Networked District Cooling Plant Offers Lower First and Operating Costs

by

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ABSTRACT

Recent improvements in HVAC control networking technologies together with an improved understanding of the nature of cooling loads in buildings offer enormous potential improvements in the cost effectiveness of district cooling plants. By carefully coordinating the district cooling plant design with a digital controls network to the loads served, the following economic advantages over traditional district cooling concepts are possible:

1. A smaller sized and therefore less costly chiller plant will serve the load.
2. A significantly higher annual operating efficiency can be achieved.

A district heating and cooling plant currently under design for a moderate sized mixed use community will utilize a fully networked control system. The network based controls permit the plant to respond to actual loads at each point of use, adjusting both flow and chilled water temperature to optimize the operating efficiency of the overall system at all times. Furthermore, the network permits distributed point of use management of cooling or heating shortages that might occur in the event of a component failure in the plant. This automatic network based management scheme will ensure that critical loads are maintained and no one load suffers disproportionately under such conditions, reducing the need for redundancy in the plant design.

This paper focuses on the cooling portion of the plant. It discusses benefits arising from the synergy of incorporating the communication and control network as part of the chiller plant design. The background and design considerations are discussed to show how the principles can be applied to other district heating and/or cooling plant designs.

Key Words: Chiller, Network, Integrated Control, Efficiency, Distribution

BACKGROUND

The project site is a new community being built around a light rail commuter transit station in Beaverton, Oregon, a suburb in the greater Portland area. The community consists of condominium housing, restaurants and retail, theaters, a hotel, and several mid rise office buildings. Area of the total facility will be approximately one million square feet of conditioned space. The area surrounding this development is fast-growing light industrial with a high-technology focus.

The developer contacted our client, a non-regulated energy services division of a major gas/electric utility, as part of an effort to find a partner to develop the infrastructure of the site. The focus of this development is to provide living space that will fully accommodate the needs and desires of those working in the local high-technology industry. The community is medium/low rise urban with a European flavor. In the initial discussions, a significant concern was voiced about the visual and acoustical issues associated with the outside heat exchangers required for air conditioning units. It was determined that if a district heating/cooling plant could be developed which provided individual accounting for each occupancy at a cost competitive with individual heating/air conditioning units, that alternative would be adopted.

CHILLER PLANT ECONOMIC ANALYSIS

When the costs of a central chiller plant, distribution piping, and building conversion equipment are compared with simple rooftop systems, it is often difficult to configure a plant that is cost competitive with the simpler distributed cooling systems. Our analysis focused on the following areas that are to the advantage of the Central Plant concept when viewed from a long term cost perspective:

1. The diversity of loads in a multi-use complex means the total size of the chiller plant is smaller than the total of the individual cooling units required.
2. By integrating the central plant with robust communications and a control system capable of effectively managing and shaping the loads it serves, plant size can be further reduced by providing load shaping during the few periods of peak cooling demand through the use of "Dynamic Control" algorithms which provide pre cooling to reduce peak cooling loads when capacity is limited.
3. By incorporating recent advanced technology developments in the design and control of the chiller plant and chilled water distribution, the system can be simpler and less costly to install, and its annual energy use can be significantly reduced.
4. By employing high quality components and a robust, intelligent communications/control network as the facility management system, improved occupant comfort, low cost energy accounting, and more efficient and less costly maintenance services can be achieved.

When the advantages of a smaller plant size and significantly lower energy and maintenance costs were considered, it was determined that a central plant was indeed a viable alternative for this facility. The developer reviewed our comparisons and accepted the central plant concept. Our design effort began.

TURNING A VISION INTO REALITY

While our economic model was conservative in its assessment of the advanced network based control technologies incorporated in the concept, it nonetheless depends on combining the plant with an efficient controls network to meet its financial targets. With the plan accepted, we now had to consider how to practically implement these advanced technology based solutions that extend well beyond the traditional boundary of a district plant. To start, we had to rethink the boundaries of this proposed district plant. Traditionally, a district plant is often isolated from the loads it serves. In this traditional approach, the plant operates to follow the loads. As the demand for chilled water increases or decreases, the plant reacts to increase or decrease the flow of cooling to the loads. Decisions regarding operation, replacement, or expansion of a district plant are usually based primarily on information gathered within the walls of the plant which are typically seen as the limits of the district plant's responsibility and control.

To make this proposed district plant work, we had to consider a new view of what a district plant can be. Instead of a separate entity that simply reacts to external loads, the central plant proposed for this project included the entire controls and communications system of the facility. Under the proposal accepted by the developer, our energy services client will own and operate not only the district heating/cooling plant, but the Direct Digital Control (DDC) facility management system as well. From the plant, our client will provide maintenance services as well as heating and cooling energy for the entire complex. This is an excellent fit into the business plan of our client's firm and also serves the desire of the developer to outsource facility operations.

Owning and operating the communication and control network also affords the energy services firm an outstanding position to expand its services business. The communication network can provide plant optimization and load shaping that contribute to the energy efficiency of the plant operation, and self diagnostic features that reduce the facility's maintenance costs. The network also provides a connection to the end users of the plant - the office tenants, retail shops, and condominium owners - and an opportunity to provide additional energy related services in order to evolve into a "comfort services" firm.

The proposed central plant required one more important break from tradition. If our client is to own, install, and operate the facility's DDC system, and provide energy accounting throughout the facility, there needs to be close coordination concerning the design of the HVAC systems themselves. Again this was a good fit for our client, since as an energy service company, it is in the business of providing energy conversion system expertise and system selection criteria. The result was that our client was invited to take charge of and manage the entire mechanical design effort for the developer. Now, the developer is receiving timely, unbiased advice concerning HVAC system alternatives and features, while the close coordination of the plant with the facility is assured. Our energy services client has contracted with a design/build contractor and the design has been proceeding for more than six months. Construction began in September.

DESIGN ISSUES FOR DISTRICT PLANTS

Over the years, we have analyzed the annual loading cycles of chiller plants serving various types of commercial buildings in many different climates. We have found through hourly simulation of typical buildings that the cooling load profiles within broad categories of commercial buildings are primarily influenced by daily and seasonal weather cycles. Furthermore, we have found that outside of tropical climates, North American climates have very similar cyclical weather patterns throughout their cooling seasons. Though the peak design dry bulb, wet bulb and solar insolation conditions vary widely across North America as do the hours during which mechanical cooling is required, the load profiles (i.e. the percent of time buildings spend operating at various ratios of peak loading) are very similar, and these loading profiles correlate very closely to weather cycles. By understanding and exploiting these similarities, basic rules can be developed and uniformly applied to district plant designs over a wide range of climates. First among the rules designers should consider is the fact that the load profiles for chiller plant operation are very similar no matter where in North America the plant is situated. This is shown in Figure 1 which was developed from our in-house hourly simulations of mixed use commercial buildings typical of the Beaverton campus in five different US climates. Figure 1 contains two plots. On the right side is a plot that shows the expected annual hours of operation of a chiller plant to serve the mixed use campus. This ranges from a high of about 68% of the year for the warm Los Angeles climate to a low of about 20% in temperate Seattle/Portland Climate. It is not shown in Figure 1, but it should be noted that the Los Angeles climate would also require a system of approximately 20% greater peak cooling capacity than the Seattle/Portland climate for an identical facility and the cooling tower would be designed for a higher wet bulb temperature. However, once those climatic adjustments were made to the cooling plant design, the actual load profiles for the system in operation are remarkably similar. This is shown in five groups of plots on the left portion of Figure 1.

Note in Figure 1 that although the hours of operation vary from climate to climate (and equipment sizing varies to serve the similar facilities), the percent of time the plant spends operating at various percentages of peak load is almost the same for each climate. Furthermore, assuming each plant is similarly designed (e.g. 85°F condenser water and 42°F chilled water at peak conditions) the reduction in wet bulb temperature from design conditions and potential increase in chilled water temperature will permit very similar temperature and flow optimization patterns in each climate. This is an important finding, for while the local climate will dictate the size of the plant and the total number of hours it operates each year, we have found the operating profile of plants to be very similar throughout the US and Canada. **Since the overall energy efficiency of a chiller plant is determined primarily by its load profile (i.e. the percent of time it spends operating at various loads), a central plant design and operations strategy**

that provides a certain annual average kW/ton in one climate, will provide very close to the same average kW/ton in any climate in which it is implemented.

A second important rule we have found and employ in chiller plant designs is that they spend an overwhelming majority of their operating hours at low part load conditions. This is illustrated very clearly in Figure 1 in which the majority of operating time is spent at loading less than 40% of design. Traditional design activities tend to focus on peak load conditions. The design of the Beaver-ton project focused its design effort on achieving efficient operation at part load conditions. Peak load is primarily a sizing issue since because the short time systems spend operating at that point, efficiency at that point usually plays only a very small role in the overall operating economics of the plant.

NEW OPPORTUNITIES WITH ADVANCED TECHNOLOGIES

The description of this project would not be complete without a brief explanation of how advanced technologies are incorporated into the design. One of the most exciting advanced technologies available to chiller plant designers today is the variable frequency drive for AC motors. The VFD, as it is usually called, offers an enormous opportunity to improve the economics of part load operation, but this opportunity is only rarely fully realized in HVAC designs because VFDs are often treated as direct replacements for mechanical flow control devices. When so applied, only a very small portion of their total efficiency improving potential is tapped. A graph of the part load efficiency for VFD operated pumps and fans is shown in Figure 2. The bottom line shows the changes in operating efficiency at various flow rates for a typical centrifugal fan or pump that utilizes a mechanical flow control device such as a vane or regulating valve. Such mechanical devices are typically employed on constant speed chillers to reduce capacity at part load conditions or on fans and pumps to reduce flow at periods of low flow demands. When properly designed, these devices maintain an approximate constant level of efficiency as flow is decreased to about 50% of maximum. Thereafter, the efficiency decreases significantly as flow is further reduced.

We know from centrifugal fan and pump laws that theoretically the connection between power and flow is a third power relationship. This means that when flow requirements are reduced to 50% of design maximum, that flow could be delivered at one-eighth the design point power. This means the 50% flow could be delivered at four times the peak load efficiencies. Despite the introduction of variable frequency technologies to our industry nearly a decade ago, high part load efficiencies are rarely achieved in actual applications because VFDs are typically applied to operate in constant pressure applications. When incorporated into typical chiller and pumping designs in this manner, the performance at various flow requirements is represented by the middle line in Figure 2. The difference between the middle and bottom line represent a substantial energy savings at part loads. But it does not capture anywhere near the full potential savings of variable speed technology which is represented by the top line.

To understand why many VFD applications result in only marginal part load efficiency improvements, consider an application in which an existing variable flow chilled water distribution system that utilizes a constant flow pump and a pressure operated bypass valve is retrofitted by installing a VFD on the motor and replacing the bypass valve with a differential pressure sensor that controls the motor speed through the VFD. Because the head pressure requirement of the circuit is unchanged, the VFD cannot slow the motor significantly as the load decreases because pump head pressure also falls as the pump speed is decreased. Thus applied, this VFD cannot slow the motor below the speed at which the pressure setpoint is the cutoff head pressure, and the full savings potential of the VFD will not be realized.

If it is suggested that the differential pressure controller be set at a lower value, a responsible operator would resist because it is possible some loads would be “starved” at pressures less than the design pressure. However, if a DDC controls network operates the pump as well as the chilled water valves on the loads it serves, this networked system can allow the supply pressure to be adjusted downward when no load control valves are fully open. This “networked” approach to VFD applications typically results in an efficiency profile as represented by the top in Figure 2. As described above chilled water systems spend most of their time operating at part loads and part flows. Consider Figures 1and 2 together for a moment. Note that highest operating efficiencies for centrifigal devices operating under variable speed, variable pressure control occur at loads where cooling plants spend most of their time operating. Therefore, the annual operating cost impact of an operations strategy that permits pressure to vary with flow such that pumps are allowed to operate as close as possible to their highest part load pumping efficiencies is enormous. Furthermore, every energy consuming element in a centrifigal chiller plant, from the tower fans to the pumps and chiller itself are subject to these part load efficiency improvements.

The design developed for the Beaverton campus employs network based optimization to exploit the benefits of variable speed and variable pressure control from each of components in the system. Our simulations of loads and operating efficiencies have shown that the energy use of such a networked based chilled water plant will be substantially less than the typical energy use associated with campus chiller plants and distribution systems.

EFFICIENT CHILLED WATER PLANT DESIGN

The design we selected for the Beaver-ton chiller plant is a very simple equipment configuration whose operation is controlled by a control system network that integrates the operation of the plant with all loads served and provides variable temperature and variable flow chilled water as required to satisfy the loads at all times. Schematics of the chilled and condenser water circuits are shown in Figure 3 and Figure 4. Three equal sized chillers are employed with headers for chilled and condenser water such that pumps are not dedicated to individual chillers. This design has been developed to ensure that any single failure will not reduce the total plant capacity by more than one-third. The design goal of the plant is also that it be resilient to multiple failures without adding the cost and complexity of redundant components. In this design, a single circuit variable flow chilled water production and distribution system supplies chilled water throughout the campus, operating to maintain a neutral pressure between the supply and return headers at each building. This approach has been employed with success in chilled water distribution systems (Kirsner 1996).

The size requirements of the chilled water plant is reduced because the plant design is combined with an integrated controls network. The controls network is designed to anticipate peak use periods with the anticipatory control features of “Dynamic Control” algorithms that permit anticipatory load leveling on peak cooling days which reduce the size of the maximum plant capacity by approximately 20% (Hartman 1988).

Variable flow secondary pumps located at each building draw chilled water from the supply header and distribute it as required to the loads within the building. The secondary pump speed is controlled to maintain the loads in the building as determined by the valve position of the cooling coils served, and other factors (Hartman 1996). The primary and secondary pump circuits are not decoupled so that in the event of a secondary pump failure, the primary supply pressure can be increased to deliver some limited flow of chilled water to the affected building until the secondary pump is restored to normal operation. This strategy results in a mechanically simple system that is also reliable but without cost penalties for redundant equipment. It is a requirement that the chilled water system operate continuously to provide chilled water as required at all times throughout the year. The neutral pressure design of the distribution network ensures that no unnecessary chilled water pump power is expended during periods of very low chilled water requirements.

Both the chilled water and condenser circuits of each chiller are variable flow. The benefits of incorporating a single variable flow hydronic circuit for chilled water production and distribution include lower first cost and higher overall operating efficiencies (Hartman 1996). The variable flow condenser circuit operates with low head, variable flow towers, which are staged as required with automatic isolation valves. An automatic brush type tube cleaner system is installed on the condenser bundle of each chiller to keep the tubes clear of sediment during extended periods of low condenser flow.

The chillers are staged as required to both condenser and chilled water circuits via electric actuated isolation valves. A plate and frame heat exchanger is also included in the plant to provide direct tower cooling chilled water in the cool and cold periods of the year. A bypass valve at the end of the chilled water distribution loop is opened at periods of very low demand to maintain water flow at all times to ensure the loop temperature remains uniform at those times.

CHILLER PLANT OPERATIONS

The Beaver-ton chiller plant will be automatically operated by the DDC Facility Management System. Operation of the chillers, pumps and tower fans will be automatically coordinated to maximize their operating efficiency at all times. An important focus of this'unique operations strategy is how the energy optimization is to be implemented. Our research in chiller plant operations has shown that operating equipment according to predetermined electrical loading ratios rather than measuring and adjusting temperature and flow setpoints is the best way to optimize chiller plant operation. Within broad temperature and flow ranges, the Beaver-ton plant network control system will operate pumps, chillers and towers to maintain the chilled and condenser water pumps, chiller, and tower fan in accordance with predetermined relative power consumption relationships. For example, as a decrease in cooling is required to meet a falling cooling load, the DDC system will decrease power to chilled water pumps, the chiller(s), condenser pumps and tower fan(s) according to a predetermined ratio of power usage. At full load, the components would all operate at 100% of their design maximum power draw. As the load decreases as determined by less chilled water pump power required to maintain the neutral pressure of the chilled water distribution system, the electrical drive units of the chillers, condenser pumps and tower fans will all be similarly reduced according to a simple control algorithm that establishes at all times the amount of power draw each component shall draw relative to one another. In this way, the chiller plant will operate as a single integrated system which is key to the energy optimization strategy.

ENERGY PERFORMANCE GOALS

Our experience is that traditionally designed chiller plants and campus distribution systems typically consume annual average total energy use of from 1.5 to well over 2 kW/ton of chilled water delivered to the loads they serve. Our analysis determined that the Beaverton cooling plant total annual energy use will be between 0.5 and 0.7 kW/ton. This includes all energy for chillers, towers, condensing pumps, and both primary and secondary chilled water pumps. Since, as described earlier in this paper, district plant cooling profiles are relatively similar throughout North America, this is a reasonable goal for a plant anywhere that employs a network based design and operations strategy.

NEW MARKETS FOR DISTRICT COOLING PLANTS

The success of this networked district cooling plant concept cannot be determined until it has been completed and has some operating history to compare with our assumptions. However, it is already known that the impact of applying advanced, networked based design concepts to building energy systems offers a significant opportunity to capture revenue from the savings stream. Networked control strategies for chiller operation within buildings have been employed successfully for many years (Hartman 1988). With the advent of energy deregulation, a number of energy service firms are emerging that wish to provide value added services beyond simply supplying electric energy. District cooling plants have the potential to become a boom industry across the US and Canada. With the CFC phase out, the stock of obsolete chillers still in use is staggering. The inherent inefficiencies of these older plant designs combined with the rapidly escalating costs of keeping these chillers operational offer an enormous business opportunity to energy service firms that wish to own and operate this new type of chiller plant. A network based chiller plant located in one building and serving several within a block can be much less costly to install than to upgrade each individual chiller plant on that block. Furthermore, the operation and maintenance staff provide an excellent springboard for the energy services firm to offer the local building owners to take over their entire energy systems operations and maintenance. This outsourcing opportunity is of great interest to the Real Estate Investment Trust (REIT) ownership that is rapidly growing in the commercial building segment.

To successfully exploit this business opportunity, energy service companies cannot simply apply traditional chiller plant and control technologies, because the most substantial competitive advantages of district plant concepts in today's market arise from their ability incorporate advanced technologies for lower construction costs and higher operating efficiencies than standard plants.

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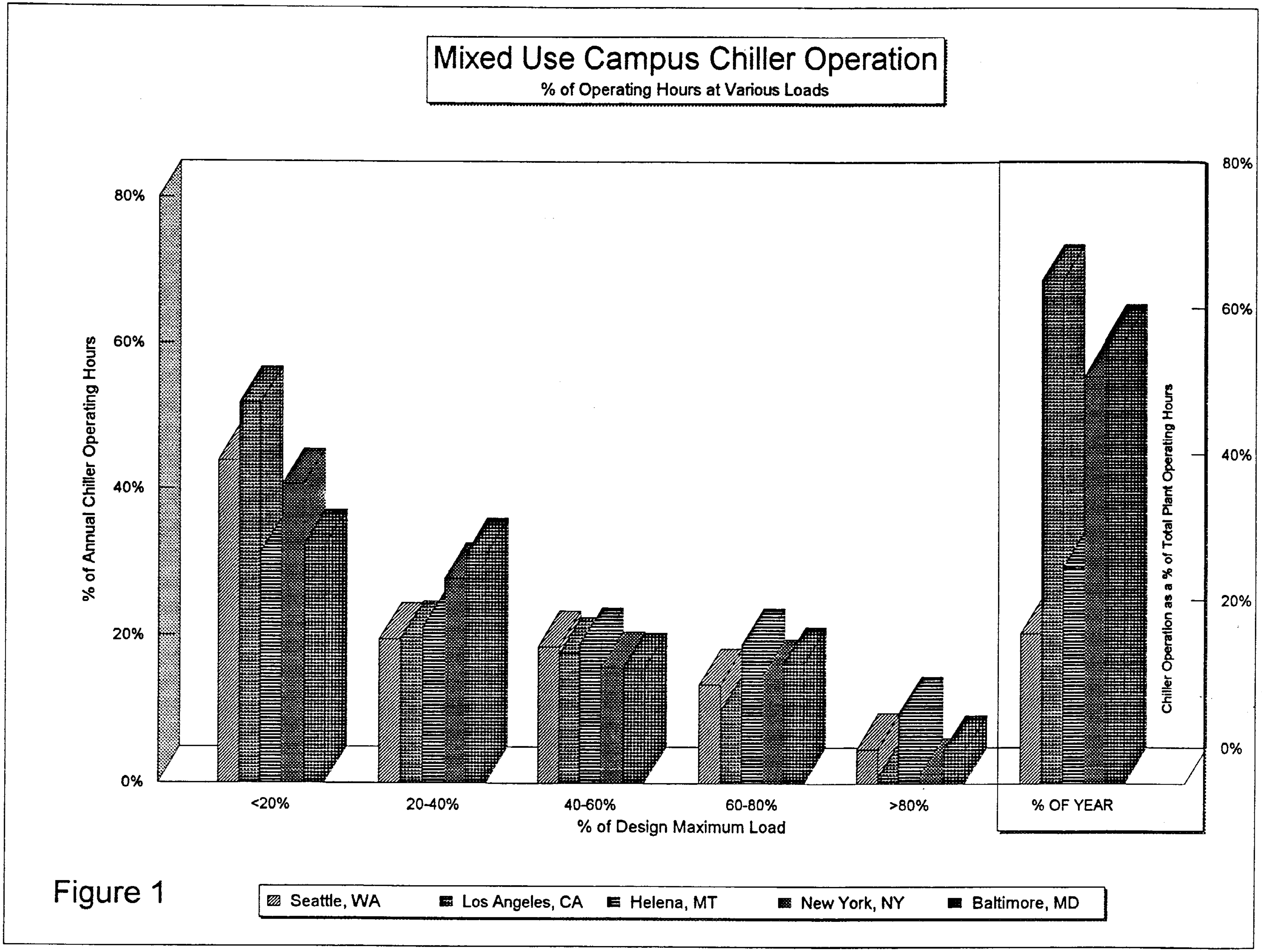


Mixed Use Campus Chiller Operation
% of Operating Hours at Various Loads
% of Annual Chiller Operating Hours
80%
60%
40%
20%
0%
Chiller Operation as a % of Total Plant Operating Hours
80%
60%
40%
20%
0%
<20%
20-40%
40-60%
60-80%
>80%
% OF YEAR
% of Design Maximum Load
Seattle, WA
Los Angeles, CA
Helena, MT
New York, NY
Baltimore, MD

Figure 1

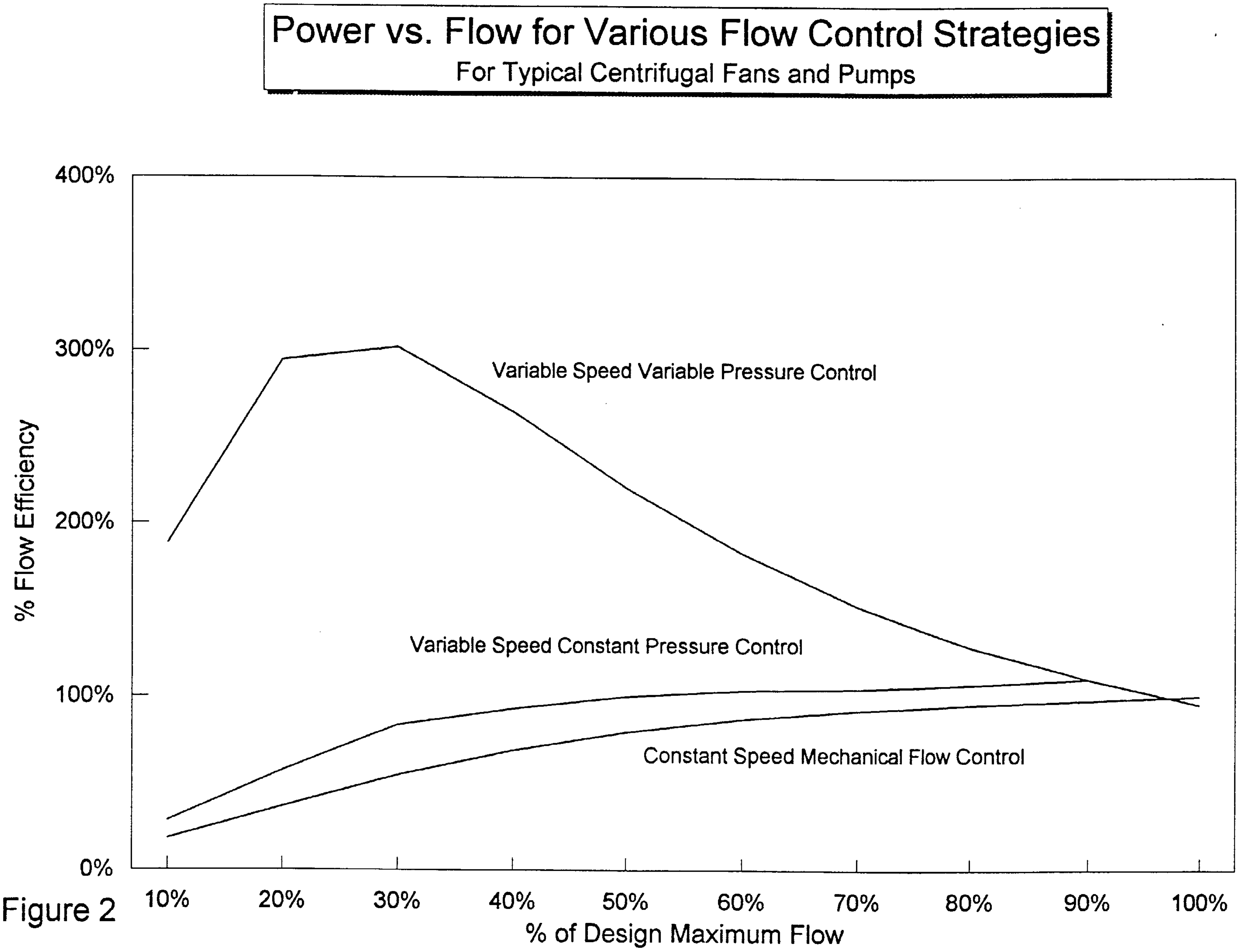

Power vs. Flow for Various Flow Control Strategies
For Typical Centrifugal Fans and Pumps
400%
300%
200%
100%
0%
% Flow Efficiency
Variable Speed Variable Pressure Control
Variable Speed Constant Pressure Control
Constant Speed Mechanical Flow Control
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
% of Design Maximum Flow
Figure 2

Figure 3

NOTE: Chilled water temperature is automatically adjusted based on demand from 42°F to 54°F

NOTE: P1 & P2 operate continuously to maintain adequate flow through chiller(s) and to maintain neutral pressure in supply/ return distribution system. System shall be a 15% glycol solution.

NOTE: All chillers are electric, centrifugal with integrated BACnet controls.

CWV1-4 & BPV-1 are electric 2-way valves for full line size.

All pumps operate via variable speed control.

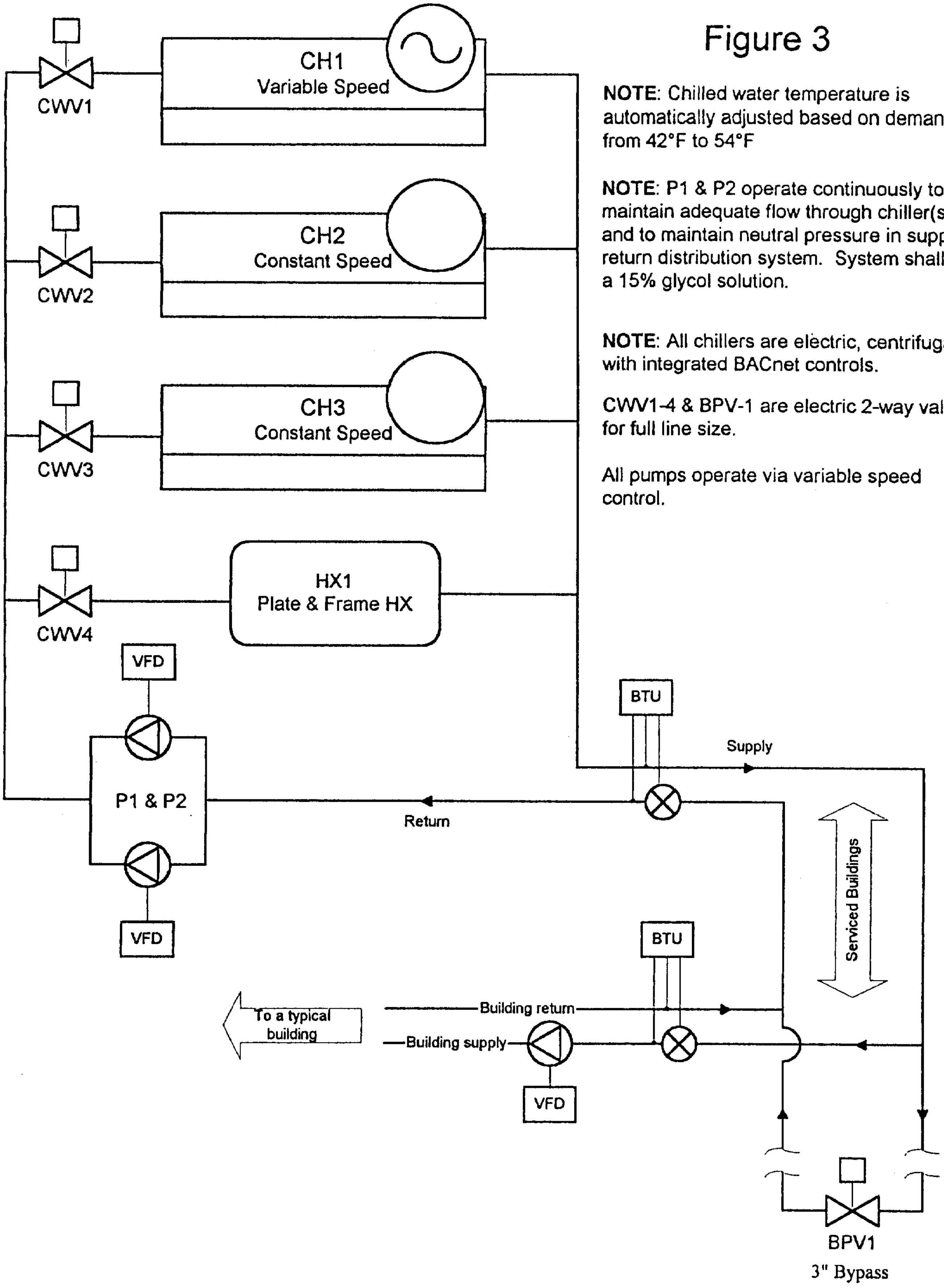
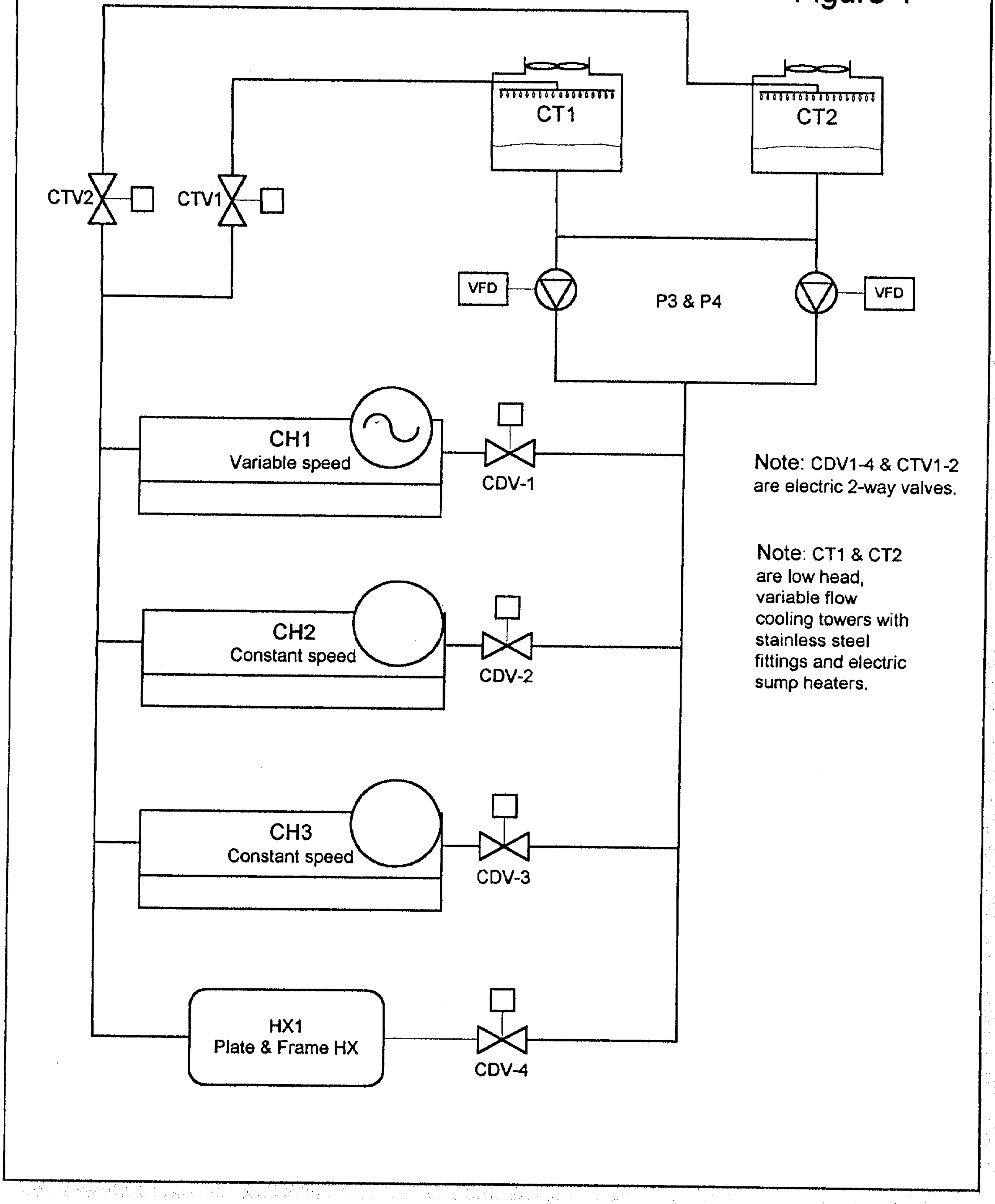


Figure 4


CT1
CT2
CTV2
CTV1
VFD
VFD
P3 & P4
CH1
Variable speed
CDV-1
CH2
Constant speed
CDV-2
CH3
Constant speed
CDV-3
HX1
Plate & Frame HX
CDV-4
Note: CDV1-4 & CTV1-2 are electric 2-way valves.
Note: CT1 & CT2 are low head, variable flow cooling towers with stainless steel fittings and electric sump heaters.