SIZING OPTIMIZATION OF A CENTRAL CHILLED WATER SYSTEM

by

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INTRODUCTION

Your organization has decided to build a central chilled water plant to supply comfort cooling to several existing and planned future buildings. Among the immediate design decisions as well as siting the facility and distribution system routing, your charge is to size the central plant. While sizing a single building's in-house chilling system might be fairly routine, the sizing of a central system is a much larger undertaking. Where do you begin? How can you be comfortable with the capacity of the plant while avoiding the problems associated with an oversized facility.

Immediately it can be seen that designing and constructing a central chilled water system is a major undertaking and there are many decisions that must be made during the design process which play a critical role in the system's performance, reliability, serviceability, etc. Almost without exception, the primary decision to be made, which will have a significant impact on the economics of the project, is the central plant sizing. The implications of under-sizing a central chilled water plant are evident - unhappy, *hot* customers whose chilling requirements are not being met. However, not quite as obvious are the implications of over-sizing a central system. The initial capital cost of the facility is tied directly to the capacity of the plant; from the chillers and pumps to the cooling towers, to the distribution system. Capital expenditure on equipment that will be under-utilized or not used at all will have a detrimental economic effect on the project. Therefore, careful thought and attention must be given to the sizing decision during the design process.

This paper will offer optimization guidelines for the sizing of a central chilling plant. Information which is normally available at the beginning of such a project will be examined and then sizing experiences of existing central chilled water systems will be reviewed in order to establish "capacity sizing guidelines" for central chilling plants.

EXISTING INFORMATION

Ordinarily, at the onset of a project, the building cooling load requirements will fall into one of two categories: 1) it is a new or renovated building and a cooling load estimate is provided by an architectural/engineering firm or 2) it is an existing building with an in-house chilling system.

If it is a new or renovated building, the architectural/engineering firm will normally provide an estimate of the cooling load for the building. This load is normally based on the type/design of the building, the building's usage, insulation qualities, etc. Note that the cooling load estimates for individual facilities will normally include safety factors and margins over and above the calculated loads.

If the building to be served is existing, chances are good that the building will already have a chilling system in place. Thus, an installed capacity for that building is known. However, unless meters are installed on the in-house system (which is unlikely), the actual cooling peak and consumption experienced by the building will not be known. Discussions with a building engineer or maintenance supervisor can help establish the estimated peak cooling loads experienced by the building. Operating information can be determined such as the number of units which operate throughout the year, frequency of operation, complaints from building tenants, etc.

Once data is gathered as previously described for all of the buildings/facilities to be served by the central plant, and the connected loads are summed, the result represents total estimated connected load. If this result were used to establish the capacity of the central plant, the plant would be significantly oversized and load factors (or equivalent full load hours) would be difficult to assess and thus, represent an educated guess at best. At this point, it would be extremely helpful to have information on existing central chilled water plants regarding sizing experiences. Information regarding existing systems such as the following would be valuable:

1. Installed central plant capacities
2. Sum of building peak cooling demands
3. Actual peak chilling demand experienced by central plants
4. Total building square footage served by the central plants
5. Annual ton-hours produced by the central plants

From this data, a number of significant design considerations could be determined. These include diversity, capacity utilization, load factor, capacity vs. building square footage and demand vs. building square footage. This information can then act as guidelines for not only the sizing of a central chilled water system, but also for optimization purposes.

BACKGROUND

This author has conducted a survey of the nature described in the prior section. Information from thirteen (13) existing central chilled water systems in the U.S. was collected and forms the foundation of this paper. The data was obtained from published literature on the systems along with conversations/discussions with plant personnel. It should be noted that this survey was conducted in the fall of 1989, however, the significance of the information included in this survey and the relevance of the resulting calculations are time independent.

SURVEY DATA

Table 1 summarizes the information gathered from the 13 central chilling systems. In order to retain the autonomy of the central chilled water systems and the respective individuals, the plants will be referenced as plants "A" through "M" throughout this paper.

TABLE 1: Summary of Survey Information

Plant	Central System Installed Capacity (Tons)	Estimated Sum of Building Loads[1] (Tons)	Peak Demand seen by Central System	Annual Ton-Hrs Produced (x 1000)	Building Square Footage Served (x 1000)
A	27,000	20,453	15,500	46,042	8,000
B	12,500	11,000	11,000	19,000 (sales)	5,000
C	16,700	15,000	14,000	37,000 (sales)	7,000
D	22,400	21,000	18,500	24,500	13,000
E	27,000	25,650	23,000	33,600	11,000
F	22,000	17,600	15,480	33,000	10,000
G	5,250	5,600	3,700	8,000	1,820
H	14,500	11,600	5,300	12,500	5,000
I	12,000	10,500	10,500	17,500	5,000
J	4,000	6,000	4,000	4,583	2,500
K	20,500	21,700	17,000	40,000	9,000
L	2,720	2,000	1,360	3,168	1,000
M	10,180	10,907	8,100	19,200	n.a.

[1] Contracted Demand

Some of the information cited in Table 1 is self-explanatory; other data deserves some discussion. The "Central System Installed Capacity" is the summation of all of the chilling capacity at the respective system; centrifugal chillers, absorption chillers, etc. The "Estimated Sum of Building Loads" is the capacity or demand which is contracted for by the individual buildings. At the beginning of a contract period, this quantity is normally an estimate established through discussions between the building owners/personnel and central system personnel. The "Annual Ton-Hours Produced" is the total annual quantity of ton-hours of cooling produced by the central system (except where noted).

DIVERSITY

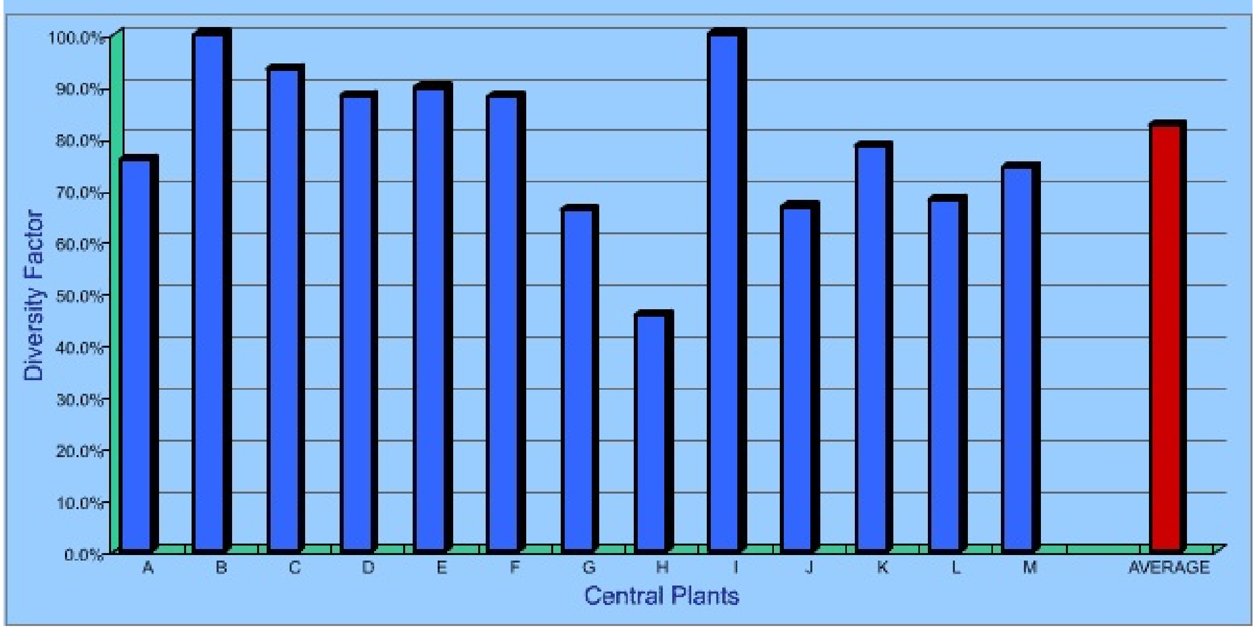
While it is generally recognized that all buildings connected to a central system will not necessarily require peak cooling coincidentally, the magnitude of this factor (diversity factor) has been difficult to quantify.

By reviewing the survey information, it can be seen that in only 2 of the 13 systems surveyed (Plants "B" and "J") does the peak demand seen by the central plant equal the sum of the individual building peaks on the respective central systems. The comparison between the sum of the individual building peaks versus the actual peak demand seen by the central system is referred to as "diversity". Figure 1 shows the result of calculating the diversities of the 13 systems.

At this point it should be noted that the majority of the buildings on these systems had stand alone, in-house chilling systems prior to being connected to the central system. Therefore, the "building loads" referred to in the third column of Table 1 are estimates of the actual peaks (contract demand) experienced by the individual buildings, it is not the summation of the displaced building equipment capacity.

As can be seen in Figure 1, the individual diversities of the 13 systems range from 46% to 100% with an average of 82%. This means that the sum of the individual building peaks were as much as 56% higher than the actual peak seen by the central plant, and on average, 18% higher than the actual peak seen by the central plant. From this result, it can be observed that, in all probability, a central plant will experience a diversity factor of less than 1.0 and therefore can be designed for a capacity less than the sum of the individual buildings peaks. Of course this is dependent upon the number and type of buildings being served, the utilization of the buildings and the proximity of the buildings to one another, etc. However, as demonstrated by this survey information, diversity will exist and thus, a capital savings opportunity on the initial investment is present. An added advantage of allowing for diversity is that the plant will operate closer to its design capacity and therefore will experience an improvement in overall efficiency.

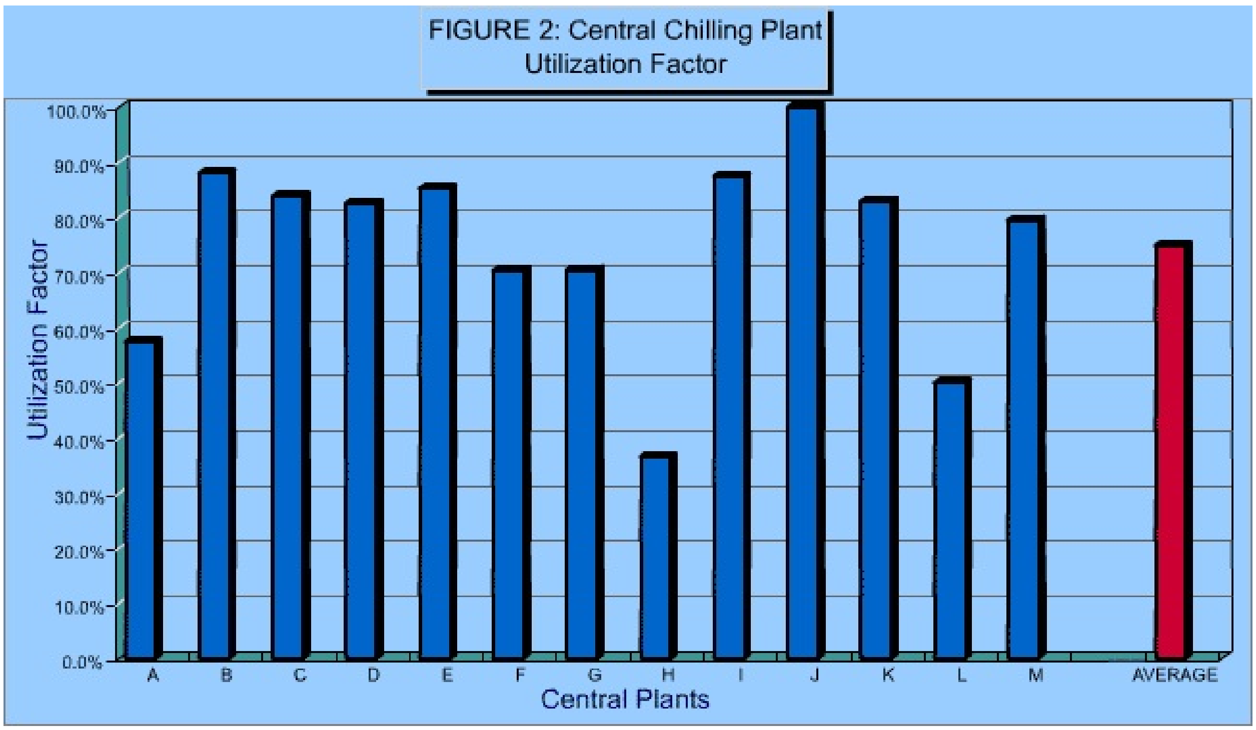
FIGURE 1: Central Chilling Plant Diversity Factor



CAPACITY UTILIZATION

Figure 2 graphically compares the actual installed central plant capacity versus the peak demand seen by the central system. This is referred to as "Capacity Utilization".

As can be seen from Figure 2, only 1 of the 13 systems achieves a 100% utilization factor, the remaining systems range from a low of 37% utilization to a high of 88%; with the average utilization being 75%. This demonstrates that there is a tremendous amount of under-utilized capacity present at some of these systems. Some of this extra capacity can be attributed to reserve and/or future capacity, however with the use of multiple units to achieve a needed capacity, reserve capacity is ordinarily "built-in". Also, while it is a good idea to design a central chilling system with some excess capacity in order to allow for future potential growth, excessiveness in this area creates unused or under-utilized capital investment which will retard the project economics.



LOAD FACTOR

The system load factor is a comparison of the total amount of cooling produced during a year in ton-hours versus the total amount of cooling which the system is capable of producing. Load factor is extremely important as it represents **actual total energy delivered**. Referencing the data collected in the system survey, the load factors for the 13 systems are determined and listed in Table 2.

From this table, it can be seen that the load factor for these systems range from a low of 9.8% to a high of 25.3% with an average of 17.2%. This information demonstrates the enormous amount of unused cooling which these systems are capable of producing. However, with the majority of the cooling load being comfort related, additional customers can not be added to the systems without increasing the peak demand on the central plant. Incorporation of less expensive "interruptable" rates or thermal storage can sometimes help a system achieve higher ton-hour sales without having to increase the chilling capacity of the system.

TABLE 2: Central System Load Factors

Plant	Central System Installed Capacity (Tons)	Actual Annual Ton-Hrs Produced (x 1000)	System Equipment Load Factor[2]	System Demand Load Factor
A	27,000	46,042	19.5%	33.9%
B	12,500	19,000[1]	17.4%	19.7%
C	16,700	37,000[1]	25.3%	30.2%
D	22,400	24,500	12.5%	15.1%
E	27,000	33,600	14.2%	16.7%
F	22,000	33,000	17.1%	24.3%
G	5,250	8,000	17.4%	24.7%
H	14,500	12,500	9.8%	26.9%
I	12,000	17,500	16.6%	19.0%
J	4,000	4,583	13.1%	13.1%
K	20,500	40,000	22.3%	26.9%
L	2,720	3,168	13.3%	26.6%
M	10,180	19,200	21.5%	27.1%
Average	15,135	22,853	17.2%[3]	23.0%[4]

[1] ton-hours sold, not total ton-hours produced
[2] Load Factor x 8760 hrs/yr = Equiv. Full Load Hours (EFLH)
[3] calculated from the average of annual ton-hours capable of being produced and "Actual Annual Ton-Hours Produced"
[4] calculated from the annual ton-hours capable of being produced at the average Peak Demand seen by Central systems and the "Actual Annual Ton-Hours Produced"

BUILDING SQUARE FOOTAGE

An often used method for sizing chilling equipment to serve a designated building is to apply an industry standard of "square foot per ton". This method involves dividing the square footage of the building by the "square foot per ton" standard and the result is the capacity of the chillers to be installed. Depending upon the building usage, a standard range of 200 ft^2/ton to 400 ft^2/ton is normally applied. Table 3 is the result of determining the square footage rating based on the peak demand seen by the central facilities and the installed capacity of the central facilities.

TABLE 3: Building Square Footage Served per Ton Analysis for Central Systems

Plant	**Central System Installed Capacity (Tons)**	**Peak Demand seen by Central System**	**Building Square Footage Served (x 1000)**	**Building Square Footage per Ton of Peak Demand**	**Building Square Footage per Installed Ton**
A	27,000	15,500	8,000	516	296
B	12,500	11,000	5,000	455	400
C	16,700	14,000	7,000	500	419
D	22,400	18,500	13,000	703	580
E	27,000	23,000	11,000	478	407
F	22,000	15,480	10,000	646	455
G	5,250	3,700	1,820	492	347
H	14,500	5,300	5,000	943	345
I	12,000	10,500	5,000	476	417
J	4,000	4,000	2,500	625	625
K	20,500	17,000	9,000	529	439
L	2,720	1,360	1,000	735	368
M	10,180	8,100	n.a.	n.a.	n.a.
Average[1]	----	----	----	592	425

[1] excludes Plant "M"

From Table 3, it can be seen that the square footage per installed ton of capacity of each central plant varies extensively from a low of 296 ft^2/ton to a high of 625 ft^2/ton, averaging 425 ft^2/ton. The square footage served per ton of actual demand has even a wider range of 455 ft^2/ton to 943 ft^2/ton, with an average of 592 ft^2/ton. As can be seen, the industry standards for square foot per ton normally applied to individual buildings, appear to be very conservative when applied to central systems. This is primarily due to the diversity experienced by a central system. It is quite evident that this can equate to *substantial* initial capital cost savings. For example, if buildings totaling 5,000,000 square feet are to be served by a central system, by using a conventional standard of 300 ft^2/ton, the central plant would require approximately 16,667 tons of chilling capacity. By applying the average square foot per peak demand ton obtained from Table 3 (592 ft^2/ton), the central plant would require only 8,450 tons. That is a 49% reduction in plant capacity! Of course, depending upon the type and utilization of the buildings being served, the ft^2/ton requirements will vary, however, this example gives an order of magnitude of the savings which can be realized.

LOAD DURATION CURVE

This paper has presented many items relating to central plant sizing, however, one invaluable tool which has not been discussed yet is a load duration curve. The load duration curve graphically depicts load demand, capacity and energy consumption. Figure 3 represents a typical cooling load duration curve.

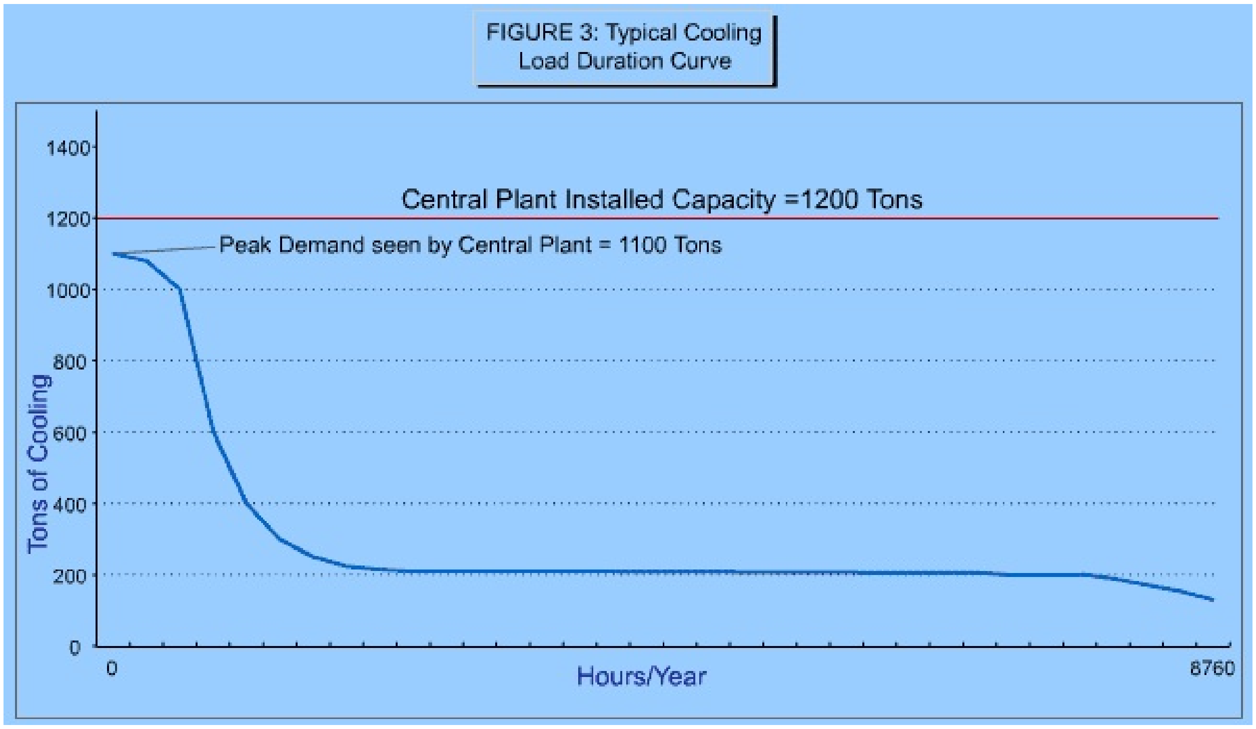
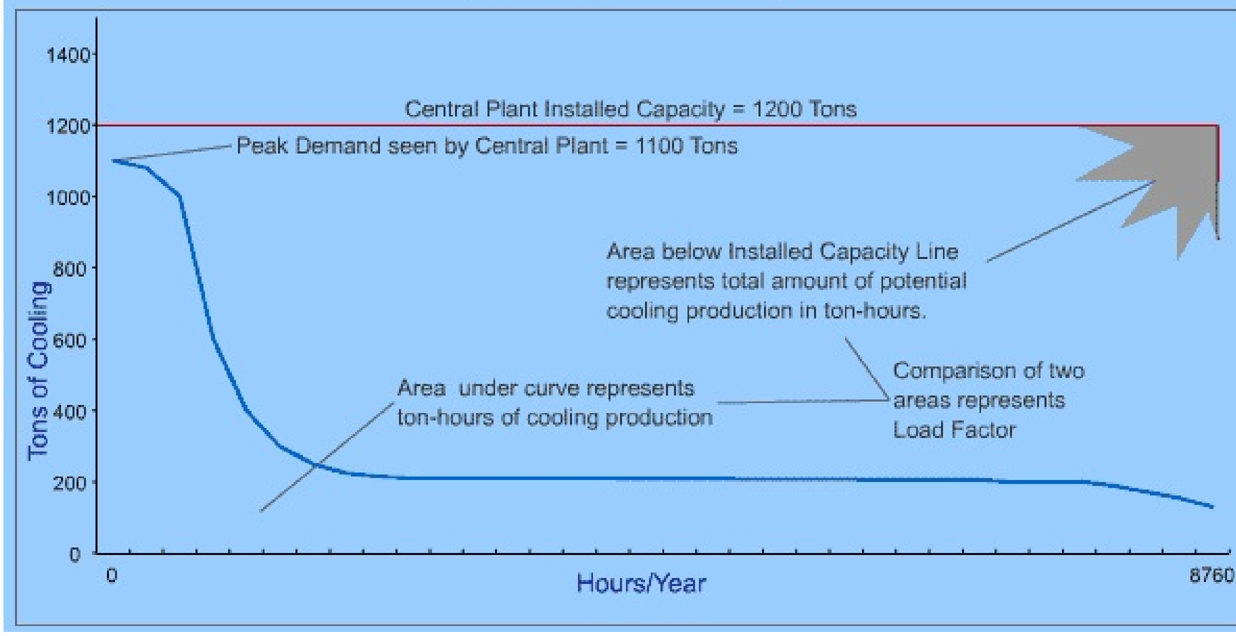


FIGURE 3: Typical Cooling Load Duration Curve

A load duration curve is a graphic model which can be extremely helpful in designing and sizing a chilled water system. The curve represents the total annual amount of time which the central plant is producing chilled water at a corresponding capacity. Figure 4 shows a load duration curve's different components.

From the curve, one can determine the installed system capacity (in this example 1200 tons), along with the peak demand (1100 tons). Graphically, the total amount of cooling produced (in ton-hours) by the central plant is represented by the area beneath the curve. The total cooling that the plant is capable of producing in ton-hours is represented by the area beneath the horizontal line designating the total installed capacity of the plant. The comparison of these two areas results in the plant load factor. In agreement with the results of Table 2, and as is represented by this graph, for comfort cooling the area beneath the curve is usually a small percentage of the total overall area beneath the installed capacity

FIGURE 4: Components of a Load Duration Curve



line. Other items which can be determined by the load duration curve include the amount of time that a specific cooling capacity existed during the year and the amount of equivalent full load hours of the plant; i.e., the number of hours during a year that the system would have to operate at peak demand in order to achieve the total number of ton-hours of chilling produced during that year.

By horizontally dividing the area beneath the curve into separate regions, the quantity and capacity of individual plant units can be determined. A chiller will work most efficiently at its rated capacity. Therefore, looking back at Figure 3, it would appear that a 200 ton chiller would be base loaded over 90% of the year. Therefore, a central plant for this load duration curve could be sized with 6 units rated at 200 tons each (Reference Figure 5).

Having a multiple number of units at a central facility is beneficial from the standpoint of being able more precisely match varying loads, however other considerations must be examined.

First, in viewing Figure 5, it is evident that the first unit is the only one which is running at a reasonable load for a substantial amount of time. The second unit is operating at a very small load for a large portion of the year. Because of the loading, this unit would be very

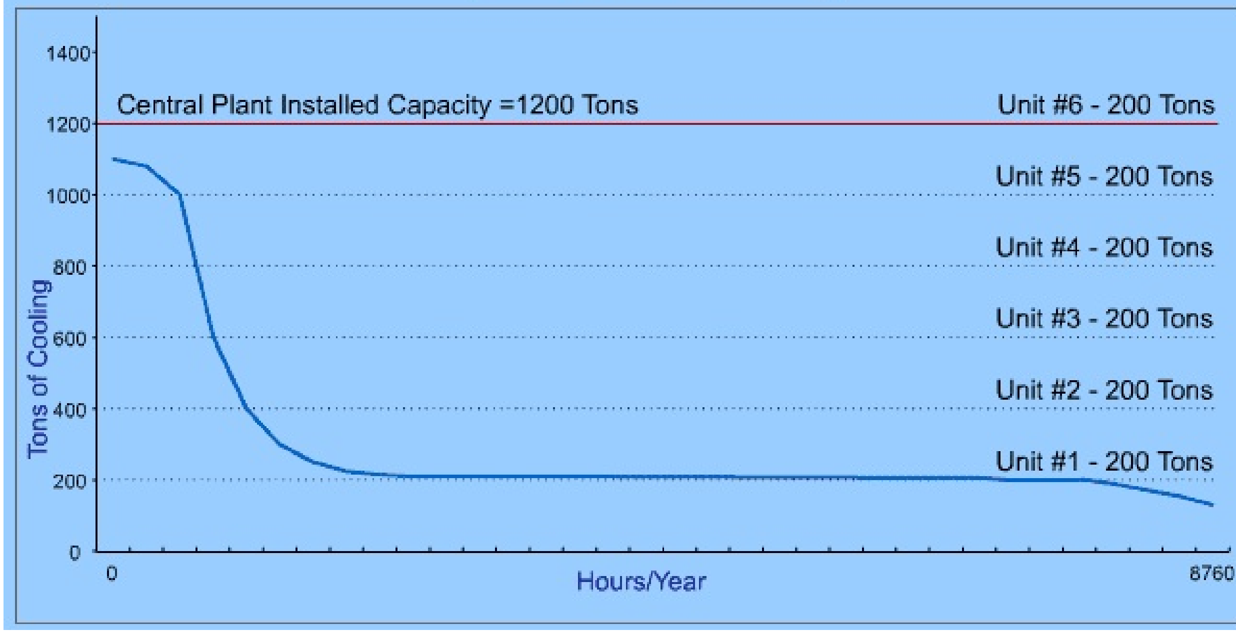


FIGURE 5: Chiller Sizing Using a Load Duration Curve

inefficient. The remaining 4 units are only operating a small fraction of the year. With the chillers and subsequent equipment sitting idle for such a large portion of the year, maintenance problems and costs could be substantial.

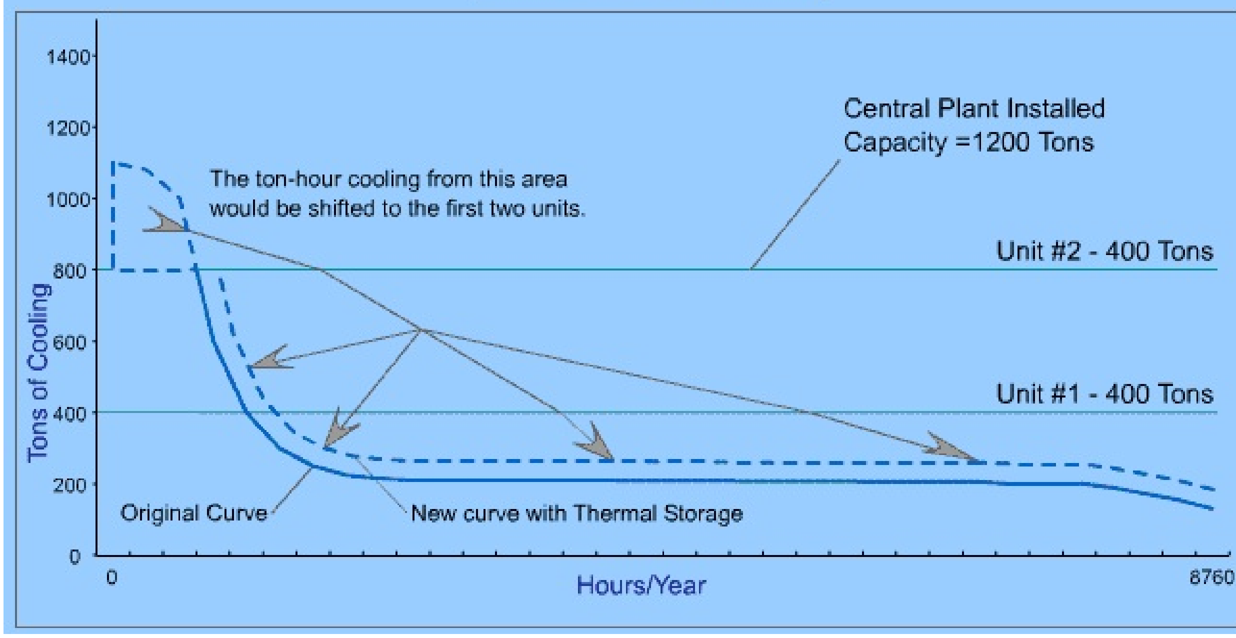
Secondly, economics play a significant role in plant sizing. As with most process systems, there normally is an economy of scale. Therefore 6 - 200 ton chillers would be more expensive than 4 - 300 ton, or 3 - 400 ton chillers, or a mixture of different sized units.

In re-examining Figure 5, if 4 - 300 ton units were selected, the first unit would operate at about a 72% load factor, the second unit at about a 9% load factor, the third unit at about 5% and the fourth unit at about 1%. If 3 - 400 ton units were selected, the first would operate at a load factor of about 57%, the second at about 8% and the third at about 1%. In examining these loadings, each configuration has one unit which is substantially loaded. The remaining units however, are lightly loaded. Therefore, based on these loadings (and assuming that an economy of scale does exist) a selection for this fictitious plant might be 3 - 400 ton units.

THERMAL STORAGE

Another item which this paper has not discussed relating to optimum facility sizing is thermal storage. Basically, thermal storage is the concept of producing chilled water and storing it until it is needed to be sent out to the distribution system. Using thermal storage can reduce the number of chillers required in a central plant facility replacing them with storage capacity. Normally, this will reduce the capital investment required by the difference of the chiller cost (and associated equipment) and the storage unit cost. However, that is the only real savings which can be experienced. The operations cost will be relatively unaffected. Instead of a chiller unit producing the required chilling at the moment it is needed, the chilled water is produced by one of the other units during a non-peaking timeframe. Therefore, the installed capacity line on the load duration curve is lowered, thus "chopping off" the top area. This area is then added back into the remaining area beneath the curve. Using the fictitious plant of 3 - 400 ton units in the previous section, Figure 6 is a graphic representation of substituting thermal storage for the third, 400 ton unit.

FIGURE 6: Graphic Analysis of Thermal Storage



Effectively, the plant is achieving the same amount of ton-hours of chilling, through a lesser installed chiller capacity. Once again, this will reduce the amount of capital investment required. Instead of installing a chiller unit and all of its ancillary equipment (pumps, cooling tower, controls, etc.) a thermal storage unit is installed. The storage unit ordinarily does require more of a footprint than a chiller and its associated equipment, however, if the space is available, then some initial capital investment can be saved. Also, if electric driven chillers are chosen and "time-of-day" electric rates favor demand side management, electricity cost can potentially be reduced with thermal storage.

SUMMARY

In summary, many guidelines have been presented in this paper in order to optimize the sizing of a central chilled water facility: diversity, load factor, square footage per ton, etc. Based on the subject survey, an average diversity factor of 82% exists among the thirteen systems. Also, an average capacity utilization factor of 75% was cited for the same thirteen systems. Once again, these factors will change depending upon the number of buildings served, the type of buildings served, the location of these buildings in relation to each other, etc. One of the more compelling results of the survey information is the average building square footage per demand ton. At an average of 592 ft^2/ton, significant capital cost savings can be realized in the central plant sizing.

In addition to these items, the load duration curve has been explored as a sizing and optimization tool in central chilled water system sizing. A central system can be graphically examined and dissected in order to optimize a system's sizing and operation.

Finally, thermal storage was briefly examined as a method of optimizing the capital investment of a central system. It was determined, given the right set of conditions that thermal storage could be a viable optimization technique.

In conclusion, it is this author's desire that the information provided by this paper is helpful and useful to anyone sizing or optimizing the sizing of a central chilled water system.

EQUIVALENT FULL LOAD HOURS

The equivalent full load hours experienced by a chilling system is number of hours during a year that the system would have to operate at peak demand in order to achieve the total number of ton-hours of chilling produced during that year. Table X establishes the respective systems' equivalent full load hours as based on the peak demand seen by the central systems.

TABLE X: Central Plant Equivalent Full Load Hours

Plant	Peak Demand seen by Central Plant	Annual Ton-Hrs Produced (x 1000)	Equivalent Full Load Hours
A	15,500	46,042	2,970
B	11,000	19,000 (sales)	1,727
C	14,000	37,000 (sales)	2,643
D	18,500	24,500	1,324
E	23,000	33,600	1,461
F	15,480	33,000	2,132
G	3,700	8,000	2,162
H	5,300	12,500	2,358
I	10,500	17,500	1,667
J	4,000	4,583	1,146
K	17,000	40,000	2,353
L	1,360	3,168	2,359
M	8,100	19,200	2,370