is the recommended storage file format for a DCICS. The selection of storage file format is very important since the data that the file stores will not only be accessed by other DCICS applications, but also by third-party, Level 5 systems (i.e., accounting, maintenance and billing systems). Most Level 5 systems should support issuing SQL queries against relational databases that will make accessing the data much easier than if proprietary files are used. Proper initial design of the storage file format and how the Level 5 applications will access the stored data can make integration much easier down the road, and can lead to ongoing savings in data maintenance. The relational database server application selected should be enterprise class, support many simultaneous connections and users, provide audit trails of all database activities and allow easy access to data by third-party applications using SQL queries. It should be capable of handling the large number of records that a typical DCICS will generate quickly and efficiently. Some acceptable relational database server applications include Microsoft SQL Server, Oracle RDBMS and OSIsoft PI.

Table 8-7. Level 4 componentry best practice tips. *Continued*

Level 4 Component	Topic	Best Practice Tips
Historical Server (continued)		Logging rates and data retention requirements should be defined during the detailed design of the DCICS. This will determine the size of the mass storage device(s) that the historical server requires.
	Data security, backup and restoration	Data security, backup and restoration activities are also important factors to consider when specifying and implementing a historical server for a DCICS. Depending on the "value" of the data, backups should be performed at regular intervals and stored off site. Following are examples of robust backup procedures: ● Automated backup to tape or other removable media performed locally at the historical server's location. Maintained by the owners of the DCICS. ● Automated backup to corporate backup servers, which in turn are backed up by other systems. Requires ongoing coordination with the IT department that owns the backup equipment, but otherwise should be transparent to the owners of the DCICS. Regardless of how the data is backed up, detailed restoration procedures must be in place that allow backed-up data to be restored and analyzed while the DCICS continues to collect historical data, real-time.
Terminal Server	Hardware	Terminal servers host applications for users who connect to them remotely. The applications are started and manipulated by the remote users, but the applications actually run on the terminal server. This allows the remote users to access the applications without having to install them locally on their computers. All that is typically needed is a standard Web browser and proper security credentials in order to access the applications on the terminal server. Due to the fact that many applications may be running on the terminal server at the same time, one of its most important specifications is the RAM it has. The more simultaneous applications that are run, the more RAM that is needed. Following are characteristics of a well-designed terminal server: ● Is a server-class machine, running a server-class operating system. ● Has large amounts of RAM. The maximum amount available for the computer being specified should be considered for a terminal server if many remote users will access it simultaneously. ● Has multiple processors (if the operating system and application software can exploit them). ● Uses standard hard drives (i.e., fault-tolerant RAID drives are typically not a requirement). ● Is equipped with standard power supplies and cooling fans (redundant power supplies and fans are not typically required). ● Has a minimum of two network interface cards (NIC), with both connected to the associated data network for communication fault tolerance and increased bandwidth.
	Redundancy	Redundancy is not typically a requirement for a terminal server unless it is critical to the provider's business activities that remote users be able to access the DCICS at all times. Data server, historical server and DCICS workstation operation should not be impacted by the loss of a terminal server. Only remote user access should be affected.
	Power	All terminal server(s) should be powered by a UPS, which is in turn backed up by an emergency generator.
	Software	Most software manufacturers who write software that can be run on a terminal server license it based on the number of concurrent users. Licensing must be thought about carefully. If there are not enough concurrent licenses available, then everyone who needs remote access to the system will not be able to get it. If there are too many concurrent licenses then the first-time cost of the terminal server software will be unnecessarily high.

Table 8-7. Level 4 componentry best practice tips.

to their Level 3 OITs and Level 4 data servers. Level 2+ data networks are used to connect Level 4 data servers to other Level 4 servers and workstations and to tie all of the local controller networks in a provider's district together. Level 2+ networks can span multiple plants and sites, and in the case of the central data network presented in the sample DCICS in section 8.6, may extend to all of the plants and command centers.

Network Category	Example networks introduced sample DCICS in section 8.6
Level 1 Networks	Remote I/O networks Energy monitoring networks Chiller controller networks VFD networks "Smart" transmitter networks
Level 2+ Networks	Controller networks Data networks
Level 5 Networks	Corporate networks (not in the scope of this chapter)

Table 8-8. DCICS network categories.

The sections that follow provide some best practices to consider concerning the specification, design and installation of Level 2+ networks.

> Level 2+ networks facilitate communications between Level 2, 3 and 4 DCICS components. They also provide a link to the Level 5 equipment and applications that run on the district cooling provider's corporate network.

8.13.2 Level 2+ network infrastructure

Level 2+ network design and deployment will depend strongly on the infrastructure already in place. Options applicable to an existing (expanding) system will be different than options for a brand-new system. The following addresses a brand-new district cooling system where there is the flexibility to create a grassroots Level 2+ network infrastructure. This infrastructure could take one or more of the following forms:

- dedicated fiber optics
- shared fiber optics
- wireless (radio frequency)
- World Wide Web through Internet service provider
- World Wide Web through leased line (dial up telephone line connection)

When selecting the infrastructure the two most significant parameters are reliability and security. Although cost is an important element, it needs to be considered in terms of satisfying reliability and security.

Monitoring requires less reliability and security than does control. If a connection for monitoring an energy meter is lost, then the data will have to be retrieved locally from the meter. Although inconvenient, it is not disastrous. However, if the provider depends on the communication backbone to control equipment and the connection is lost, then the impact might not be known until it is too late to do anything about it. It should be noted that control is actually done at the local plant controller – Level 2. Even when a satellite plant is "controlled" remotely, the remote input is to issue requests to control equipment and to change setpoints. The actual control and setpoint maintenance is done by the local controller.

Fiber optics

From the reliability/security perspective, the best solution would be to install a fiber-optic system dedicated to and controlled by the provider. Fiber optics is the best backbone for speed, flexibility and maintainability, but it has the disadvantage of higher first cost. If a fiber-optic system is (or will be) already in place in the district cooling provider's district, then sharing bandwidth might be a feasible alternative. However, the provider should assume some security and privacy will be lost. Alternatively, the provider could install the fiber-optic system and then lease bandwidth to others. That way the provider could exert greater control over its operation, at least in theory. Generally, fiber-optic systems will be more expensive than wireless and Internet options. However, costs can be reduced if the fiber can be installed with the district cooling piping in new installations.

> A dedicated fiber-optic system is the most robust, reliable and secure communication backbone.

Although fiber is the most secure of the options, it can still be "hacked." Unlike the other options, hacking into a fiber system requires the intruder to be physically present at some location where the fiber can be tapped into.

Wireless

Wireless is one alternative to fiber optics. Before proceeding with wireless technology, it would be advisable to confirm government regulations concerning licensing of radio frequencies. The financial benefit of using wireless technology could be lost if franchise fees become excessive or if government approval becomes bogged down by an inexperienced bureaucracy. Although most utility companies use wireless technology in some form to monitor meter readings, it is not commonly used for control. Wireless connections are limited to 1 or 2 km unless repeater stations are installed. Antennas require line of sight; that is, a clear shot without hills or buildings. It is important to remember that installation of antennas will require approval from the building owner if the building is not owned by the district cooling provider.

Wireless systems can be hacked from the curbside using a laptop, making it a much less desirable option then fiber optics, but it is still acceptable provided the appropriate security measures are put in place.

Internet

Monitoring and control through Internet connections is also fairly common. Service through an Internet provider's high-speed infrastructure should be much quicker than through a leased line and would be the better Internet choice. Regardless, the connectivity to the satellite plants will depend on the quality of the Internet connection. If the Internet connection is weak, these options should not be considered.

Hacking through the Internet is extremely convenient as the intruder can do it any time from any place in the world, making it a much less desirable option than fiber optics, but it is still acceptable provided the appropriate security measures are put in place.

> Often the decision to staff individual plants or to monitor and control them remotely from a central location is based on the pool of competent operators available.

8.13.3 Remote control vs. manning individual plants

The preceding discussions assumed a brand-new system into which the DCICS Level 2+ network infrastructure would be deployed. The reason the Level 2+ network infrastructure is needed at all is so the district cooling provider can remotely monitor and control any or all of their plants from a central location. The question then is why it would be desirable to control multiple plants from a central location. The two most common reasons are staff cost and staff competence. If competent operators are available at reasonable labor rates, then it might be best to staff each plant with operators for all or significant parts of the day. If operators are also mechanics and electricians, then job duties could be shared, with obvious benefits in cost and time. However, if there is not a sufficient pool of competent operators, it may be beneficial for the provider to control and monitor many plants from a central location.

Controlling from a central location removes significant portions of the staffing problems. By having a small group of qualified operators in one location, several plants can be controlled and the labor cost can be spread over more units of production. Additionally, methods and procedures can be standardized within a smaller group of people in a central location. Training operators is also more convenient.

The key element to the success of remote control is having a fairly sophisticated DCICS Level 2+ network infrastructure in place.

8.13.4 Sophistication

When controlling from remote locations, it is critical that process variables be available to the remote operators on a timely basis. When the plant is locally manned, an operator may detect a problem developing simply by the sound a machine is making, an unusual odor or any symptom that can be physically sensed. These human senses are impossible to replicate with sensors and computers. Thus, any time a plant is operated remotely, the provider is putting itself at a potential risk.

The extent of the risk depends on the plant's complexity. On the complex side, a diesel electric generation plant with steam heat-recovery generators and absorption chillers would be a difficult plant to control safely from a remote location. On the simple side, an electric centrifugal chiller plant could be safely controlled from a remote location (this is often done). Since the most complex procedure is starting up a system, if the startup is to be initiated remotely, then the controls will have to be appropriately sophisticated. For example, if a steam turbine drive is to be started remotely, then the procedures for draining and warming must be available to the remote operator.

> When remote control is done from a central location, the DCICS and its associated Level 2+ network infrastructure must be robust and relatively sophisticated.

It is also important to point out that local government code and regulations may require staffed operation for plants that use certain types of refrigerants.

8.13.5 Performance

Once the plant complexity is determined, then the task is to develop a district cooling instrumentation and control system Level 2+ network infrastructure that is economical and meets acceptable risk levels. The term "acceptable risk level" is deliberately ambiguous, as the district cooling provider must define this term based on its specific conditions and aversion to risk. Performance criteria to consider when specifying a Level 2+ network infrastructure are

- data throughput,
- reliability and
- security.

8.13.6 Security

Security on any type of distributed system, like a large-scale DCICS, needs to be implemented at the hardware and software levels and needs to be as robust as possible to prevent unauthorized access, either accidental or malicious.

On the hardware side, secure/intelligent hubs, switches, routers and firewalls that can be configured to limit access to authorized people and/or computers should be used extensively.

On the software side, security should be implemented at the operating system level using the most modern, robust security schemes available. Items such as unique and complex user names and passwords and password expiration should be considered. In general, all of the security-related recommendations made by the operating system's manufacturer should be followed closely.

Ring-type network topologies should be deployed whenever possible to help prevent a single point of failure from affecting large segments of the network.

The operating system must provide a means of auditing who logged into the system and when. It should support multiple user levels and have the ability to assign users to groups. A user assigned to a particular group should inherit all of that group's privileges.

On a large, highly distributed DCICS, it is important that the security information for the entire system be stored at a central location that is accessible remotely by authorized administrators. This allows users to be added, removed or have their privileges modified from one location instead of physically traveling to all of the plants and command centers to do it.

Modern virus protection software should be deployed and updated regularly on every applicable DCICS component to detect, prevent and remove threats posed by external sources.

8.13.7 Physical network topologies

Multi-drop and trunkline-type network topologies should be avoided since a single break in the network cabling or a failure in a single network interface device has the potential to affect communications to large portions of the network.

Instead, ring-type topologies should be used. This style of network topology provides two paths of communications from any point to any point, so if a cable does break or a single network interface device does fail, network operation will be minimally affected.

8.13.8 Network monitoring via OPC

Many of the network interface devices (hubs, switches and routers) that are available in today's market support network monitoring via OPC (OLE for process control). Some of the data typically available includes

- device status,
- link status and
- network statistics.

The ability to read this information using an OPC server allows it to be incorporated into most modern HMI applications where it can be trended, alarmed and displayed along with all of the other process data being accessed. Separate applications (other than the appropriate OPC server) are not required to access this data. It can be embedded into the same HMI application that is used to control and monitor the rest of the equipment in the district cooling provider's plants.

8.13.9 Network bridging and controller pass-through

Network bridging and controller pass-through are two concepts that should be supported by a well-designed and deployed DCICS.

Network bridging involves 'hopping' from one network (or network segment) to another network (or network segment) through a network bridge. The network bridges used should be intelligent devices that can be configured to limit access to authorized personnel and/or authorized computers only.

Controller pass-through technology allows authorized users to connect to one communications port in a controller's rack, 'pass through' the rack's back-plane, and go out through another port to access devices on a completely different network. Proper pass-through technology allows seamless connectivity between two dissimilar networks that may use different media and/or protocols, as well as between two similar networks.

An example of network bridging and controller pass-through will further clarify these points. Referring to the sample DCICS presented in section 8.6, let's say that an authorized user whose computer resides on the provider's corporate network needs to access an energy meter in order to reconfigure it. The energy meter resides on the energy monitoring network at the ETS in Plant-F2. Users would log on to their computers, 'bridge' from the corporate network to the DCICS central data network, 'bridge' again to the DCICS local controller network that services Plant-F2 and connect to a port on one of the communication modules in the ETS controller's rack. From there the user would 'pass through' the controller's back plane and go out through

The use of network devices that support the ability to monitor network health and statistics via an OPC server is highly recommended.

a different port to access the energy monitoring network in Plant-F2. Finally, the user would access the energy meter needed to configure over the Plant-F2 energy metering network.

The example above illustrates the power of network bridging and controller pass through from a serviceability point of view. Personnel do not need to travel to the individual plants to service the equipment in them. With this power also comes the potential for malfeasance by unauthorized personnel, so robust security measures must be put in place if network bridging and controller pass through are implemented.

8.13.10 DCICS network and Level 4 equipment ownership

Most large providers have internal Information Technology (IT) departments that operate and maintain the networking equipment, servers and workstations on the district cooling provider's corporate network.

While IT departments provide an invaluable service to the provider's overall operation, they should not be the department that 'owns' the DCICS network equipment, servers, or workstations unless they are made aware of the criticality of this equipment and agree to modify their standard operating procedures where this equipment is concerned. Most IT departments have procedures in place that if applied to an operational district cooling instrumentation and control system could render it inoperable.

For instance, a typical task that IT departments perform on a regular basis is to shut down network hubs for maintenance. This is fine on the corporate network where the shutdown can be scheduled during off hours and the impact to the provider's operation is minimized. However, shutting down a DCICS hub, regardless of the time of day, can have disastrous consequences, resulting in loss of visibility to one or more plants.

Another typical IT function is to automatically download patches and updates to the servers and workstations on the corporate network. This is a valuable service that IT departments provide. It helps to keep the provider's corporate computers up to date with the most recent versions of software and free of viruses. However, the software implemented in a typical DCICS is designed, deployed and tested using certain revision levels of operating systems and other software. If this software is updated without first testing the updates in a controlled environment, the entire DCICS may stop working.

The choice of what department owns and operates the DCICS network infrastructure is left up to the individual provider, but it is important to emphasize that special care must be taken when servicing any piece of DCICS network equipment.

It should be pointed out that the data being generated by a typical DCICS needs to be made available to systems that run on the provider's corporate network, such as billing and accounting systems. For this reason the two departments (DCICS and IT) will need to interface regularly and a high level of cooperation needs to be maintained between the two.

The standard operating procedures that most IT departments have in place work well in a corporate networking environment, but if applied to DCICS level 4 and networking equipment could result in failures of large parts of the system.

Another example of DCICS equipment interfacing to IT equipment has to do with archiving critical data. Some providers may elect to back up DCICS generated data to corporate backup servers, which themselves are automatically backed up to removable media and taken off site for permanent storage. This automatic backup function is a service that most IT departments provide and if available should be taken advantage of by the DCICS because it will eliminate the first-time and ongoing costs of installing and operating a backup system solely for the district cooling instrumentation and control system. However, it further stresses the need for cooperation between the two departments (DCICS and IT).

8.13.11 DCICS Level 2+ network component power requirements

DCICS Level 2+ networks allow large portions of the DCICS to communicate with each other. Without proper thought, a failure of a single Level 2+ network component can result in a substantial loss of visibility to the provider's plants. One of the first things to consider is how this equipment will be powered.

It is highly recommended that all Level 2+ network equipment be backed up by emergency generators and/or uninterruptible power supplies (UPS).

Emergency generators require the use of an automatic transfer switch (ATS) to automatically toggle between normal power and the emergency power generator that is started when normal power is lost. The automatic starting of an emergency generator and the activation of the ATS takes time (<30 seconds typically). A UPS is needed to keep the Level 2+ networking equipment energized for the short amount of time required to start the generator and transfer to emergency power. The UPS should be sized to keep the equipment energized during this short power transitional period.

There may also be situations where an emergency generator is not available at a particular plant. In these situations a UPS is required and should be sized to keep the Level 2+ networking equipment energized for a much longer period of time. The length of time is dependent on the individual provider's requirements.

8.14 Control Functions

This section presents an overview of the types of control algorithms that a well-designed and implemented DCICS should be able to support. Details on these control schemes are beyond the scope of this chapter and would typically be defined by the DCICS contractor during detailed design.

In general, a well-designed and implemented DCICS should be able to perform all of the control functions necessary to meet the provider's main objective of providing chilled-water energy to its customers in the most cost-effective manner possible. This includes, but is not limited to, the following:

All level 2+ network equipment should be backed up by emergency generators and/or uninterruptible power supplies.

- Schemes
  - primary-secondary systems
  - preferential loading systems
  - sidestream systems
  - variable primary systems
- Chiller-water plants
  - cooling tower staging
  - condenser-water pump control
  - condenser loop control
  - head pressure control
  - chiller staging
  - primary pump control
  - secondary pump control
  - energy monitoring
- TES plants
  - cooling tower staging
  - condenser water pump control
  - condenser loop control
  - chiller staging
  - TES pump control
  - TES heat exchanger staging
  - TES heat exchanger discharge temperature control
  - TES heat exchanger discharge pump control
  - energy monitoring
- Pumping (lift) stations – located well downstream of the chilled-water production plants.
  - pump control
  - energy monitoring
- Energy transfer stations
  - heat exchanger staging
  - heat exchanger customer-side temperature control
  - heat exchanger customer-side pump control (depending on customer)
  - energy monitoring

8.15 Human-Machine Interface Functionality

The provider's staff can interface to the DCICS in many different ways from many different locations:

- Local to plants
  - local Level 3 OITs
  - local Level 4 workstations
- Command centers
  - data servers
  - historical data servers
  - command center Level 4 workstations
- Indirectly from Level 5 applications by accessing the data stored in the relational database(s) on the historical server(s).
- Remotely from anywhere in the world, with the proper security credentials, using standard Web browsers via the terminal server(s) that are installed in the command centers.

Some of the HMI functions that a DCICS must support are listed below:

- Present the status of the equipment in all of the provider's plants to the user on graphical user interface screens.
- Allow users with the proper security credentials to operate equipment, modify setpoints and change operating modes.
- Provide alarm annunciation.
- Provide access to historically stored data via graphs and spreadsheets.
- Generate reports from historical and real-time data.
- Automatically issue pages, emails, phone calls and other types of notifications when critical alarms occur in any of the provider's plants.

8.16 Standardization

Standardization is essential to the successful implementation of any new DCICS. Time spent during the early stages of the DCICS design developing standards will result in a DCICS that is maintainable and serviceable for years to come.

At a minimum, standards should be developed for the following:

- HMI standards

Controller instruction sets must address tasks such as advanced math, totalization, sequencing, timing, counting, closed-loop control and feed-forward control.

- Graphical user interface (GUI) screen standards. GUI screens should have the same "look and feel" from one plant to another. This will result in operators needing less training when working across multiple plants. General screen layout, color codes, screen navigation and animation preferences should all be standardized.
- Standard objects. Real-world devices such as isolation valves are found all over a typical provider's various plants. If a standard HMI object is created for an isolation valve, encompassing all of the attributes that are typical for an isolation valve, then the same object can be deployed over and over again instead of creating a new object every time an isolation valve is placed on a GUI screen. This can save enormous amounts of time in programming. The concept of object programming should be used extensively.
- Standards for historical data collection and display should be developed and adhered to. Similar process variables should be displayed in the same color (i.e., pressure = red, flow = blue, temperature = yellow, setpoints = black).
- Alarming standards, such as common annunciation methods, color codes, alarm descriptions, logging and acknowledgement, should be followed across the entire DCICS so that alarms are consistent, easy-to-understand and can be responded to quickly, regardless of what plant generated the alarm.

- Controller programming standards
  - General. Good controller programming standards are key to the maintainability and ongoing operation of a DCICS. Service personnel should be able to be trained on one controller program in one plant and then be able to go to any controller in any other plant and debug it with relative ease.
  - Standard modules. As is the case with standard objects in HMI applications, standard controller modules should be deployed when there are large numbers of the same type of device used repetitively. The module should be written once, tested, and libraried. The libraried module would then be duplicated as needed, passing in the parameters that are particular to each individual call to the module.
  - Documentation standards. The controller programming standard must spell out the documentation standards that are expected in all DCICS controller programs. Items such as common memory maps, variable naming, variable descriptions, code segment comments and module comments should be addressed.
- Naming standards
  - Standard tag naming and device description standards should be developed early on and adhered to from site to site. Tag names should be consistent across
    - end field devices,
    - P&IDs and other drawings,
    - design specifications,
    - variable names in the PLC,
    - tag names in the HMI application,
    - tag names when an alarm is annunciated and
    - tag names when a point is historically logged.
- Communications addressing
  - Proper planning for how devices are addressed (i.e., IP addresses) on the various networks upfront can make maintaining and expanding the networks easier in the future.

8.17 Standard Design Documents

The following design documents should be provided by any contractor implementing a new or modified district cooling instrumentation and control system:

- Functional requirements specification (FRS). This document describes what the system (or the modifications to the system) is supposed to do. It outlines the district cooling provider's requirements for the system.
- Design specifications (DS). These documents describe how the system (or the modifications to the system) will be built to meet the requirements stated in the FRS. There are typically two types of design specifications required:
  - Hardware (HDS). Must include an instrument list, detailed instrument data sheets and annotated manufacturer cut sheets that clearly indicate all of the options being specified for every field instrument being provided.
  - Software (SDS). Must describe the sequence of operations, provide the HMI specifications, summarize the alarm and trend requirements and specify any other software-related items necessary.
- Computer systems design specifications (CSDS). In situations where there will be a large amount of Level 4 equipment being installed, such as servers, workstations, hubs, switches, routers, printers and the like, it may advantageous to break out the specification of these components, the cabinets and furniture they will be installed in, and their associated software, into a separate computer system design specification. Typically, the people who will review this document will be different then the people who will review the DS, so breaking it out may streamline the review process.
- Drawings. The following drawings are typically provided:
  - process and instrumentation diagrams (P&IDs)
  - panel layout drawings, bill of materials, terminal block and label schedules and power distribution schematics
  - I/O module wiring schematics
  - instrumentation riser diagrams

- communication riser diagrams
- instrumentation loop diagrams
- instrumentation location diagrams
- installation details

8.18 Standard Testing Documents

The following testing documents should be provided by any contractor implementing a new or modified DCICS to prove that all of the requirements stated in the FRS have been met and that all of the design specifications (HDS/SDS) were followed:

- Factory acceptance testing (FAT) protocols. Testing procedures executed at the contractor's factory, prior to shipment to the district cooling provider's site. There are typically two types of protocols generated and executed:
  - Hardware factory acceptance testing (HFAT) protocols. Tests that any hardware that is pre-assembled by the contractor before it is sent to the provider's site has been built according to specifications (i.e., panels).
  - Software factory acceptance testing (SFAT) protocols. Tests that all software has been programmed according to specifications. Tests are performed at the contractor's factory, prior to installing the software at the provider's site.
- Site acceptance testing (SAT) protocols. The procedures test that all of the hardware and software have been installed properly at the provider's site and that they function properly. Successful completion of these protocols are required before turning the system over to the provider.

9. Procurement and Project Delivery

There are a variety of options for procurement of design and construction services for district cooling systems. Although there are many variations, these options can be grouped into the following major categories:

- design/bid/build (DBB)
- engineer/procure/construct (EPC)
- packaged plant

In the following discussion, it is useful to note that the optimal procurement strategy may vary for different district cooling system elements (plant, distribution and ETSs).

Choice of the appropriate procurement approach depends on a range of factors. Major procurement decision criteria include

- first cost,
- life cycle cost,
- schedule,
- equipment quality,
- contractor qualifications and established owner-contractor relationship and
- performance guarantees.

While EPC procurement can be an attractive option for plants, it presents more challenges for distribution and ETS systems. Design of these systems is highly site-specific and it is difficult to benefit from many of the advantages of the EPC approach.

While EPC procurement can be an attractive option for plants, it presents more challenges for distribution and ETS systems.

Because of long production cycles for large or specialized district cooling equipment, procurement of the equipment before completion of construction documents may be required. Equipment that may be affected includes

- chillers,
- pumps,
- cooling towers,
- water treatment and
- main electrical transformers, motor control centers, etc.

One procurement-related issue that has become a primary concern is the availability of materials and equipment. In recent years the unprecedented skyrocketing of global demand for commodities and equipment has stretched lead times for certain items and, in some cases, effectively precluded use of certain materials due to unacceptably long lead times. For example, there was a period in 2005-2006 where titanium was so difficult to procure that some equipment vendors were not able to fill orders for equipment with titanium components.

Another area of concern with regard to availability in recent years is distribution piping. High demand for large-diameter piping worldwide, especially steel, has made it very difficult to procure with reasonable lead times. In some cases, district cooling companies have had to change distribution piping material type for projects due to unacceptable lead times for their preferred pipe material. It is important for piping procurement issues to be explored and accounted for early in the planning and design stages to avoid unexpected surprises.

It is important for piping procurement issues to be explored and accounted for early in the planning and design stages to avoid unexpected surprises.

Even prior to the recent increase in demand, lead times for fittings could impact the chilled-water distribution pipe material selection. For the large-sized piping used for chilled-water mains, fittings generally have a much longer lead time than the pipes themselves. Therefore, for pipe routings where there is a risk of unknown obstacles requiring unforeseen directional changes, steel piping may be preferable to a material like ductile iron. With steel piping, miters and custom fittings with required angles can be fabricated in the field by the installation contractor. For pipe materials where fittings cannot be customized in the field, the owner must either have a stock of fittings of various sizes and angles ordered ahead of construction, at significant expense, or accept delays when unexpected obstacles are encountered.

9.1 Design/Bid/Build (DBB)

In this approach, also called "plan and spec," a consulting engineer prepares a detailed design including plans and specifications that are put out to bid to qualified contractors.

Design/bid/build is most frequently used for complex or unique district cooling projects. The following are primary advantages of DBB:

- The designer is looking out solely for the interests of the owner and is in the best position to develop a design that minimizes life-cycle costs instead of first costs.
- If a single consultant is designing all district cooling system elements (plant, distribution, ETSs), it is more likely that a fully integrated system design will result with DBB procurement.
- The owner has more control over the design and the final product produced by the design, including integrating consideration of ongoing operations and maintenance into the design.
- DBB can result in lower costs than other options as a result of competitive bidding on a clear and detailed scope of work; there is less need for

contractors to increase the price to cover contingencies.

If a single consultant is designing all district cooling system elements (plant, distribution, ETSs), it is more likely that a fully integrated system design will result with DBB procurement.

The following are key disadvantages of DBB:

- It is generally a more time-consuming option to reach initiation of construction and to respond to any redesign issues that may arise during construction.
- The separation of design and construction create multiple sources of responsibility, resulting in a "gray area" if problems occur, with the potential for mutual finger-pointing between the designer and contractor.
- DBB requires more staffing and coordination costs for the owner.
- Changes in design, or delays caused by one of many contractors or authorities, will likely become the owner's responsibility. In these circumstances, or in the case of minor design errors, contractors have large opportunities to use the situation to their advantage.

9.2 Engineer/Procure/Construct (EPC)

In this approach, also called "design/build," the design and construction are contracted for with a single entity, the EPC contractor. This approach is used to minimize the owner's project risk and reduce the delivery schedule by overlapping the design phase and construction phase of a project. For the design phase, the EPC contractor may use a combination of in-house engineers and consultants.

Typically, the owner's requirements are established in a document called the Owner's Requirements Document (ORD) or Owner's Project Requirements (OPR).

There are many variations in this procurement approach, e.g., the owner may directly procure major equipment.

The following are key advantages of EPC procurement:

- It has a single point of responsibility and there are likely fewer contracts between the owner and others.
- There is a reduction in time required, leading to an earlier online date.
- Determining the most cost-effective design can be enhanced through the contractor's input during the design phase.
- Cost savings can result from reduced coordination costs, reduced time for carrying a construction loan (which typically carries a higher interest rate than permanent financing) and an earlier online date.
- Large EPC contractors are executing many projects on an ongoing basis and normally have a project organization with well-established methods and routines in place. Since the owner executes large projects less frequently than an EPC contractor, it may lack up-to-date experience and staffing.

Large EPC contractors are executing many projects on an ongoing basis and normally have a project organization with well-established methods and routines in place.

The following are major disadvantages of EPC procurement:

- A cursory or poorly developed ORD can result in a fundamental tension between the owner's desire for high reliability and low life-cycle costs and the EPC contractor's desire to minimize construction costs.
- EPC procurement requires the owner to rely a great deal on the integrity, acumen and competence of the design-builder.
- Changes may be expensive due to fast-tracking and increases in costs for items that are affected by changes, but are not competitively bid.
- The compressed schedule can conflict with regulatory review, resulting in costly change orders to bring the project into compliance with regulatory requirements once full review is performed.
- It is difficult to clearly delineate the boundaries between the owner's and the contractor's responsibilities and risks. A major category of risks relate to environmental issues and permits given by the authorities. These issues are normally dealt with by the owner and are impossible to transfer completely to the contractor.

There is a wide variation in the level of detail in ORDs, ranging from a brief summary of key performance specifications to a specific conceptual design. An example table of contents for a detailed ORD for a district cooling plant is presented in Table 9-1.

It is important that the ORD clearly distinguish between the owner's requirements and the conceptual design. The EPC contractor must fulfill the project requirements, whereas the conceptual design represents one possible way to do the design to meet the requirements. In the end, the EPC contractor must take full responsibility for the design.

9.3 Packaged Plants

A third option for procurement of design and construction of district cooling plants is purchase of packaged or modular plants. With this approach, plant modules are manufactured in a factory, including

- **General**
  - System Description
  - Plant Design Description
  - Definitions
  - Codes and Standards
- **Design Overview and Concepts**
  - System Design Requirements
  - Utility Cost Information
  - Plant Phasing and Project Schedule
- **Plant System Descriptions and Design Criteria**
  - Mechanical
    - Chilled-water system
    - Condenser-water system
    - Water makeup and treatment systems
    - Safety systems
      - *Refrigeration storage and handling*
      - *Ventilation*
      - *Monitoring*
      - *Over-pressure protection*
  - Control
    - System control descriptions
      - *Architecture*
      - *Integrator*
  - Electrical
    - Utility power supply
    - Short-circuit protection systems
    - Voltage regulation systems
    - Grounding systems
    - Lighting and small power systems
  - Building Services
    - Acoustics, sound and vibration
    - HVAC
    - Lighting
    - Plumbing
    - Security
- **Plant Equipment Requirements**
  - Mechanical Equipment Requirements
    - Centrifugal water chiller packages
    - Cooling towers
    - Distribution pumps
    - Chiller pumps
    - Condenser-water pumps
    - Chilled-water expansion tanks
    - Water treatment
      - *Chilled water*
      - *Condenser water*
    - System Piping and Materials
      - *Piping*
      - *Fitting and branch connections*
      - *Flanges*
      - *Joints*
      - *Valves*
      - *Insulation*
    - Plant air compressor
  - Control Equipment Requirements
    - Instruments
    - Programmable logic controllers
    - Flow meters
    - Transmitters
  - Electrical Equipment Requirements
    - 66 kV substation
    - 11 kV and 3,300-volt switchgear
    - Dry-type transformers
    - Plant power factor
    - Safety switches
    - Raceway system
    - Wire and cable - 600 volts and below
    - Medium-voltage cable
    - Wiring devices
    - Substation earthing (grounding)
    - Ground and lightning protection system
    - Panelboards
    - Variable-speed drives (VSDs)
    - Lighting
    - UPS system
    - Fire alarm and detection
    - Motors
    - Distribution system controls
  - Building Service Equipment Requirements
    - Acoustics, sound and vibration
    - HVAC
    - Lighting
    - Plumbing
    - Security
  - Building Construction Requirements
    - Architectural/civil/structural description
      - *General*
      - *Design criteria for structure*
    - Space programming requirements
    - Construction materials
  - Environmental
    - Permits and approvals
  - Owner's Review Process
    - Preliminary design phase
    - Final design phase
    - Construction/startup phase
    - Commissioning
  - Standards of Acceptance

Table 9-1. Example detailed outline of Owner's Requirements Documents (ORDs) for engineer/procure/construct (EPC) procurement.

chillers, chilled-water pumps, condenser-water pumps, motor control centers, digital controls, enclosure, cooling towers and cooling tower support structure. The package is then shipped to the site, installed on a foundation and connected to site utilities.

In a packaged plant, chiller/pump/motor control center/cooling tower modules are factory-assembled as complete units for field installation as a standalone plant, usually with minimal field construction and with or without facades. In a modular plant, equipment modules are installed in a conventional building.

The following are key advantages of packaged plants:

- Costs tend to be lower than, or comparable to, built-up plants, because
  - vendors have already invested significantly in design of optimized plant systems,
  - fabrication labor can be used more efficiently than in the field and
  - volume procurement offers the opportunity for cost economies for some equipment and components.
- Since the modules can be fabricated in parallel with civil works, packaged plants can reduce construction time, and revenue generation can start sooner.
- Manufacturing occurs in controlled conditions where it is easier to achieve quality control.
- Fabrication of the plant can proceed concurrently with obtaining permits from the authorities.
- Packaged plant vendors typically provide some type of performance guarantee.
- Package and modular plants offer greater flexibility compared to built-up plants, facilitating staged addition of capacity to meet increasing customer demand. This has the beneficial effect of delaying capital expenditures until they are needed.
- Smaller packaged plants can be used as temporary plants for several years in advance of building a full-scale plant. The packaged plant can then be moved to the next development.
- Alternatively, packaged plants can be used as temporary plants and then, if siting constraints permit, be converted into permanent plants by adding modules and facades.

Since the modules can be fabricated in parallel with civil works, packaged plants can reduce construction time, and revenue generation can start sooner.

The following are disadvantages of packaged plants:

- The ability to integrate plant controls with the ETS control systems may be constrained.
- Architectural flexibility, including ability to minimize plant site area, is constrained. The footprint of a packaged plant is larger than for a multi-story built-up plant.
- There are constraints on fitting standard modules into an oddly shaped plant or site.
- There can be potential challenges in creating cross-redundancy between chillers, towers and pumps.
- Maintenance can be more difficult with compressed plant configurations common in packaged plants.
- Historically, packaged plants have put functionality ahead of aesthetics, although vendors have significantly upgraded facades to improve appearance.
- Generally, packaged plants are designed around electric centrifugal chillers using standard cooling towers. Case-specific factors may require non-standard design elements, such as engine-driven chillers, plants with seawater cooling towers or once-through seawater heat rejection, or other technologies.

10. Commissioning

Numerous definitions and opinions of commissioning exist, but ASHRAE's definition is especially noteworthy. ASHRAE defines commissioning as "a systematic process of ensuring that systems are designed, installed, functionally tested and capable of being operated and maintained to perform in conformity with design intent."

ASHRAE Guideline 0-2005 addresses the commissioning process for an entire project, from initial conception through operations. The process is organized as follows:

- Pre-design – Owner's Project Requirements (OPR) are defined.
- Design – Based on the OPR, construction documents are prepared by the engineer.
- Construction – Based on the construction documents, bids are received. Equipment and systems are installed, inspected, tested and placed into operation to meet the OPR.
- Occupancy and Operations – Starting at substantial completion, functional performance testing is preformed and ongoing operations and maintenance are verified against the final OPR.

Commissioning is frequently considered to focus on startup, testing, adjusting and balancing, and some standards focus on these tasks. For example, the U.S. National Environmental Balancing Bureau (NEBB) Standard emphasizes the performance of work identified in the following ASHRAE Construction and Occupancy/Operations phases:

- Testing, Adjusting and Balancing (TAB) – Traditional measuring and setting of balancing devices for obtaining proper flows and performance.
- Field Installation Verification (FIV) – Are the equipment and system ready for startup?
- Operational Performance Testing (OPT) – Is the equipment operating as intended?
- Functional Performance Testing (FPT) – Is the equipment operating as efficiently as intended?

Commissioning is much more than just these tasks. Testing, adjusting and balancing are a necessary first step before dynamic operations are tested as a key part of the commissioning process. However, in addition to making sure that all the individual equipment is installed correctly and with the necessary safety and controls systems, commissioning focuses on ensuring that the entire system works as designed through all conditions that will occur during operations, including startup, part- and full-load, shutdown and alarm conditions. Testing and balancing usually focuses on minimum and maximum conditions, whereas commissioning addresses sequence of equipment operation and optimization of performance across a range of conditions.

Commissioning should be integrated into the design and construction processes and should be a key part of the procurement and project delivery process. Because the different major elements of a district cooling system (plant, distribution, ETSs) are often procured in separate packages, it is especially important that there be one entity that has the responsibility and authority to ensure that all elements are designed, installed and operated as an integrated whole. To ASHRAE this entity is known as the commissioning authority (CA), but sometimes many of the same roles are discharged by the owner's engineer (OE).

Commissioning should be integrated into the design and construction processes and should be a key part of the procurement and project delivery process.

Effective integrated commissioning of district cooling systems is rarely achieved, with the result that the district cooling provider's operations staff bear the burden of trying to make sure that all systems operate effectively together, which may be difficult or impossible to achieve after the fact. Compressed schedules exacerbate this problem.

It is especially important for the commissioning process to address district cooling system design and performance as it relates to delta T, energy use, available equipment capacity and customer comfort. Chapter 5 details metrics that may be used at the customer ETS to assess system performance at the interface with each customer. Performance metrics should also be provided for the plant very early in the design and planning process. To the greatest extent possible, the CA must be capable of broadly evaluating the chilled-water system, including details beyond the customer interface, to ensure that the chilled-water return temperature to the plant meets or exceeds system design at peak- and part-load conditions. It is equally important to ensure that the supply-water temperature provided to customer buildings is sufficient to meet contractual obligations and satisfy customer cooling requirements. Poor delta T performance is a very common industry problem that has an adverse impact on equipment capacity and energy consumption and may also affect customer comfort and chilled-water revenue. The commissioning process should pay special attention to this issue long before the system is in construction and operation.

A project's implementation is driven by cost, time and quality. Construction managers typically concentrate on the first two elements – cost and time – and commissioning authorities concentrate on the third element – quality.

The owner expresses the desired outcome through what ASHRAE calls the OPR and others call the Owner's Requirements Document (ORD). Then it is the commissioning authority's role to ensure that the owner's requirements are achieved as the project is planned, designed, installed, tested, operated and maintained. The CA brings value to the owner through focused attention to quality, process and system performance within the context of the district cooling provider's business case. The CA should understand the nature of the district cooling business and the often complex relationships between customer load, capital investment and annual operating expenses.

It is important to require the contractor to provide a comprehensive equipment list, full as-built drawings and useful O&M manuals for all equipment and systems.

As the design is developed, the CA develops commissioning process requirements for the construction documents, reviews essential portions of the specifications and drawings, defines training requirements and prepares the scope and format for the Systems Manual. The Systems Manual is a comprehensive document that is focused on systems operation and thus will be an important tool during training as well as ongoing operations and maintenance. The Systems Manual goes beyond the compilation of operation and maintenance manuals typically collected by the construction contractor.

In the construction phase, the CA reviews essential contractor submittals for compliance with the ORD and verifies that systems are installed such that the owner's requirements can be achieved. The commissioning authority updates the commissioning plan, prepares checklists, witnesses tests and verifies that test reports are documented.

It is important to require the contractor to provide a comprehensive equipment list, full as-built drawings and useful O&M manuals for all equipment and systems. For projects in the Middle East, oftentimes the O&M manuals supplied by the contractor are simply a collection of vendor literature and not proper O&M manuals, which makes it difficult for district cooling system operating personnel to operate the district cooling system efficiently.

Most of the testing and performance verification will be completed during the construction phase. However, full commissioning is not always possible until there is sufficient load to commission systems across an adequate range of loads. Also, sometimes initial commissioning must take place using temporary generators instead of grid power, resulting in incomplete commissioning. Consequently, re-commissioning must take place once the proper conditions exist. Re-commissioning throughout the plant's operating life will optimize system performance as equipment wears in and will facilitate operator training.

A district cooling system represents a significant investment, especially when life-cycle operating and maintenance expenses are included. These life-cycle costs can be minimized through thoughtful planning, intelligent design and thorough commissioning.

Appendix A – Abbreviations and Definitions

The list has been alphabetized by abbreviations, then by terms where abbreviations are not applicable.

AISI
American Iron and Steel Institute

ARI
Air-Conditioning and Refrigeration Institute

ARTI
Air-Conditioning and Refrigeration Technology Institute

ASHRAE
American Society of Heating, Refrigeration and Air-Conditioning Engineers

ASME
American Society of Mechanical Engineers

standard atmosphere
A unit of pressure equal to 101.325 kPa (14.696 psi)

balancing valve
A valve used in a piping system for controlling fluid flow; not usually used to shut off the flow.

bar
A unit of pressure equal to 100 kPa (14.50 psi).

BAS
building automation system

BOE
barrel of oil equivalent
A unit of energy based on the approximate energy released by burning one barrel of crude oil, about 6.1 million KJ (5.8 million Btu).

Btu
British thermal unit
A unit of energy approximately equal to the heat required to raise a pound of water 1 degree F.

butterfly valve
A type of valve typically used for isolation. The "butterfly" is a metal disc mounted on a rod.

bypass valve
A valve that controls flow via a bypass pipe typically between the supply and return of a chilled-water system.

C
degree Celsius

CFC
chlorofluorocarbon
A class of refrigerants for which production has been banned worldwide due to their destructive impact on stratospheric ozone.

check valve
A valve that normally allows fluid to flow through it in only one direction.

CHP
combined heat and power (sometimes called "cogeneration")
A general term describing a number of energy technology configurations that produce both electricity and thermal energy from one fuel source in an efficient process; or a facility that recovers thermal energy for productive use that is normally wasted in power-only generating plants.

CHW
chilled water

CHWRT
chilled-water return temperature

CHWST
chilled-water supply temperature

CO_2
carbon dioxide
The most common greenhouse gas, emitted as a result of combustion of fossil fuels.

combined cycle
A type of power plant that employs more than one thermodynamic cycle, e.g., combined use of a combustion turbine driving a generator to produce electricity with a steam turbine generator driven with steam produced to produce additional electricity with the hot exhaust gases from the combustion turbine.

COP
coefficient of performance
The ratio of useful energy output to energy input in an energy conversion device.

crossover bridge (or decoupler)
A branch pipe connection between supply and return that is intended to hydraulically decouple two independently pumped water loops.

CW
condenser water

DB
dry bulb

dBA
decibel
Unit measurement of sound pressure level using the "A" weighting filter.

DBB
design/bid/build
A project delivery process in which a consulting engineer prepares a detailed design including plans and specifications that are put out to bid to qualified contractors.

DC
direct current

DCICS
district cooling instrumentation and controls system

DDC
direct digital controller

DCS
distributed control system

debt ratio
Ratio of debt to total capital.

decoupled
Hydraulically independent.

decoupler (or crossover bridge)
A branch connection between supply and return that is intended to hydraulically decouple two independently pumped water loops.

delta P
The pressure difference between supply and return.

delta T
The temperature difference between supply and return.

DER
debt-to-equity ratio

desalination
Any of several processes that remove excess salt and other minerals from water.

DIR
debt interest rate

DR
dimension ratio
The ratio of HDPE pipe outside diameter to pipe wall thickness.

ECWT
entering condenser-water temperature

EEMS
expert energy management systems

EEPROM
electrically erasable programmable read-only memory

EFLH
equivalent full-load hours
Ratio of total annual energy consumption to peak hourly demand.

EPC
engineer/procure/construct
A project delivery process in which the design and construction are contracted for with a single entity.

equalizer piping
Piping connecting basins of multiple cooling towers or cells to maintain a common water level.

ER
equity ratio
Ratio of equity to total capital.

ETS
energy transfer station
The thermal energy transfer interface between the district cooling provider and each customer, typically consisting of metering, valves, piping, controls and in the case of indirect connections, a heat exchanger.

expansion tank
A tank used in a closed-water system to accommodate water volume changes due to thermal expansion and contraction.

F
degree Fahrenheit

FIV
field installation verification

FPT
functional performance testing

FRP
fiberglass-reinforced plastic

fps
feet per second

gpm
gallons per minute

GHG
greenhouse gas
Gases present in the earth's atmosphere that warm near-surface global temperatures through the greenhouse effect.

globe valve
A type of valve used for regulating flow in a pipeline consisting of a movable disk-type element and a stationary ring seat in a generally spherical body.

GRP
glass-reinforced plastic

GWP
global warming potential
A measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is a relative scale that compares the gas in question to that of the same mass of carbon dioxide (whose GWP is by definition 1). A GWP is calculated over a specific time interval. In this document the GWP figures reflect the commonly used 100-year interval.

HCFC
hydrochlorofluorocarbon
A commonly used class of refrigerants.

HDA
historical data acquisition

heat rate
A measure of how efficiently a power generator uses fuel, expressed as the number of British thermal units of fuel required to produce a kilowatt-hour of electricity.

hermetic drive
A chiller arrangement in which the motor is contained within the same housing as the compressor and is in direct contact with the refrigerant.

HDPE
high-density polyethylene

HEX
heat exchanger
A device for transferring thermal energy between two hydraulically separated systems.

HFC
hydrofluorocarbon
A commonly used class of refrigerants.

HMI
human-machine interface

hot tapping
An operation in which a branch connection is made to a pipe main while the pipe remains in service or "hot."

hp
horsepower

HRSG
heat-recovery steam generator
A boiler producing steam from recovered heat; often used in a combined-cycle configuration to effectively utilize thermal energy for power production or additional heat uses.

HV
high voltage

HVAC
heating, ventilation and air conditioning

impeller
The rotating element in centrifugal pumps and compressors that transfers energy from the motor to the fluid to create pressure head.

I/O
input/output

IEEE
Institute of Electrical and Electronics Engineers

I&C
instrumentation and controls

IDEA
International District Energy Association

ISO
International Organization for Standardization

isolation valves
Valves that allow a piece of equipment to be isolated from the rest of the system to facilitate maintenance, equipment removal and shutdown.

IT
information technology

jacket water
Fluid circulated within a reciprocating engine for the purpose of heat rejection.

kPa
kilopascal

kVA
kilovolt ampere

kW
kilowatt

kWh
kilowatt-hour

LCWT
leaving condenser-water temperature

LNG
liquefied natural gas

m
meter

mADC
milliamps DC

mbar
millibar

MED
multi-effect distillation

micro-tunneling
A trenchless construction method for installing pipelines.

MID meter
An electronic flow meter that measures flow by induction of voltage in a conductor moving in a magnetic field. These devices are often called “magmeters.”

mm
millimeter

MMBtu
million British thermal units

MMBtu/hr
million British thermal units per hour

MSF
multi-stage flash distillation

MW
megawatt

MWh
megawatt-hour

mps
meters per second

µS/cm
micro-Siemens per centimeter
A unit of specific conductivity.

NEBB
National Environmental Balancing Bureau

NFPA
National Fire Protection Agency

NPV
net present value

O&M
operation and maintenance

ODP
ozone depletion potential
The relative amount of degradation to the ozone layer a given chemical can cause, with trichlorofluoromethane (R-11) being fixed at an ODP of 1.0.

OIP
operator interface terminal

OLE
object linking and embedding
A technology that supports the linking and embedding of objects from one application seamlessly into another application.

OPC
OLE for process control
A standard that specifies communication of real-time plant data between devices from different manufacturers.

open-drive motor
A motor arrangement in which the motor is outside the compressor housing.

OPR
Owner’s Project Requirements

OPT
operational performance testing

ORD
Owner’s Requirements Document
Documents establishing an owner’s requirements for the purpose of soliciting engineer/procure/construct bids.

OSHA
Occupational Safety and Health Administration

ozone-depleting refrigerant
Refrigerants that contribute to depletion of the stratospheric ozone layer.

part load
Operation of equipment at less than 100% load.

PC
personal computer

PE 80 or PE 100
Material classes for the resins used to construct polyethylene piping products.

PEX
cross-linked polyethylene

PLC
programmable logic controller

pneumatic control
Control devices that utilize compressed air signals to control inputs and outputs.

PPE
personal protective equipment

ppm
parts per million
Denotes one part per 1,000,000 parts and a value of 1×10^{-6}.

provider
District cooling provider. An entity providing district cooling services, usually as a commercial enterprise.

psi
pound per square inch
A unit of pressure equal to 68.95 millibar.

psig
pounds per square inch gauge
Pressure above standard atmospheric pressure, measured in psi.

PVC
polyvinyl chloride

RAM
random access memory

RF
radio frequency

RO
reverse osmosis

ROE
return on equity

ROI
return on investment

RTTMS
real-time thermal modeling and simulation

SCADA
supervisory control and data acquisition

S/cm
Siemens per centimeter
A unit of specific conductivity.

shadow prices
An assumption of CO_2 emissions cost for the purpose of comparing options.

SI
Standard International

solenoid
A type of actuator that operates in a two-position (open/closed) mode.

SOP
standard operating procedure

standard atmosphere
A unit of pressure equal to 101.325 kPa (14.696 psi).

T&D
transmission and distribution

TAB
testing, adjusting and balancing

TCP/IP
transmission control protocol/internet protocol
A protocol for communication between computers used as a standard for transmitting data over networks and as the basis for standard Internet protocols.

TEAAC
totally enclosed air-to-air-cooled

TEFC
totally enclosed fan-cooled

TES
thermal energy storage

TEWAC
totally enclosed water-to-air-cooled

three-way valve
A valve having either a single inlet and two outlets or two inlets and a single outlet.

ton
A measure of cooling capacity or demand equal to removal of 12,000 British thermal units (Btu) per hour; sometimes the abbreviation TR is used, for "tons refrigeration."

ton-hr
A measure of cooling energy consumption equal to one ton over a one-hour period.

TSE
treated sewage effluent

turbine meter
A device that measures the rate of flow in a pipe via a rotor that spins as the media passes.

turndown
The ratio between maximum and minimum flow or capacity for the controllable operating range of a piece of equipment.

two-way valve
A valve having two ports that can be open or closed, used for controlling flow to equipment.

ultrasonic meter
A device that measures flow by measuring the time between the transmission and reception of ultrasonic signals over an exactly known distance.

UPS system
uninterruptible power supply system
A power supply system that includes a battery to maintain power in the event of a power outage.

US$ or USD
United States dollar

valve authority
The ratio between pressure drop across the control valve and the total pressure drop across the circuit.

VAV
variable air volume

VDC
voltage DC

VGD
variable geometry diffusers

VSD
variable-speed drive
A system for controlling the rotational speed of powered machinery (e.g., pump or fan) by controlling the frequency of the electrical power supplied to the machinery; also known as variable-frequency drive (VFD).

WACC
weighted average cost of capital

WB
wet bulb

Y-strainer
Filtration device that retains solids when a liquid passes through it.

ZLD
zero liquid discharge

Appendix B – Conversion Factors

The following conversion factors can be used to convert between English (IP) and metric (SI) units.

Multiply	**by**	**to obtain**
bar	100	kilopascal (kPa)
barrel [petroleum]	159.0	liter (l)
barrel [petroleum]	42	gallon (g)
Btu	1.055	kilojoule (kJ)
Btu	0.0002931	kilowatt-hour (kWh)
Btu/hr	0.2928	watt (W)
cubic feet (ft^3; cu ft)	0.0283	cubic meter (m^3; cu m)
cubic feet/minute (cfm)	0.4719	liter/second (lps; l/s)
feet (ft)	0.3048	meter (m)
feet (ft)	304.8	millimeters (mm)
ft^2/ton	0.09290	m^2/ton
feet of water (ft) [head]	2.989	kilopascal (kPa)
feet/minute (fpm)	0.00508	meter/second (m/s)
feet/second (fps; ft/s)	0.3048	meter/second (m/s)
gallon (gal) [US]	0.003785	cubic meter (m^3; cu m)
gallon (gal) [US]	3.785	liter (l)
gallons/minute (gpm)	0.06309	liters/second (l/s)
horsepower (hp)	0.7457	kilowatt (kW)
inch (in)	25.4	millimeter (mm)
inch (in)	1000	mil
mile (mi)	1.609	kilometer (km)
mile/hour (mph)	1.609	kilometer/hour (km/h)
millibar (mB)	0.1	kilopascal (kPa)
ounce (oz)	28.35	gram (g)
pound (lb) [mass]	0.4536	kilogram (kg)
lb/in^2 (psi)	0.06895	bar
lb/in^2 (psi)	2.307	feet of water (ft) [head]
lb/in^2 (psi)	6.895	kilopascal (kPa)
psi/100 ft	226.2	Pascal/meter (Pa/m)
square feet (ft^2; sq ft)	0.09290	square meter (m^2)
therm	105.5	megajoule (MJ)
ton [refrigeration]	3.516	kilowatts (kW)
ton [refrigeration]	12,000	Btu/hr
ton-hr	3.516	kilowatt-hour (kWh)
ton-hr	12,000	Btu
yard (yd)	0.9144	meter (m)
to obtain	**by**	**Divide**

NOTE: All approximate conversion factors above are presented with four significant digits.

Other useful conversions:

degree C = (degree F - 32) x 0.5556

degree F = (degree C x 1.8) + 32

kW/ton = 3.516 / coefficient of performance (COP)

lb/in^2 absolute (psia) = psig + 14.70

lb/in^2 gauge (psig) = psia - 14.70

one year = 8760 hr

Appendix C – Arc Flash

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Arc Flash: Do you understand the dangers?

Arc flash is the result of a rapid release of energy due to an arcing fault between a phase bus bar and another phase bus bar, neutral or a ground. During an arc fault, the air is the conductor. Arc faults are generally limited to systems where the bus voltage is in excess of 120 V.

Lower voltage levels normally will not sustain an arc. An arc fault is similar to the arc obtained during electric welding; the fault has to be manually started by something creating the path of conduction or a failure such as a breakdown in insulation.

The cause of the short normally burns away during the initial flash, and the arc fault is then sustained by the establishment of a highly conductive plasma. The plasma will conduct as much energy as is available and is only limited by the impedance of the arc. This massive energy discharge burns the bus bars, vaporizing the copper and thus causing an explosive volumetric increase – the arc blast, conservatively estimated as an expansion of 40,000 to 1. This fiery explosion devastates everything in its path, creating deadly shrapnel as it dissipates.

The arc fault current is usually much less than the available bolted fault current and below the rating of circuit breakers. Unless these devices have been selected to handle the arc fault condition, they will not trip, and the full force of an arc flash will occur. The electrical equation for energy is volts x current x time. The transition from arc fault to arc flash takes a finite time, increasing in intensity as the pressure wave develops. The challenge is to sense the arc fault current and shut off the voltage in a timely manner before it develops into a serious arc flash condition.

Why the Focus on Arc Flash?

In the early 1980s a paper by Ralph Lee, "The Other Electrical Hazard: Electric Arc Blast Burns," was published in the IEEE Transactions on Industrial Applications. The effect of this paper was to realize the need to protect people from the hazards of arc flash. Four separate industry standards pertain to the prevention of arc flash incidents:

- OSHA 29 Code of Federal Regulations (CFR) Part 1910 Subpart S
- NFPA 70-2002 National Electrical Code
- NFPA 70E-2000 Standard for Electrical Safety Requirements for Employee Workplaces
- IEEE Standard 1584-2002 Guide for Performing Arc Flash Hazard Calculations

Compliance with the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) involves adherence to a six-point plan:

1. A facility must provide, and be able to demonstrate, a safety program with defined responsibilities.
2. Calculations for the degree of arc flash hazard.
3. Correct personal protective equipment for workers.
4. Training for workers on the hazards of arc flash.
5. Appropriate tools for safe working.
6. Warning labels on equipment. Note that the labels are provided by the equipment owners, not the manufacturers. It is expected that the next revision of the National Electric Code will require that the labels contain the equipment's flash protection boundary, its incident energy level, and the required personal protective equipment.

Companies will be cited and fined for not complying with these standards.

Personal Protective Equipment

Categories of personal protective equipment (PPE) as described in NFPA 70E are:

Category	Cal/cm²	Clothing
0	1.2	Untreated cotton
1	5	Flame retardant (FR) shirt and FR pants
2	8	Cotton underwear, FR shirt and FR pants
3	25	Cotton underwear, FR shirt FR pants and FR coveralls
4	40	Cotton underwear, FR shirt, FR pants and double-layer switching coat and pants

Cal/cm^2 are the units of incident energy that the PPE can withstand. Note that a hard hat with full-face shield and the appropriate gloves are required also.

Steps Required for a Flash Hazard Analysis

To perform an arc flash hazard analysis, data is collected about the facility's power distribution system. The data includes the arrangement of components on a one-line drawing with nameplate specifications of every device. Also required are details of the lengths and cross-section area of all cables. The utility should be contacted for information including the minimum and maximum fault currents that can be expected at the entrance to the facility. Once the data has been collected, a short-circuit analysis should be performed, followed by a coordination study. The resultant data can then be fed into the equations described by either NFPA 70E-2000 or IEEE Standard 1584-2002. These equations will produce the necessary flash protection boundary distances and incident energy to determine the minimum PPE requirement.

Flash Hazard Analysis – A New Approach

Once the data is prepared and a flash hazard analysis has been performed, most likely it will be discovered that Category 4 PPE will be required in most places. This is most unfortunate as this type of PPE is very unwieldy and could be costly in terms of time taken to perform work and the potential for mistakes. Prior to the new arc flash regulations, coordination studies were targeted at reliability with all settings adjusted toward the high side. Compliance with the new arc flash regulations means that not only does the coordination study need to be more accurate but it also needs to take into account the fact that the arc fault current is less than the bolted fault current.

The data can be used to perform a sensitivity study to adjust breaker/fuse characteristics to lower the PPE requirement. To achieve this goal, the existing breakers may need to be replaced, generally by more modern counterparts. Old breakers have relatively slow reaction times and will trip at too high a current. To limit the flash hazard, the breakers are adjusted to trip earlier than before. It is expected that the outcome of this sensitivity study, when implemented, will result in most Category 4 PPE requirements being decreased to Category 1 or 2.

Short-Circuit Study

The short-circuit study is based on a review of one-line drawings. The drawings must be created if they do not exist and field-verified if they do. Maximum available fault current is calculated at each significant point in the system. Each interrupting protective device is then analyzed to determine whether it is appropriately designed and sized to interrupt the circuit in the event of a bolted type of short circuit. Next, the associated equipment must be reviewed to insure that the bus bar is adequately braced to handle the available fault current. Finally, the bolted fault currents are converted into arc fault currents for additional analysis.

Coordination Study

A coordination study is the examination of the electrical system and available documentation with the goal of ensuring that over-current protection devices are properly designed and coordinated. Over-current protective devices are rated, selected and adjusted so only the fault- current-carrying device nearest the fault opens to isolate a faulted circuit from the system. This permits the rest of the system to remain in operation, providing maximum service continuity. The study consists of time-current coordination curves that illustrate coordination among the devices shown on the one-line diagram. Note that protective devices are set or adjusted so pickup currents and operating times are short but sufficient to override system transient overloads, such as inrush currents experienced when energizing transformers or starting motors.

The above figure is a person in a full Category 4 suit. This suit will provide the necessary protection, but it is cumbersome to work in, is hot and provides poor visibility. The suits will make many tasks very difficult, if not impossible, to perform. Because of their restrictions to vision and movement, they may even make some tasks more dangerous. There are definitely times when this type of protection is both necessary and required, but being overly conservative will result in excessive stress for workers and require an unacceptably long time to make repairs or adjustments.

The Problems

Once the hazards associated with arc flash are understood, the challenge becomes to eliminate or at least reduce them. The following section discusses some of the problems and subtleties involved in implementing corrective action.

There are several problems in dealing with arc flash analysis:

1. Being overly conservative in the short-circuit analysis may result in the required PPE category being set at a level higher than necessary.

2. Relying on quick analysis methods can result in exposure to unexpected liabilities. There are a number of shortcuts being offered by individuals and companies that can have disastrous results. Companies should be sure their methods will stand up to analysis and peer review. Cure-all solutions are being promoted, such as the installation of current-limiting fuses. Many firms rightfully believe in the use of fuses, particularly current-limiting types, but as will be shown below, they are not always the answer. They are definitely not a quick-fix solution.

3. Being overly conservative when performing a short-circuit analysis results in the misapplication of circuit protection equipment, which in turn has the consequence of calculated arc flash levels being higher than they actually are.

4. The calculated bolted fault or short-circuit current is a worst-case calculation that assumes very low short-circuit impedance. A bolted short-circuit connection is based upon two conductors being "bolted" together to form the short. In reality, most short circuits are less than ideal, resulting in fault currents that are less than the calculated bolted short-circuit condition.

5. On the other hand, the arc fault should be a more predictable occurrence. The arc fault calculations assume that there is a physical gap between conductors that was bridged by something resulting in the arc formation. Once the arc is formed and plasma is produced, the arc current should closely approximate the calculated fault levels. The arc fault calculations are an approximation based upon research and testing similar to the short-circuit analysis methods. They are not exact, and therefore care needs to be taken when using the results.

Solution

The solution is to first perform, as accurately as practical, a short-circuit analysis. The goal for most people performing a short-circuit analysis has always been to err on the conservative side. For example, when a cable length was needed, it is the practice to always use the shortest practical value, which would result in higher calculated short-circuit current values. When the public utility is contacted, it is the practice to only ask for the worse case short-circuit value.

The overall result is that the short-circuit values are always calculated on the high side. When doing a short-circuit analysis for sizing the interrupting capability of protection equipment, this is the best practice. It is not the best practice, however, when evaluating equipment for arc faults and establishing PPE requirements. This is an extremely significant, and quite nonintuitive, situation.

Arc fault current (I_{fc}) is derived from the available bolted short-circuit or fault current (I_{sc}) and is always substantially less than its corresponding short-circuit current. The Institute of Electrical and Electronics Engineers (IEEE) has established a formula for calculating (estimating) the (I_{fc}), and they provide a spreadsheet. The following are examples of results from using their formula:

Bolted Fault Current @ 480 V	Arc Fault Current
10 kA	= 6.56 kA
20 kA	= 11.85 kA
30 kA	= 16.76 kA
40 kA	= 21.43 kA

What is now important is to obtain?

1. The maximum expected (worse case) bolted short-circuit current.
2. The minimum and maximum voltage to the facility.
3. The minimum expected short-circuit current.

Also needed are definitions of the operating modes of the facility, such as

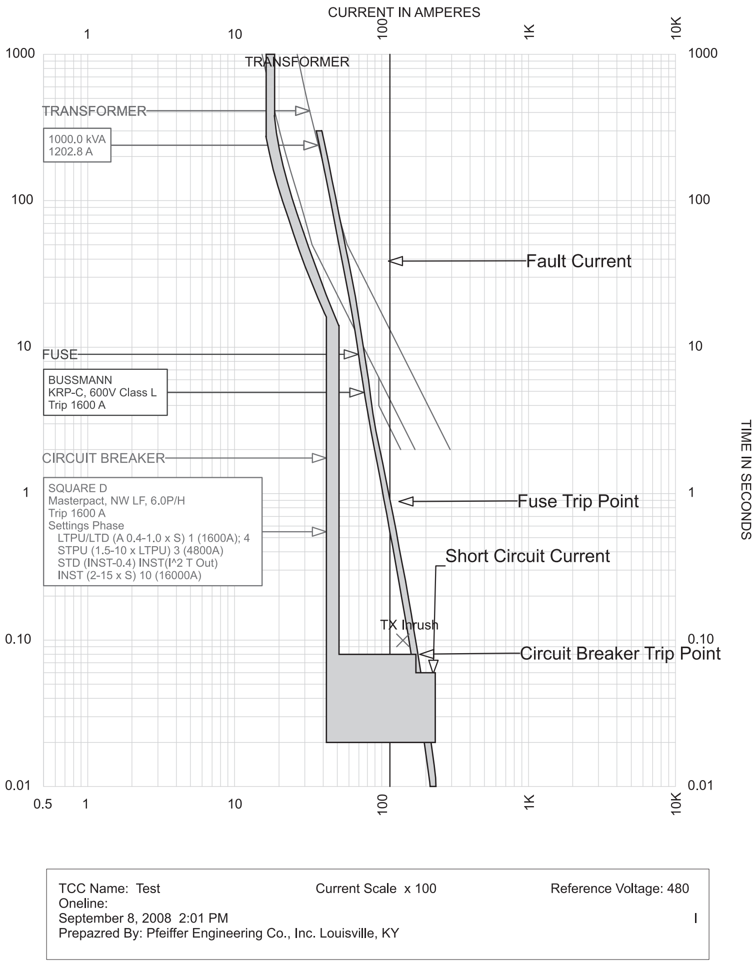
- the minimum and maximum motor loads expected during normal operation and off-hour operation; and
- variation in the sources of supply to the plant, such as alternate feeders or cogeneration.

The data from the public utility and the determination of the facility's modes of operation should be converted into the maximum and minimum arc fault current at various locations in the plant. These results are applied to protective device coordination studies, where the protective devices are evaluated, and adjusted if necessary, allowing the proper PPE categories to be determined.

The curve on the next page illustrates the point.

This figure shows the coordination curve for the secondary of a 1,000- kVA 480 V transformer. The curve shows two types of secondary protection, a fuse and a circuit breaker, each selected based on the National Electrical Code requirements. The fuse is a KRP-C 1600A and the circuit breaker is a Square D Masterpack breaker with a Digitrip.

All transformers limit the amount of fault current that can pass through the transformer. This is a function of the transformer's impedance. The coordination curve shows a line for the (I_{sc}), the maximum short-circuit current that can pass through this transformer (24,056 amps). The (I_{sc}) value used assumes that there actually is sufficient current available at the primary to provide 24,056 amps on the secondary.



Based on the IEEE formula, the calculated arc fault current (I_{fc}) is 11,701 amps. Using these two currents and the coordination curve, the time the circuit breaker and the fuse will take to clear the fault can be estimated.

Bolted Fault Condition
- Fuse clears in 0.02 seconds
- Circuit breaker clears in 0.08 seconds

Arc Fault Condition
- Fuse clears in 0.90 seconds
- Circuit breaker clears in 0.08 seconds

From these current levels and clearing times, the PPE category can be determined.

E_{mb} (maximum in cubic box incident energy)
- Fuse 36 cal/cm^2 Category 4 PPE
- Circuit breaker 2.5 cal/cm^2 Category 1 PPE

Clearly, in this example the circuit breaker outperforms the current-limiting fuse resulting in a minimal "worker-friendly" PPE requirement.

In the above example, both the arc fault current and the bolted fault current are less than the current-limiting point for the fuse, which is approximately 28,000 amps. Thus, there is no current-limit effect from using the fuse. Current-limiting fuses often do provide additional protection, and they are very good devices, but they must be applied properly. In this example, the circuit breaker provides the best protection.

In this example, it can also be assumed that the fuse and the circuit breaker are at the main of a facility and that the facility is served by a much larger transformer where the worse-case bolted short-circuit current as reported by the utility is 60,000 amps. Under this condition, the arc fault current would be 30,300 amps. In this case, the fuse would open in quarter cycle and would limit the fault current.

The **E_{mb}** would equal 1.15 cal/cm^2, which falls under a Category 0 PPE.

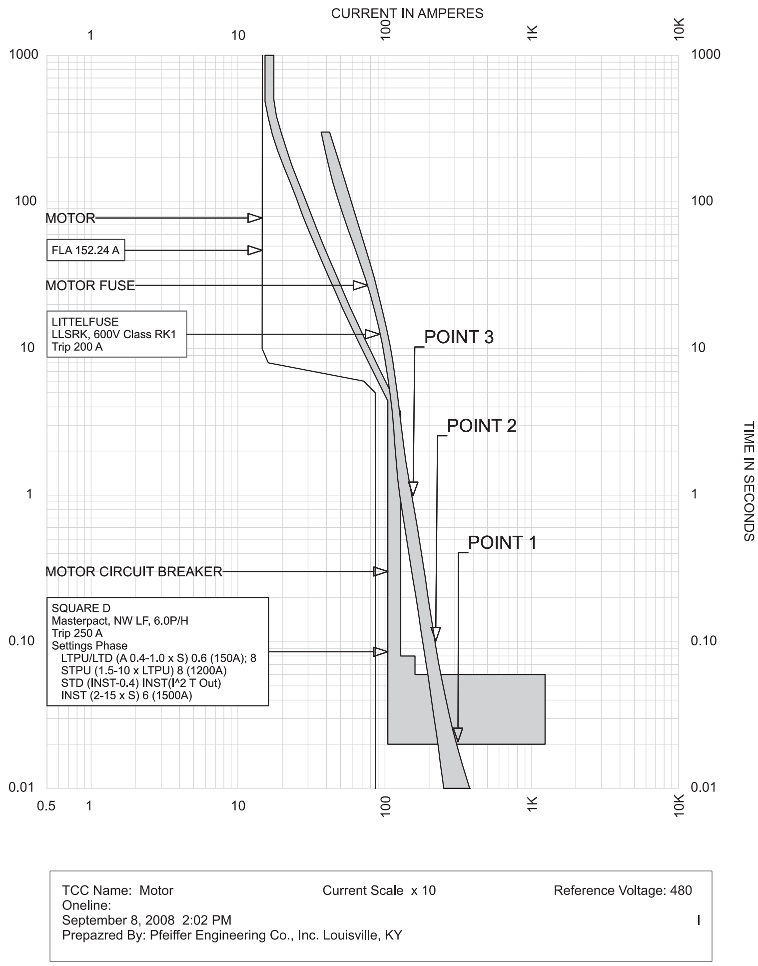
The figure on the next page involves a fuse and a circuit breaker protecting a 125 HP motor. The fuse is a LLS-RK 200 A and the circuit breaker is a Square D Masterpack with an electronic trip. There are three arc fault currents analyzed.

Point 1
- Arc fault current 1600 amps
- Bolted fault current 3200 amps
- Results:
  - Circuit breaker clears in 0.06 seconds 4.57 cal/cm^2 PPE Category 2
  - Fuse clears in 0.02 seconds 1.45 cal/cm^2 PPE Category 1

Point 2
- Arc fault current 1400 amps
- Bolted fault current 2400 amps
- Results:
  - Circuit breaker clears in 0.06 seconds 4.57 cal/cm^2 PPE Category 2
  - Fuse clears in 0.1 seconds 7.62 cal/cm^2 PPE Category 2

Point 3
- Arc fault current 1100 amps
- Bolted fault current 1600 amps
- Results:
  - Circuit breaker clears in 0.06 seconds 4.78 cal/cm^2 PPE Category 2
  - Fuse clears in 1.0 seconds 79.8 cal/ cm^2 PPE Category >4

At an arc fault current of 4000 amps the fuse will begin to current limit and will open the circuit in quarter cycle,



reducing the PPE category to 0.

The three points analyzed show that a relatively small change in calculated bolted fault current has a major effect on the calculated arc fault current. This situation could easily lead to the misapplication of circuit protection equipment or inappropriate adjustment of same. It should also be noted that as the calculated arc fault current is reduced, the clearing time increases, resulting in the incident energy level increasing and thus the PPE requirement increasing.

In reality, the arc current is primarily affected by facility operating conditions, i.e., motor contribution and changes in the fault current coming from the utility. The examples illustrate that the accuracy required when calculating short currents has to be improved over traditional methods. Both reliability and arc fault conditions must now be considered when performing coordination studies.

The Risk

In a study of 33 plants with 4892 busses or switch points under 600 V, the median incident energy was only 2.1 cal/cm^2, however, many busses had quite high incident energy levels[2] :

- 24% of busses over 8 cal/cm^2 PPE Category 2
- 12% of busses over 40 cal/cm^2 PPE Category 4
- 5% of busses over 85 cal/cm^2 deadly – no protection
- 1% of busses over 205 cal/cm^2 deadly – no protection

Risks to personnel include[3]

- burns,
- damaging sound levels and
- high pressure (720 lb/ft^2 eardrums rupture; 1728 to 2160 lb/ft^2 lung damage).

Conclusions

1. Arc fault analysis is actually risk management. There are basically three choices:
   - Be very conservative and require PPE Category 4, in most cases resulting in higher maintenance cost.
   - Do nothing and suffer the consequences (pay later).
   - Perform the necessary analysis and make adjustments to reduce the arc fault conditions resulting in reduced PPE requirements.

2. A reduction in bolted fault current and thus a reduction in arc fault current can actually result in a worse situation. In the motor example above, an arc fault current reduction from 4000 amps to 1800 amps resulted in an increase in arc fault energy from 0.6 cal/cm^2 to 78.8 cal/cm^2. This is exactly the opposite of what one would expect before doing the math. In terms of the above example coordination curves, this occurs because the arc fault current moves from the instantaneous portion at the bottom of the coordination curve to a point higher up, incurring a the time delay before the device trips.

3. Overly conservative short-circuit analysis will result in bolted short-circuit numbers that may well result in the misapplication of circuit protection equipment.

4. It is very important to obtain the minimum available short-circuit current as well as the maximum short-circuit current from the electric utility. Voltage fluctuations in the plant supply should be considered when developing the short-circuit calculations. The arc fault calculations need to be evaluated at more than just the worst-case and the minimum-case conditions. In the example above, a reduction in the arc fault current actually resulted in worse conditions. This represents a subtle,

but extremely significant, change in the methodology of short-circuit analysis.

5. Apart from the fines, nominal compliance with the regulations will cause workers to have to wear cumbersome PPE. This will result in little or no high-voltage maintenance being performed, eventually compromising safety, equipment operation and ultimately productivity. Arc flash is a risk management issue.

[1] "Arc Flash: Do You Understand the Dangers" ©Copyright 2008. Pfeiffer Engineering Inc. All rights reserved. John Pfeiffer, president, Pfeiffer Engineering Co. Inc., www.pfeiffereng.com.
[2] "A Summary of Arc-flash Hazard Calculations," D.R. Doan & R.A. Sweigart.
[3] "Arcing Flash/Blast Review with Safety Suggestions for Design and Maintenance." Tim Crnko & Steve Dyrnes.

Your comments are welcomed!

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