OPTIMIZATION OF CHILLED WATER SYSTEMS

B. N. Gidwani, P.E.
Project Director
Roy F. Weston, Inc.
West Chester, Pennsylvania 19380

ABSTRACT

Chilled water systems are one of the major energy consumers in industrial, commercial, and institutional complexes. The centralization of chilled water systems has considerable advantages, namely: simplified controls, the installed capacity is reduced due to diversity, consolidated maintenance and operation, etc. With central chilled water systems, the following areas present potential energy and cost savings:

- Chilled Water Reset
- Condenser Water Reset
- Sequencing of the Chillers
- Chilled Water Storage
- Variable Chilled Water Pumping

In this paper the feasibility aspect of each of the above items will be discussed.

CHILLED WATER RESET

DISCUSSION

Chilled water systems are selected for full-load design conditions that are represented by a pre-determined water temperature to the coil and temperature rise across the coil. These conditions do not occur the majority of the time. During loads less than full-load conditions, a higher chilled water supply would meet the system requirements.

The chiller efficiency can be increased by raising the return chilled water temperature. This is indicated in Figure 1. For each 1°F rise in chilled water supply temperature, there is an increase of 1 to 1.5% in coefficient of performance (COP). Even for the same temperature difference (10°F between supply and return water) the power consumption is considerably less for a chiller with a range of 58°F to 48°F than for a chiller with a 54°F to 44°F range.

As indicated in Figure 1, the coefficient of performance varies with the type of chiller. The screw type chiller has the greatest increase in COP while the absorption chiller has the least increase in COP per degree change in supply water.

METHODS OF IMPLEMENTATION

Using Space Conditions

(Figure 2). By evaluating the performance of all of the cooling coils through a selector switch and then establishing the greatest cooling coil load requirement, the supply chilled water can be raised proportionally. This assures that the chilled water temperature is low enough to satisfy the worst condition and the chiller controls can be adjusted accordingly.

Using Return Water Temperature

(Figure 3). This method is based on the assumption that lower return water temperature indicates a reduced cooling load. This is only true if the system is a constant flow type (i.e., using three-way control valves). A two-way control valve or variable flow system reduces its flow as the load drops; hence, return water temperature will not indicate actual load conditions. This return water temperature method of control is less desirable, since, even in a constant-flow system, certain areas may be at full load whereas others may be at very low load. Thus, increasing the supply water temperature based on average return water temperature will not satisfy the full-load areas.

Through Outside Air Temperature

By evaluating the enthalpy of outside air and enthalpy of design conditions, the chilled water supply temperature can be varied proportionally.

Cost Savings

Energy Saving (kWh/Year).

= Chiller Average Load (tons) x Operating Hours x Average kW/ton x Saving (%) per Degree Reset x Number of Degrees Reset

Table 1 shows the method of calculating:

- Chiller average load.
- Operating hours.
- Average kW/ton.

Proceedings of the First Symposium on Improving Building Systems in Hot and Humid Climates, August 1984

CONDENSER WATER RESET

DISCUSSION

Cooling towers in the past have been designed to maintain a constant supply water temperature to the condenser (approximately 85°F±). The reasons were that chillers are easier to control with a condenser water temperature of around 85°F± and that a savings in fan horsepower results.

Recent studies have indicated that modern chillers can tolerate a considerable variation of condenser water temperature. This temperature is established by the ambient wet bulb temperature plus wet bulb approach. Normally, approach varies between 5 to 10°F. Thus, as the ambient wet bulb temperature drops, the condenser water temperature can drop. An increase in efficiency of a centrifugal chiller can be approximately 1% per degree drop in condenser water temperature (Figure 4). This more than compensates for any additional fan horsepower required for continuous operation of the fans.

METHOD OF IMPLEMENTATION

(Figure 5). Condenser supply water temperature can be controlled through ambient wet bulb temperature plus the tower approach value. However, this method has a drawback due to difficulty in maintaining the accuracy of the wet bulb signal. This drawback can be eliminated by use of two outdoor sensors, namely, dry bulb and dew point, which can be combined to derive an outdoor wet bulb temperature. This temperature value can then be used to reset the condenser water temperature.

RESET CONDENSER WATER TEMPERATURE

Calculations

Energy Savings.

$$= \text{Average Load (tons)} \times \frac{\text{kW}}{\text{ton}} \times \text{Operating Hours} \times \text{Percent Power Reduction}$$

Where:

Percent Power Reduction

= (Design Condenser Water Temperature -

Average Condenser Water Temperature)

x Percent Power Reduction per Degree

Table 1 shows the method of calculating:

- Average load.
- Operating hours.
- Average kW/ton.

Table 2 shows the method of calculating:

- Average condenser water temperature.

SEQUENCING OF THE CHILLERS

DISCUSSION

Both centrifugal and absorption chillers operate most efficiently in the middle to upper range of their design capacity.

As loads increase or decrease in a central system, the number of chillers operated and (where possible) the size of chiller(s) used should be selected to maximize total chiller efficiency. This can be done manually, using a prescribed operating procedure for each load level, or through automatic controls.

The system configuration plays an important role in establishing the economics of sequencing. For example, sequencing of chillers in series will be economically more feasible than chillers in parallel for the simple reason that no additional pumps have to operate for multiple chillers. Also, primary/secondary pumping systems are a good opportunity for sequencing since the primary pumps which are interlocked with the chillers are usually small in size.

Figures 6 and 7 show the operation of three chillers of a chiller plant of an industrial complex and Table 3 shows method of calculating the savings.

CHILLED WATER STORAGE

DISCUSSION

A conventional chilled water system produces chilled water, as required, to meet the building load. In most parts of the country, a substantial penalty charge is levied on electricity consumed during daytime periods. The purpose in a chilled water storage system is to allow a surplus of chilled water to be produced and stored, during periods when no penalty clause is in effect, for use during on-peak periods.

An important factor in determining the feasibility of a chilled water storage system is the building's cooling load profile. A profile with a marked difference between on-peak and off-peak loads is more appropriate for storage than a profile that is relatively level. The "peak/valley" type profile allows chillers that are normally at low load or idle during the night to operate at near capacity and store surplus chilled water. The stored chilled water is then used during on-peak hours to minimize the load seen by the chillers.

ANALYSIS

The analysis of chilled water storage must begin with the establishment of a building cooling load profile (Figure 8). Using the area under the curve during on-peak and off-peak hours and the maximum chiller capacity, possible storage operating modes can be established (Figures 9 and 10). The storage tank(s) will be sized to fit the proper operating mode. Storage tank configuration is another variable that is specific to each application. The number of storage tanks installed presents a trade-off: the more tanks, the smaller the gross capacity required and the better the separation between supply and return water; with more tanks, however, the larger the surface area to volume ratio and the higher the tank cost.

COST SAVINGS

The potential cost savings from chilled water storage is a function of the local electric rate structure. In order to calculate the potential savings, the local electric contract must be thoroughly analyzed. The items of most significance are time of day consumption rates, time of day demand charges, and the demand ratchet clause. With a typical 12-month ratchet clause, a peak month reduction in on-peak demand can reduce as many as 12 monthly electric bills. Chilled water storage will affect on-peak demand by minimizing chiller requirements during on-peak hours. A sophisticated control system with demand limiting capabilities will be required with the system to monitor and maintain an acceptable demand level. Since any demand peak above the ascribed limit will increase the demand charge for the ensuing 12 months, the role of these controls is a crucial one.

Another component of the electric rate schedule that can be exploited with a chilled water storage system is time of day consumption charges. In some areas of the country, a kilowatt-hour of electricity is more expensive during "on-peak" hours than off-peak hours. This presents another potential savings from off-peak generation and chilled water storage.

SUMMARY

It is important to note that chilled water storage, which is a cost saving opportunity, must be completely analyzed for every application. Very few generalizations can be made regarding these systems. Too much depends on system size, type, load profile, and local electric rates to define any "rules of thumb."

VARIABLE VOLUME PUMPING

DISCUSSION

A significant energy and cost savings can be realized by the installation of variable speed pump drives. Standard centrifugal pumps provide nearly the same flow under all load conditions. Essentially all chilled water in excess of that required to meet the load is being pumped unnecessarily through a bypass system. If the chilled water system utilizes three-way valve control, this bypass occurs at the three-way valve. If the system is primarily two-way valves, the bypass occurs between the supply and return lines, usually near the chilled water pump.

Variable volume pumping allows the elimination of the bypass by supplying only enough chilled water to meet the cooling load. One requirement of a variable volume system is that control be provided with two-way valves. If the existing system utilizes three-way valves, a complete replacement program would be required.

ANALYSIS

The energy savings resulting from variable volume pumping come directly from reducing electric motor consumption. Installing variable-speed drives on each pump motor makes this possible. Variable speed drive types include, but are not limited to the following:

1. Variable voltage.
2. Eddy current clutch.
3. Hydraulic clutch.

By controlling motor speed, only the required quantities of chilled water are circulated. The required chilled water quantity is a function of the total head seen by the pump (Figure 11). Monitoring this pressure with a micro-processor based control system allows a speed control signal to be generated. Operating the pump at partial load, though somewhat less efficient than at full load, still provides a substantial energy savings over 100% full-load operation.

CALCULATIONS

Pump Energy Consumption:

$$E = (HQ/5{,}300\ \eta\ \text{drive}\ \eta\ \text{pump}) = \text{"kW"}$$

H = Total Head (ft)
Q = Flow (GPM)
η = Efficiency
E = Energy Consumed (kW)

This equation represents pump energy consumed during one operating hour.

COST SAVINGS

The kW calculated above is then referred to Table 4 which indicates the savings per year in dollars.

SUMMARY

As discussed, all of the above five areas can save considerable energy. Hence, it is very important that each of the above items be evaluated in detail for both existing and new central chilled water plants.

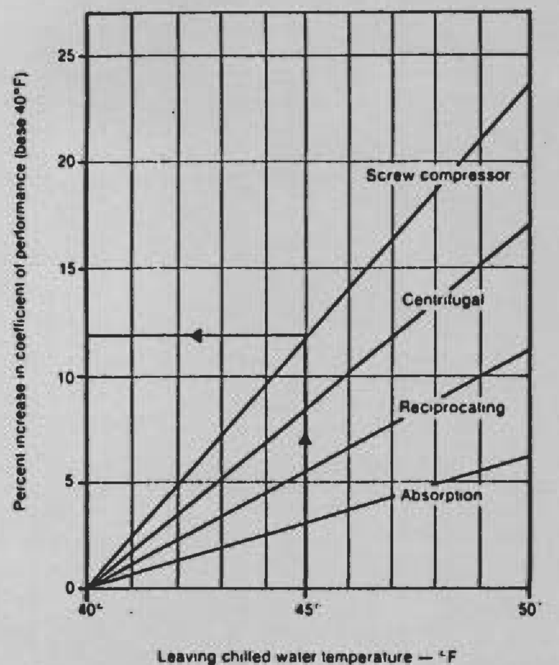

Figure 1 Effect of Chilled Water on Chiller Coefficient of Performance

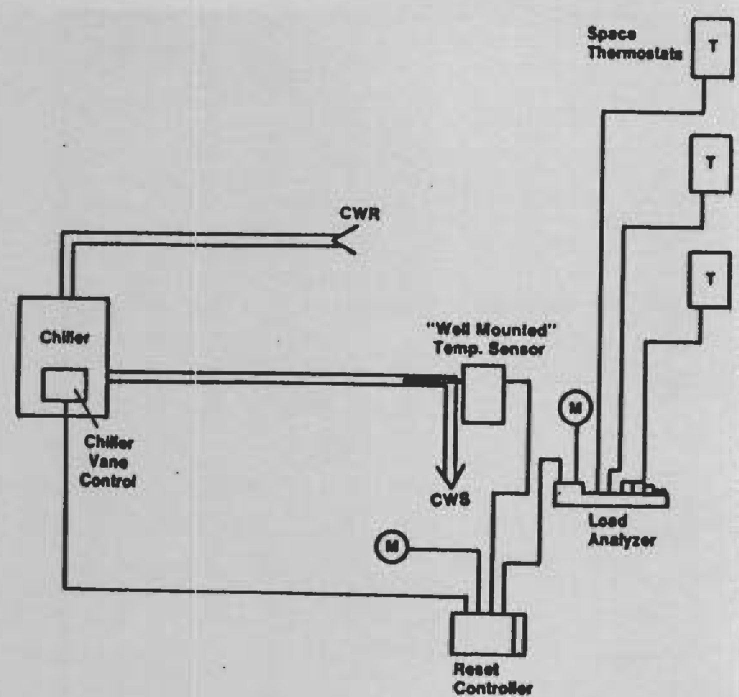

Figure 2 Chilled Water Reset from Space

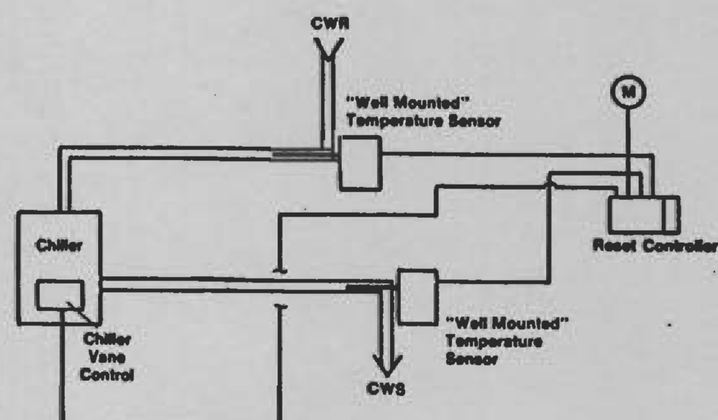

Figure 3 Chilled Water Reset from Return Water Temperature

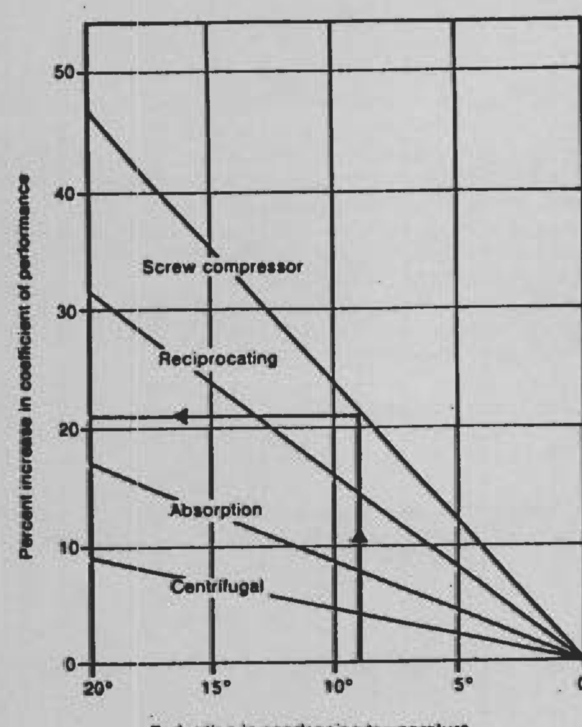

Figure 4 Effect of Condenser Temperature on Chiller Coefficient of Performance

TABLE 1
RESET CHILLED WATER TEMPERATURE
CALCULATIONS FORMAT

(1) Load Range (k Tons)	(2) Average Load (k Tons)	(3) Hours/Year Operation — Chiller 1	(4) Hours/Year Operation — Chiller 2	(5) Hours/Year Operation — Chiller 3	(6) Total Operation Hours	(7) k Ton · Hr/Yr = (2) x (6)	(8) Existing kW/Ton
0.0 - 0.2	0.1					0	0
0.2 - 0.4	0.3					0	0
0.4 - 0.6	0.5					0	0
0.6 - 0.8	0.7	8			8	6	1.705
0.8 - 1.0	0.9	24			24	22	1.585
1.0 - 1.2	1.1	72			72	79	1.340
1.2 - 1.4	1.3	272			272	354	1.148
1.4 - 1.6	1.5	428			428	642	1.029
1.6 - 1.8	1.7	348			348	592	0.884
1.8 - 2.0	1.9	400	12		412	783	0.835
2.0 - 2.2	2.1	400	4		404	848	0.784
2.2 - 2.4	2.3	296	12		308	708	0.777
2.4 - 2.6	2.5	224	24		248	620	0.794
2.6 - 2.8	2.7	136	100		236	637	0.875
2.8 - 3.0	2.9	100	132		232	673	0.896
3.0 - 3.2	3.1	28	232		260	806	0.906
3.2 - 3.4	3.3		236		236	779	0.908
3.4 - 3.6	3.5		320	8	328	1,148	0.867
3.6 - 3.8	3.7		348	4	352	1,302	0.847
3.8 - 4.0	3.9		376	24	400	1,560	0.831
4.0 - 4.2	4.1		240	24	264	1,082	0.824
4.2 - 4.4	4.3		324	60	384	1,651	0.826
4.4 - 4.6	4.5		228	60	288	1,296	0.813
4.6 - 4.8	4.7		276	64	340	1,598	0.797
4.8 - 5.0	4.9		164	170	334	1,637	0.845
5.0 - 5.2	5.1		144	96	240	1,224	0.822
5.2 - 5.4	5.3		92	112	204	1,081	0.828
5.4 - 5.6	5.5		88	124	212	1,166	0.827
5.6 - 5.8	5.7		84	180	264	1,505	0.815
5.8 - 6.0	5.9		20	168	188	1,109	0.844
6.0 - 6.2	6.1		4	212	216	1,318	0.830
6.2 - 6.4	6.3			164	164	1,033	0.818
6.4 - 6.6	6.5			140	140	910	0.811
6.6 - 6.8	6.7			132	132	884	0.794
6.8 - 7.0	6.9			120	120	828	0.807
7.0 - 7.2	7.1			80	80	568	0.794
7.2 - 7.4	7.3			80	80	584	0.772
7.4 - 7.6	7.5			52	52	390	0.749
7.6 - 7.8	7.7			80	80	616	0.762
7.8 - 8.0	7.9			68	68	537	0.761
8.0 - 8.2	8.1			52	52	421	0.750
8.2 - 8.4	8.3			60	60	498	0.750
8.4 - 8.6	8.5			36	36	306	0.750
8.6 - 8.8	8.7			32	32	278	0.741
8.8 - 9.0	8.9			4	4	36	0.726
Total					8,602	34,133	0.856 (Avg.)

• Chiller Average Load = $\frac{\text{Ton Hours}}{\text{Total Hours}}$ = 3,968 Tons

TABLE 2

CALCULATION OF AVERAGE WET BULB TEMPERATURE ABOVE °55

(1) Wet Bulb Temperature	(2) Occurance (Hr/Yr)	Degree · Hr = (1) x (2)
81	6	486
80	24	1,920
79	156	12,324
78	309	24,102
77	441	33,957
76	465	35,340
75	486	36,450
74	417	30,858
73	345	25,185
72	387	27,864
71	399	28,329
70	408	28,560
69	309	21,321
68	288	19,584
67	180	12,060
66	156	10,296
65	171	11,115
64	186	11,904
63	195	12,285
62	123	7,626
61	125	7,625
60	132	7,920
59	141	8,319
58	168	9,744
57	132	7,524
56	93	5,208
55	108	5,940
	6,350	443,846

$$T_{WB\ AV} = \frac{443,846}{6,350} = 69.90^0$$

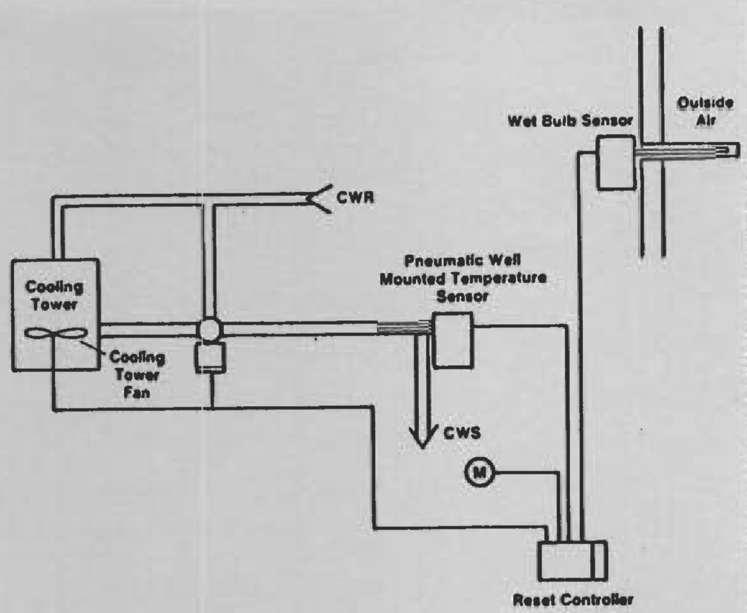

Figure 5 Condenser Water Reset Thru Wet Bulb Temperature

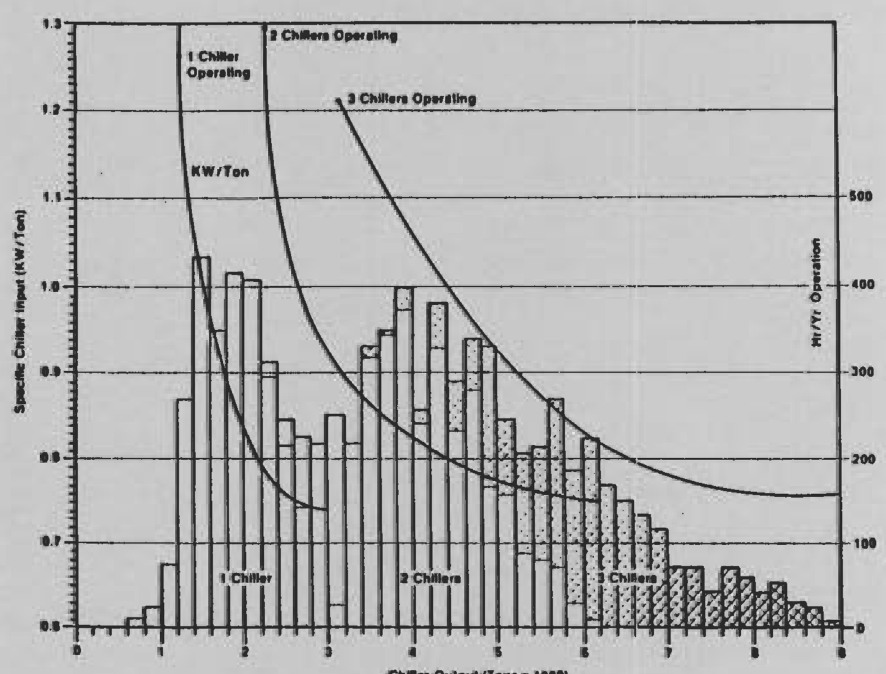

Figure 6 Sequencing of Chillers

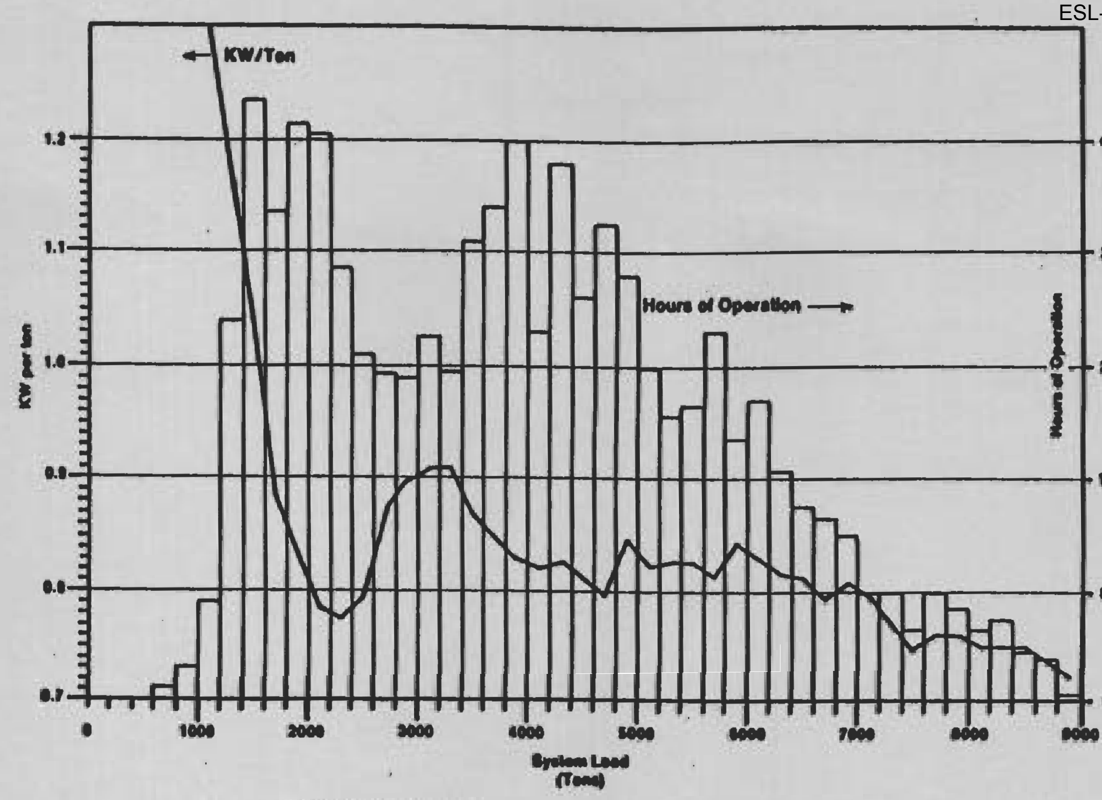

FIGURE 7 CHILLED WATER SYSTEM OPERATING PROFILE

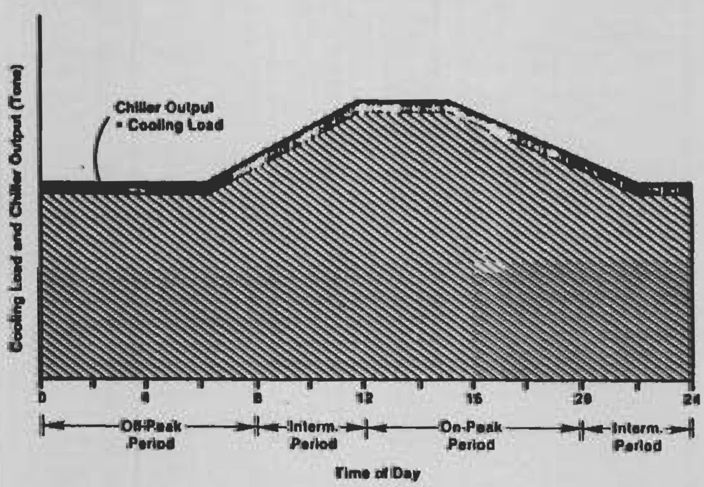

Figure 8 Chilled Water Storage Systems

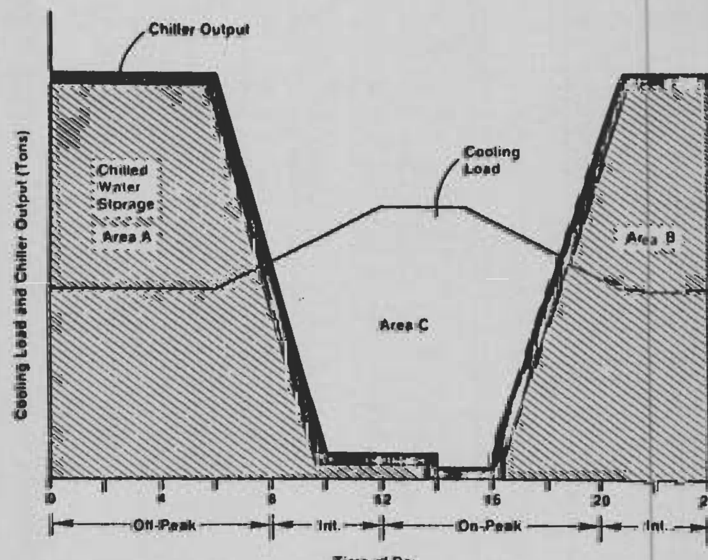

Figure 9 Chilled Water Storage Systems

TABLE 3

SEQUENCING OF CHILLERS

(1) Load Range (Tons x 1,000)	(2) Hr/Yr Low Eff. Oper.	(3) Low Eff. Oper. kW/Ton	(4) Present Ineff. Oper. kWh/Yr = (1) x (2) x (3)	(5) High Eff. Oper. kW/Ton	(6) Proposed Effic. Oper. kWh/Yr = (1) x (2) x (5)	(7) Savings kWh/Yr = (4) - (6)
1.8 - 2.0	12	1.50	34,200	0.83	18,900	
2.0 - 2.2	4	1.31	11,000	0.79	6,600	
2.2 - 2.4	12	1.20	30,200	0.76	21,000	
2.4 - 2.6	24	1.11	66,600	0.745	44,700	
2.6 - 2.8	100	1.03	278,100	0.735	198,400	
2.8 - 3.0	132	0.98	375,100	0.73	279,400	
Subtotal			795,200		569,000	226,200
3.4 - 3.6	8	1.19	33,300	0.87	24,400	
3.6 - 3.8	4	1.15	17,000	0.84	12,400	
3.8 - 4.0	24	1.11	103,900	0.815	76,300	
4.0 - 4.2	24	1.07	105,300	0.80	78,700	
4.2 - 4.4	60	1.03	265,700	0.785	202,500	
4.4 - 4.6	60	1.00	270,000	0.77	207,900	
4.6 - 4.8	64	0.97	291,800	0.765	230,100	
4.8 - 5.0	170	0.95	791,400	0.755	628,900	
5.0 - 5.2	96	0.92	450,400	0.75	367,200	
5.2 - 5.4	112	0.89	528,300	0.75	445,200	
5.4 - 5.6	124	0.87	593,300	0.745	508,100	
5.6 - 5.8	180	0.85	872,100	0.745	764,400	
5.8 - 6.0	168	0.83	822,700	0.742	735,500	
Subtotal			5,145,200		4,281,000	863,600
Grand Total			5,940,400		4,850,600	1,089,800

TABLE 4

CONSTANT VS. VARIABLE PUMPING

% Rated RPM	% Full Load Head*	% Full Load Flow*	Actual Power (kW)	Operating Hrs/Year	Actual kWh	Annual Cost @ 7¢
Constant Volume System						
100	100	100	75.00	4,800	360,000	$25,200
Variable Pumping System						
100	100	100	75.00	0	0	0
90	81	90	54.70	144	7,877	$550
80	64	80	38.40	432	16,589	$1,160
70	49	70	25.70	1,008	25,906	$1,810
60	36	60	16.20	1,104	17,885	$1,250
50	25	50	9.40	1,104	10,378	$730
40	16	40	4.80	1,008	4,838	$340
Subtotal	---	---	---	4,800	83,473	$5,840
Savings	---	---	---	---	276,527	$19,360

*From pump curves.

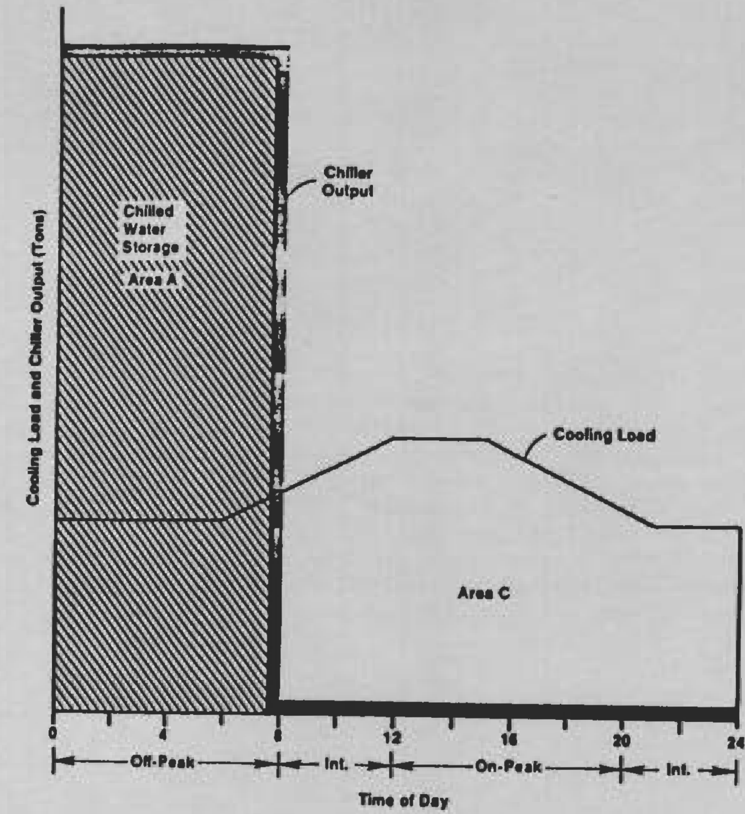

Figure 10 Chilled Water Storage Systems

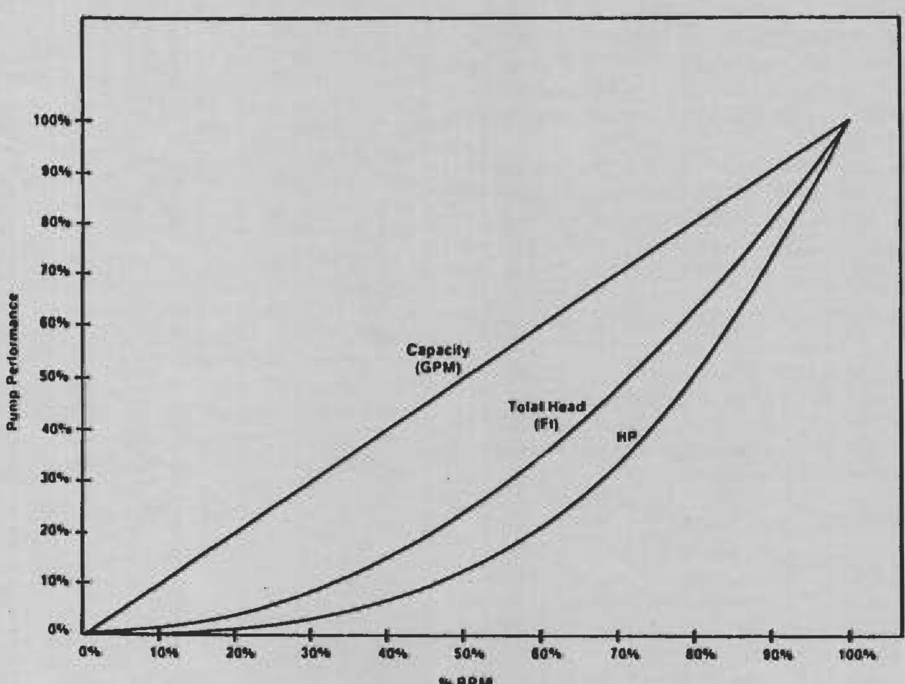

Figure 11 Pump Performance Curves