Chilled Water Plant Redesign

OVERVIEW

The chilled water plant redesign includes the addition of a thermal energy storage system. This allows for economic and operational benefits for the facility by storing cooling capacity. The ability to shift loads will reduce peak demand and offer electric utility savings. Although hospitals have 24-hour operation, the majority of use in patient rooms typically occurs in the daytime, which represent a large amount of floor space, lighting, and equipment use at Sinai Hospital. The electric load profile can be shifted by generating cooling capacity at night when the building's electric load is at a minimum and employing it in the afternoon when it is at its peak. Additionally, less stress is placed on the chiller at night due to lower outdoor ambient conditions.

Furthermore, with the proposed future addition of a 2,000-ton electric centrifugal chiller, retrofitting the chilled water plant will be substantially simpler and offer more savings. The storage system can be sized to accommodate both current and future capacity needs.

OBJECTIVES

- Shift loads during peak hours of operation to off-peak hours
- Achieve economical benefits by taking advantage of time-of-use rates
- Increase plant flexibility by utilizing the future chiller to generate capacity through storage and directly
- Perform a feasibility study of locating storage equipment on-site
- Attain a reasonable payback period

**Note: This depth study satisfies the*

Integrated Program (M.A.E/B.A.E) requirements.

DESIGN

The first step in adding a thermal energy storage system to the existing chilled water plant is to determine the amount of storage needed for the hospital. This requires generating a load profile which depicts the amount of cooling, electricity use, and time per day at which the plant operates. Because the hospital has not yet been occupied, a load profile or any utilization data for the South Tower Vertical Expansion is unavailable. Trane's Trace software will be used to simulate the facility's operation history. This will dictate the size of the tank, whether water or ice storage will be implemented, and the location and arrangement of the system.

The chilled water plant was designed to not only support the three additional floors of the South Tower Vertical Expansion but also provide more cooling capacity for the ground and first floors of the emergency center (ER-7), the second and third floors, and the cafeteria. However, the expansion will be treated as its own building, and therefore, thermal energy storage will only be evaluated for floors four, five, and six, and the link and lobby. For analysis purposes, the fourth floor will be duplicated to also represent the fifth floor since the fifth floor layout has not yet been completed; both floors offer similar services.

INPUT DATA (TRACE 700)

Weather Information:	Baltimore, MD
Internal Loads:	<u>People</u> 250 BTU/hr sensible 200 BTU/hr latent <u>Lighting</u> 2 W/ft^2 <u>Miscellaneous Loads</u> 2 W/ ft^2 ▪ See Appendix A
Ventilation:	5 cfm/person 0.06 cfm/ft^2
Infiltration:	0.6 air changes/hr
Thermostat:	<u>Cooling</u> 75°F dry bulb, 50% relative humidity <u>Heating</u> 70°F dry bulb, 50% relative humidity

TABLE 3.1

EQUIPMENT DEMAND

Figure 3.1 depicts the daily electrical demand of the South Tower Vertical Expansion's cooling equipment (chiller, compressor, pumps, fans), miscellaneous equipment (computer, kitchen, medical, etc.), and lighting. Peak demand in the year occurs in the month of July.

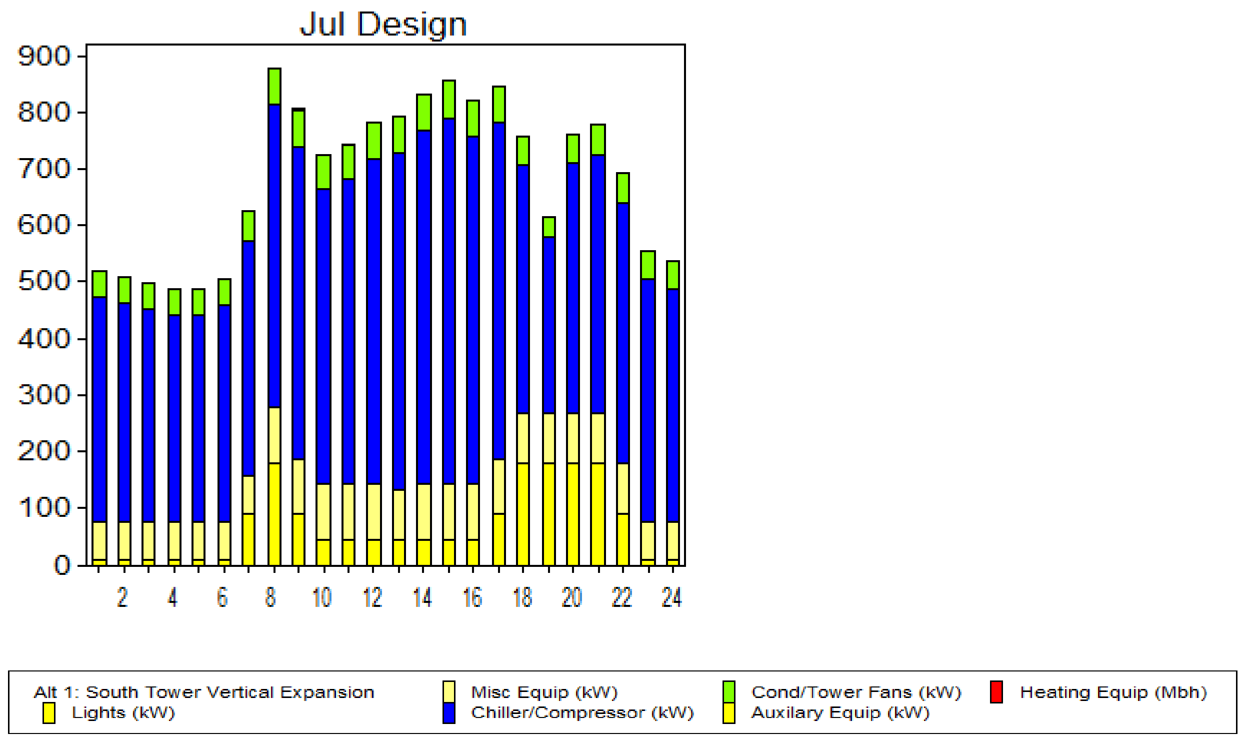

FIGURE 3.1

Based on this graphic, the peak electrical demand for the South Tower Vertical Expansion occurs at approximately 3 PM in the afternoon. The fairly sharp curvature of the profile shows the potential to shift a substantial load from the middle of the day to the evening and night hours. Since the greatest portion of the electrical demand is a result of the cooling equipment, generating cooling capacity during those low peak times will provide a measurable electric utility cost savings.

THERMAL ENERGY STORAGE DEMAND

Figure 3.2 represents the cooling load required during each hour for the cooling design day in July. The peak load from this figure is approximately 600 tons. More detailed values will be determined in the following sections of this report. In order to simplify the redesign, it will be assumed that the load profile for the remaining spaces (the ground and first floors of the emergency center (ER-7), the second and third floors, and the cafeteria) is flat, and the capacity allocated to those spaces is around 1,300 tons. This means that thermal energy storage can only be applied to the South Tower Vertical Expansion.

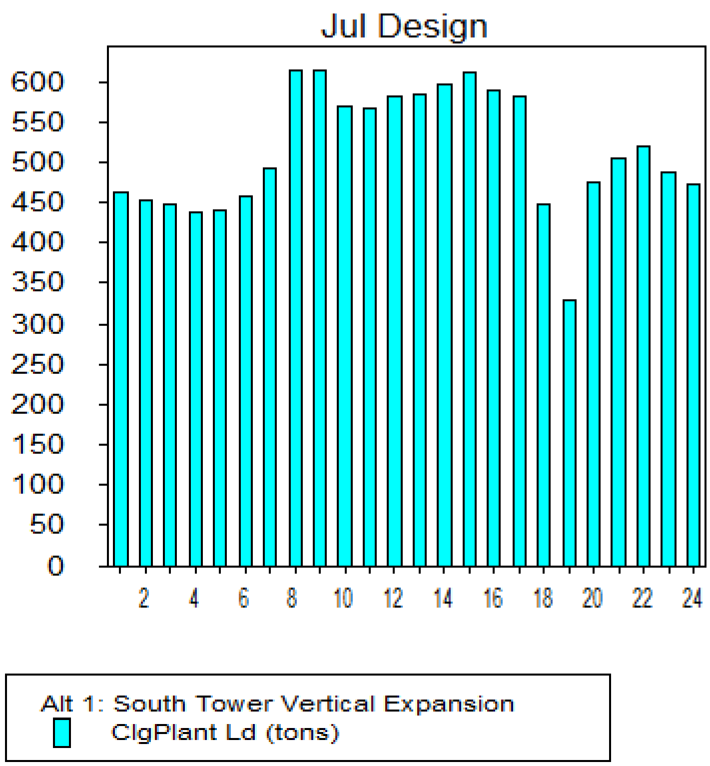

FIGURE 3.2

From Figure 3.2, it will be possible to create a smooth load profile to determine the average load, peak load, and total load. Based on these values, the amount and type of storage needed can be determined.

LOAD PROFILE

Representing cooling loads from Figure 3.2 as data points, a trend line can be produced to portray the chilled water plant cooling design day operation. This is illustrated in Figure 3.3.

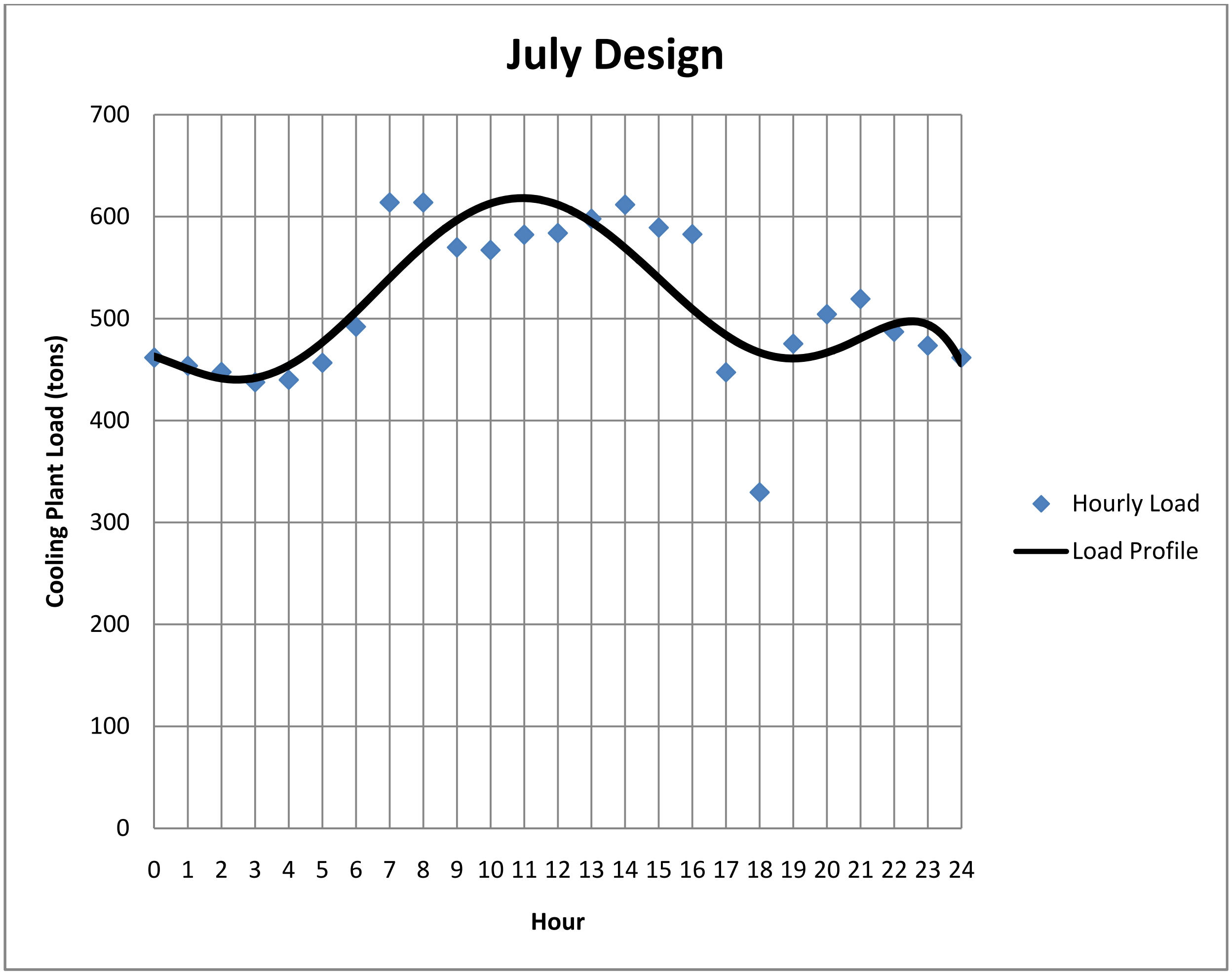

FIGURE 3.3

Trend Line Equation
$y = -0.000214849198201697x^6 + 0.0139792112743158x^5 - 0.313622180670263x^4 + 2.64550027413572x^3 - 4.39777417477859x^2 - 10.2315167506266x + 462.741019309213$

TABLE 3.2

The trend line given in Table 3.2 can be used to calculate the total cooling plant load required for the hospital's cooling design day through integration.

COOLING PLANT LOAD

Total Plant Load:	12,345 ton-hr
Minimum Hourly Plant Load:	441 tons
Average Hourly Plant Load:	515 tons
Peak Hourly Plant Load:	619 tons
Load Factor:	83.2%

TABLE 3.3

From Figure 3.3, the load factor for the Sinai Hospital South Tower Vertical Expansion was determined to be 83.2%. Because a future chiller has been proposed, it will be utilized to generate storage capacity at night in order to fulfill chilled water capacity needs during the day. This will maximize the time-of-use savings. Therefore, full storage will be applied.

FULL STORAGE

ADVANTAGES

- Minimize costs by generating cooling capacity only during the night
- Favorable payback
- Maximize efficiency

DISADVANTAGES

- Size of storage equipment

Based on time-of-use electric utility rates from Baltimore Gas & Electricity, the cheapest time to operate equipment is between 9 PM and 7 AM. To maximize payback, thermal energy storage would need to be generated during this time. To do so, the plant load must be determined by calculating the area under the curve in Figure 3.3. This procedure is performed in Figure 3.4. Further economic analysis will be provided later in the report.

CHARGING & DISCHARGING

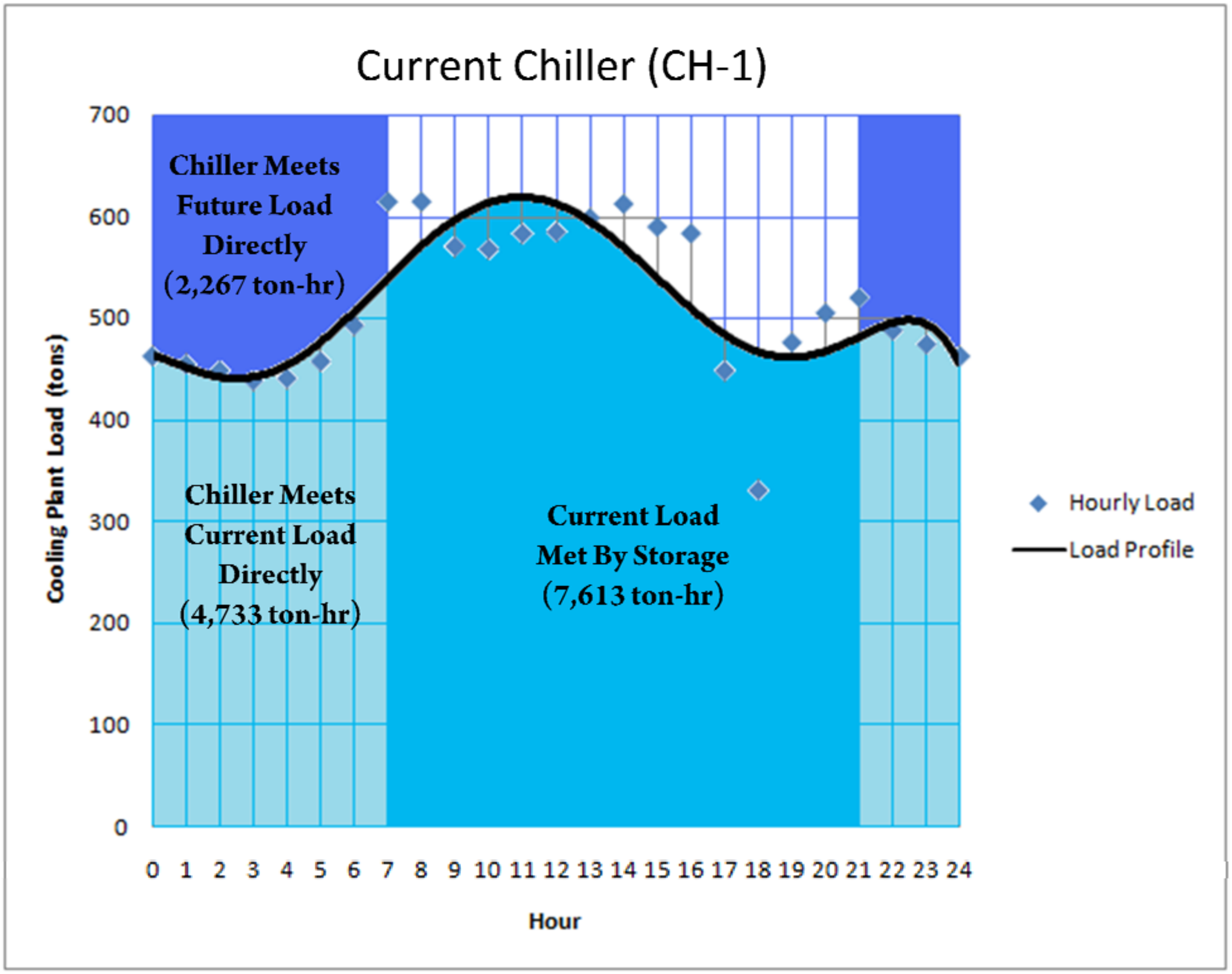

FIGURE 3.4

Table 3.4 breaks down the hours when loads are met directly by the chiller and the hours when loads are met by storage.

Hours	Plant Load
0-7 (12 AM - 7 AM)	3,269 ton-hr
7-21(7 AM - 9 PM)	7,613 ton-hr
21-24 (9 PM - 12 AM)	1,464 ton-hr

TABLE 3.4

Based on values from Table 3.4, the thermal energy storage required to meet peak cooling demand for the South Tower Vertical Expansion is 7,613 ton-hr. This requires an hourly generation during off-peak hours of:

$$\frac{7{,}613\ [ton-hr]}{10\ [hr]} = 762\ [tons]$$

FUTURE OPERATION

The additional 2,000-ton chiller was proposed to meet any future capacity. No determination has been made as to what the additional loads will be. To accommodate for future needs, nighttime capacity will be provided by any remaining capacity on both the current and future chillers during off-peak hours. Daytime capacity will be provided by the future chiller directly during peak hours. If more capacity is still required, the current chiller will also have to operate during peak hours.

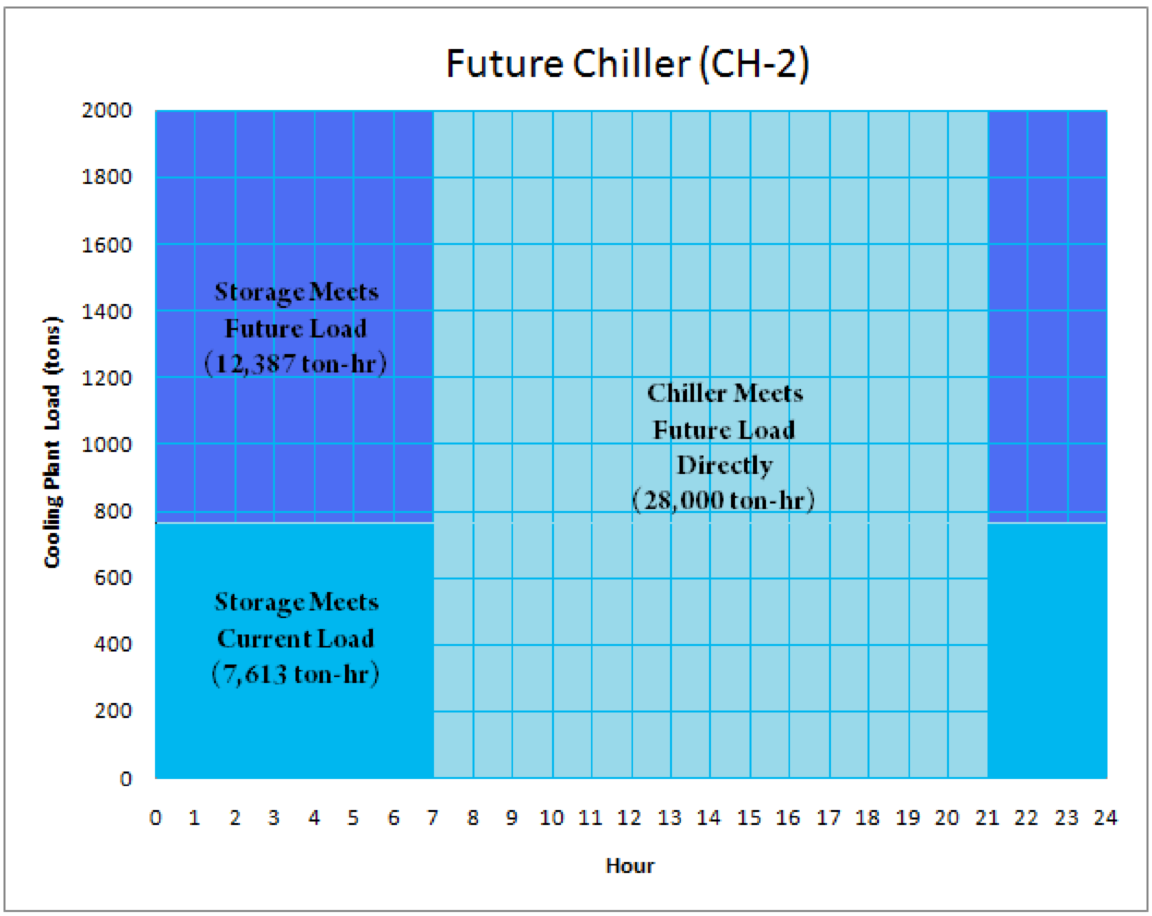

FIGURE 3.5

Available future capacity is indicated on Figure 3.5. Table 3.5 will summarize those values.

	Chiller	Hours	Capacity	Per Hour
Nighttime: (Met By Chiller Directly)	Current (CH-1)	9 PM - 7 AM	2,267 ton-hr	227 tons
Nighttime: (Met By Storage)	Future (CH-2)	9 PM - 7 AM	12,387 ton-hr	1,284 tons
Daytime: (Met By Chiller Directly)	Future (CH-2)	7 AM - 9 PM	28,000 ton-hr	2,000 tons
Total:			42,654 ton-hr	1,778 tons

TABLE 3.5

TOTAL STORAGE

The amount of storage required by the South Tower Vertical Expansion is 7,613 ton-hr between 9 PM and 7 AM. In addition, the remaining capacity of the chiller allows for 12,387 ton-hr of storage for the future.

Current Storage:	7,613 ton-hr
Future Storage:	12,387 ton-hr
Total Storage:	20,000 ton-hr

TABLE 3.6

Based on this quantity, there are several important factors that will determine whether water or ice storage is utilized.

SYSTEM CONSIDERATIONS

- Tank size
- Available space
- Required modifications to existing chilled water equipment

TANK SIZE

The size of the storage tank is critical to overall system design. If the tank is small enough, it would be able to be located on the roof. Otherwise, it would have to be located on the ground or underground. Having the tank or tanks closer to the chiller will reduce piping and pumping costs.

For water storage (sensible thermal energy storage), the required tank volume would be:

$$V = \frac{1{,}440 \times S\ [ton - hr]}{FOM \times \Delta T[°F]}$$

$$V = \frac{1{,}440 \times 20{,}000\ [ton - hr]}{0.85 \times 21\ [°F]}$$

$$V = 1{,}613{,}446\ [gal] = 215{,}687\ [ft^3]$$

Assumptions:	▪ Naturally stratified tank ▪ ΔT = 21°F ▪ Figure Of Merit = 0.85 (worst-case scenario)

TABLE 3.7

For ice storage (latent thermal energy storage), (47) 162 ton-hr CALMAC Ice Banks would be required to meet current storage needs. Up to 77 more tanks can be added to meet future storage needs. Each tank has a dimension of 89 in x 101 in (O.D. x H) for a volume of 364 ft^3. See Appendix D for tank specifications.

Storage Capacity	# Of Tanks	Tank Volume
162 ton-hr	1	364 ft^3
7,613 ton-hr (current)	47	17,108 ft^3
12,387 ton-hr (future)	77	28,028 ft^3
20,000 ton-hr (total)	124	45,136 ft^3

TABLE 3.8

WATER & ICE COMPARISON

Figure 3.6 illustrates the ratio of the required tank size using water storage and ice storage.

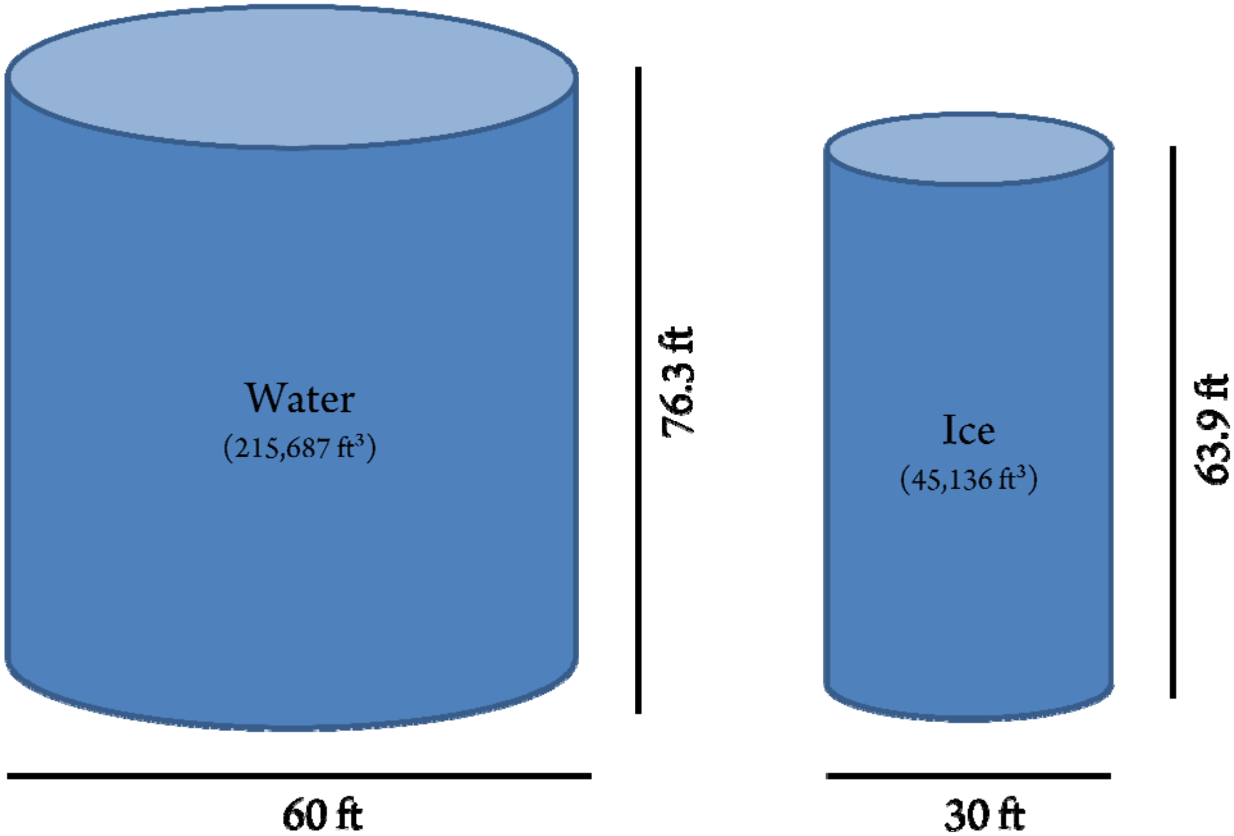

FIGURE 3.6

AVAILABLE SPACE

Because space is at a premium at Sinai Hospital, the best decision is to use latent thermal energy storage and ice tanks, where the required storage is 21% of the required storage using sensible thermal energy storage.

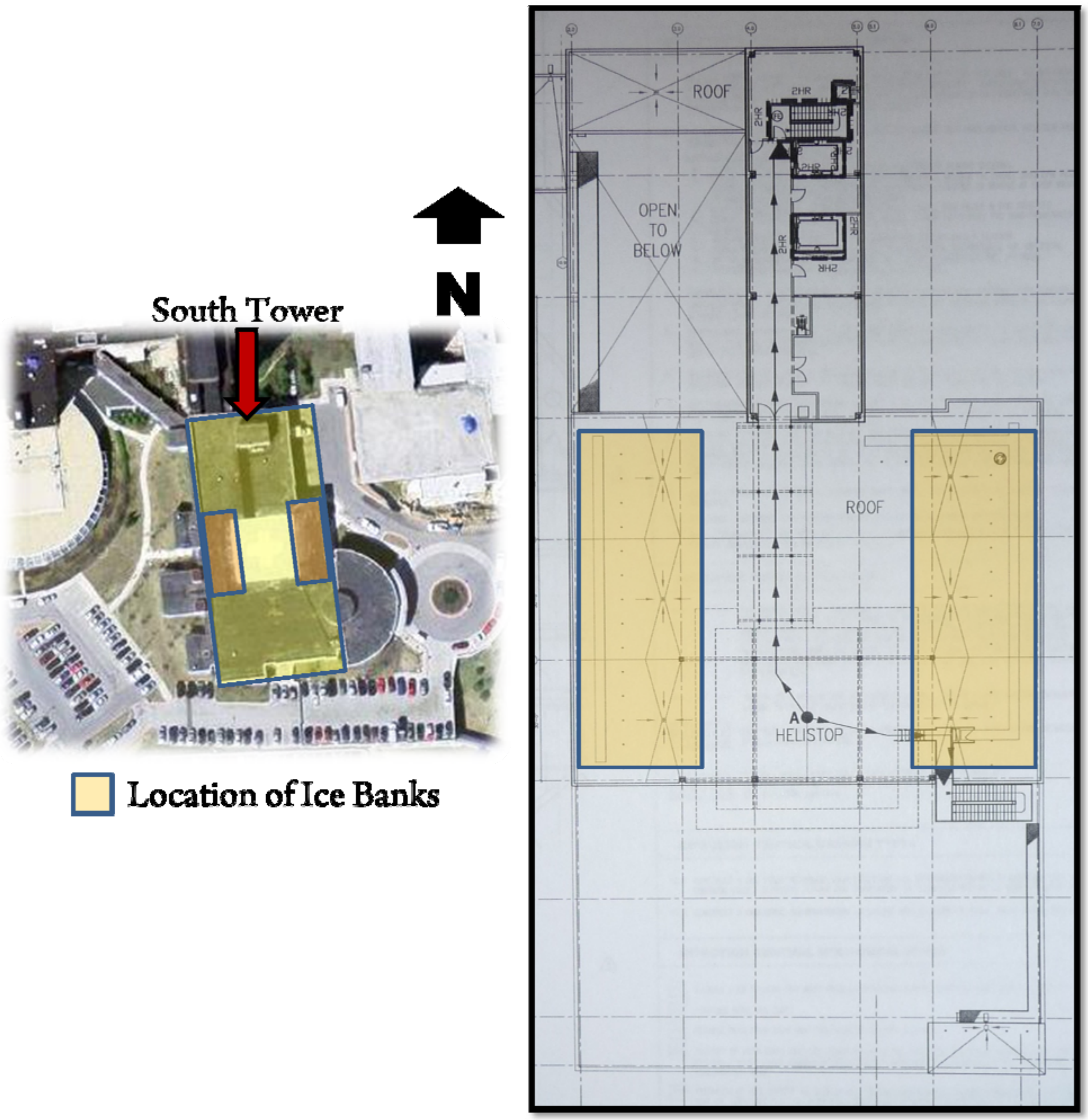

FIGURE 3.7

The best place available to locate the ice tanks is on the west and east sides of the South Tower roof adjacent to the helipad and above the penthouse. See Figure 3.7 for details. The storage tanks will be closer to the chillers and pumps located in the penthouse, reducing piping and pumping costs.

The footprint of the available roof space is 88 ft x 32 ft (L x W) on each side for a total area of 5,632 ft^2. In order to install all of the ice tanks, they must be stacked above one another on two separate levels. Structural support must be provided to accommodate the weight. In addition, a screen will be needed to hide the ice tanks from pedestrian view. These issues will be explored in the breadth sections later in this report. The setup will be described next.

SETUP

There will two levels of ice tanks on each side. Each level will support 30 ice tanks each (3 rows x 10 columns/22.7 ft x 75.6 ft). Figure 3.8 shows the typical arrangement for one level. The required height of each level is 11.5 ft (8.5 ft for the ice tanks and 3 ft of clearance), requiring a total height of 20 ft. For current storage needs, only 47 ice tanks need to be installed.

FIGURE 3.8

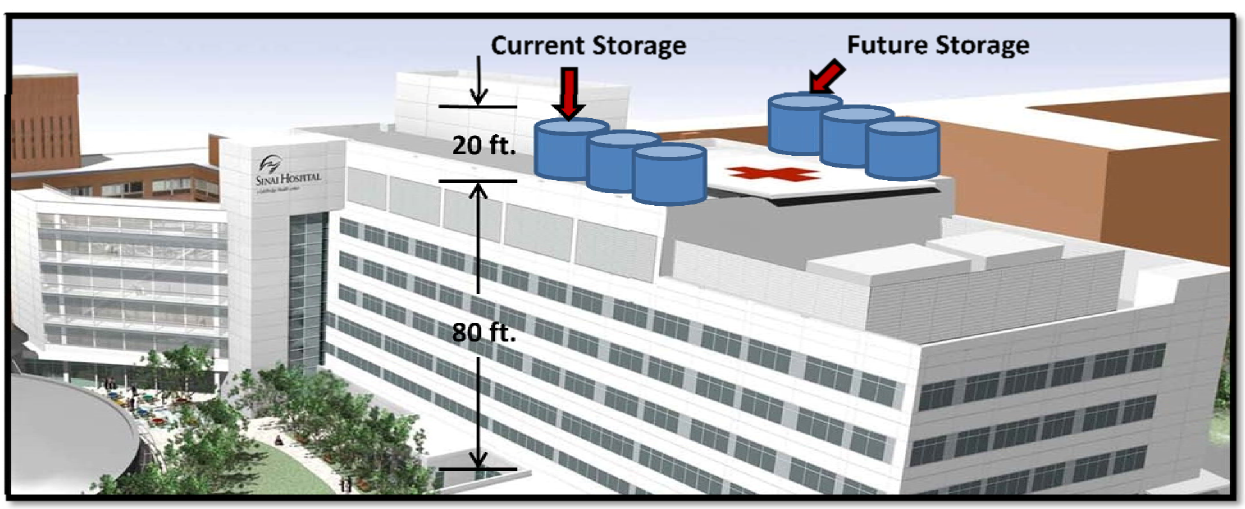

FIGURE 3.9

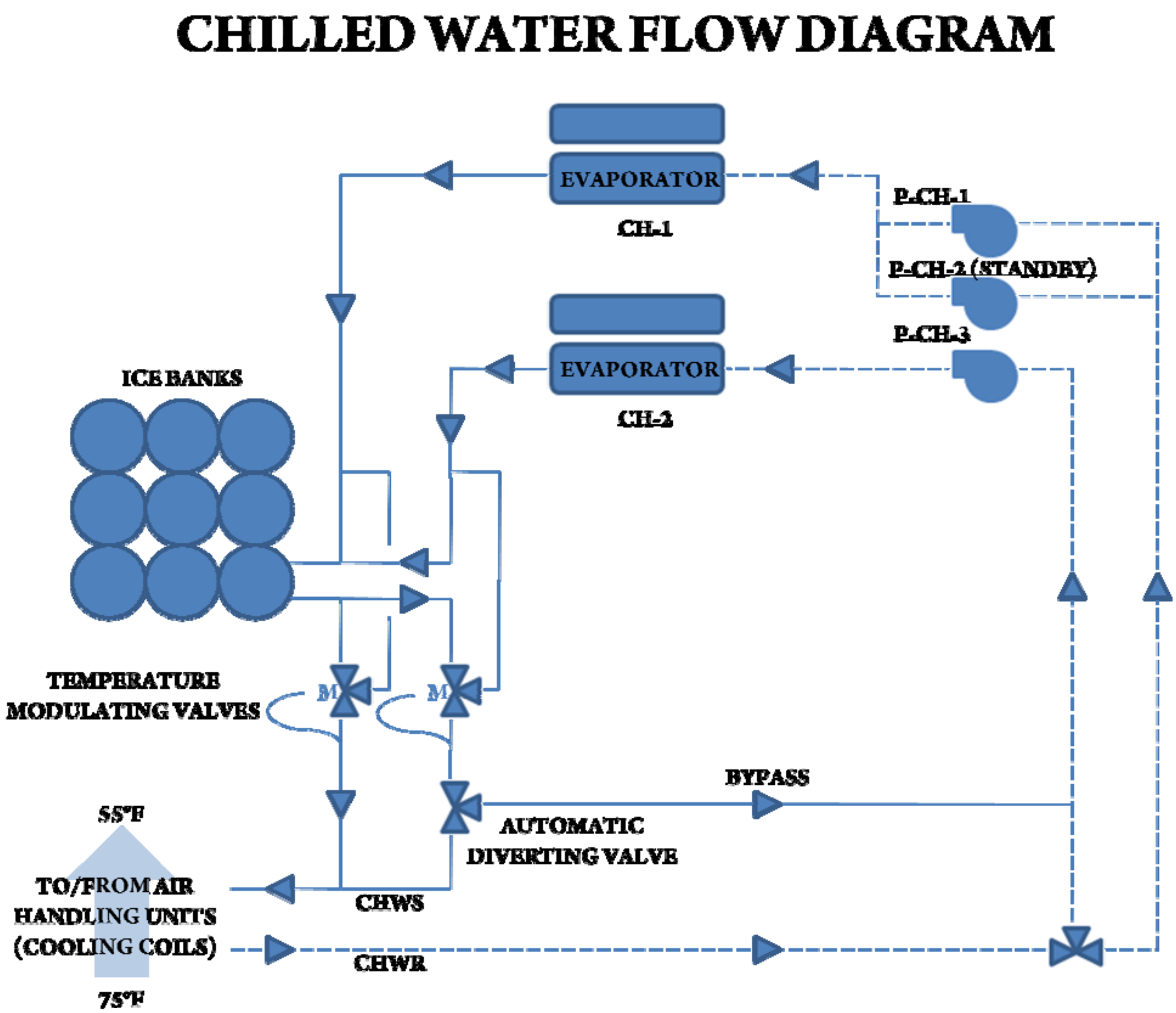

FIGURE 3.10

SYSTEM MODIFICATIONS

Because the model of the chiller, McQuay WDC126, has been designed for use in a thermal energy storage system, the modifications to the chilled water plant should be less complicated. For normal air-conditioning conditions, the entering water temperature at the evaporator is 57°F and the leaving water temperature is 42°F. When ice is being produced during off-peak hours in the future chiller, however, the leaving fluid temperature must be between 22°F and 26°F. Therefore, in order to accommodate such low temperatures, a water-glycol solution must be utilized.

FLUID

The solution that will be used is an ethylene glycol-based industrial coolant. Because this fluid inhibits corrosion, it can be used in standard pumps, air handling unit coils, and seals. This permits the current installed chiller, CH-1, to use the solution with damaging any equipment.

CHARGING (9 PM – 7 AM)

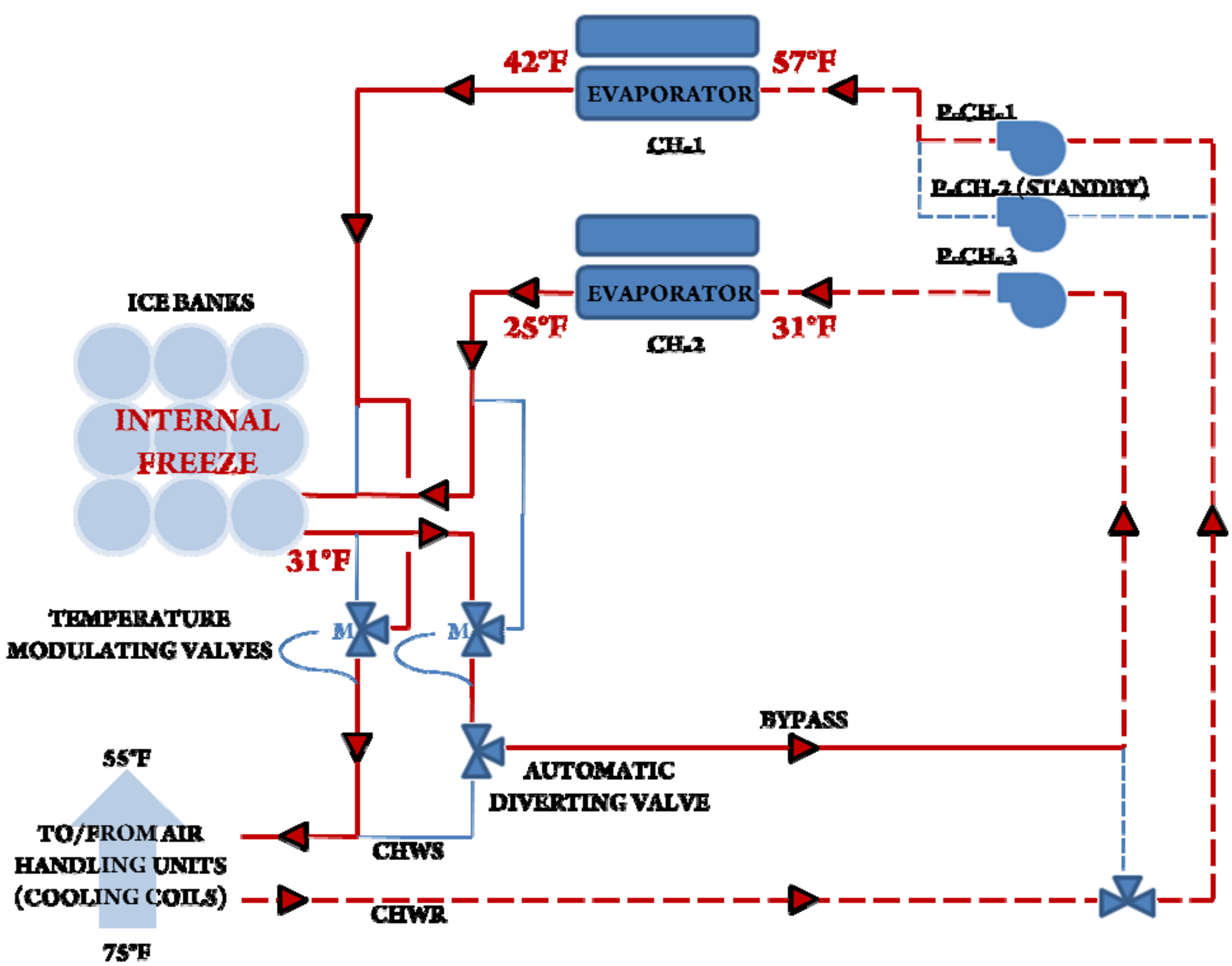

FIGURE 3.11

OPERATION

The added thermal energy storage system will operate in conjunction with the existing chilled water plant distribution. Future chiller CH-2 cycles water through the ice tanks during off-peak hours, internally freezing the water inside the tanks. Current chiller CH-1 provides cooling capacity directly to the hospital at this time. During peak hours, between 7 AM and 9 PM, future chiller CH-2 shuts down. Current chiller CH-1 then utilizes the charged ice tanks to provide cooling capacity to the hospital by internally melting the ice.

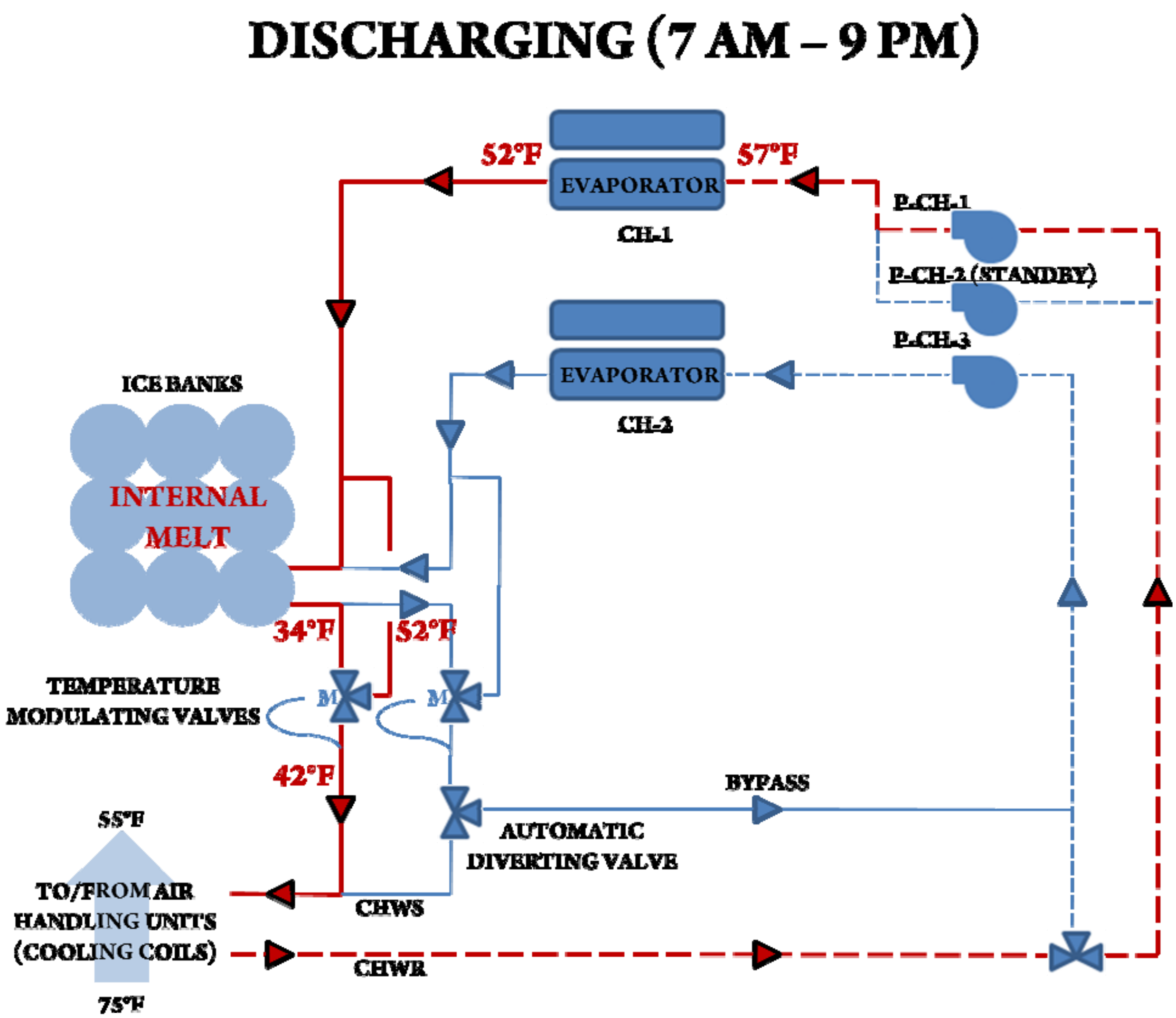

FIGURE 3.12

When future loads are added and more capacity is needed, future chiller CH-2 will have to operate during peak hours. Figure 3.13 illustrates how both chillers operate at this time, working in parallel.

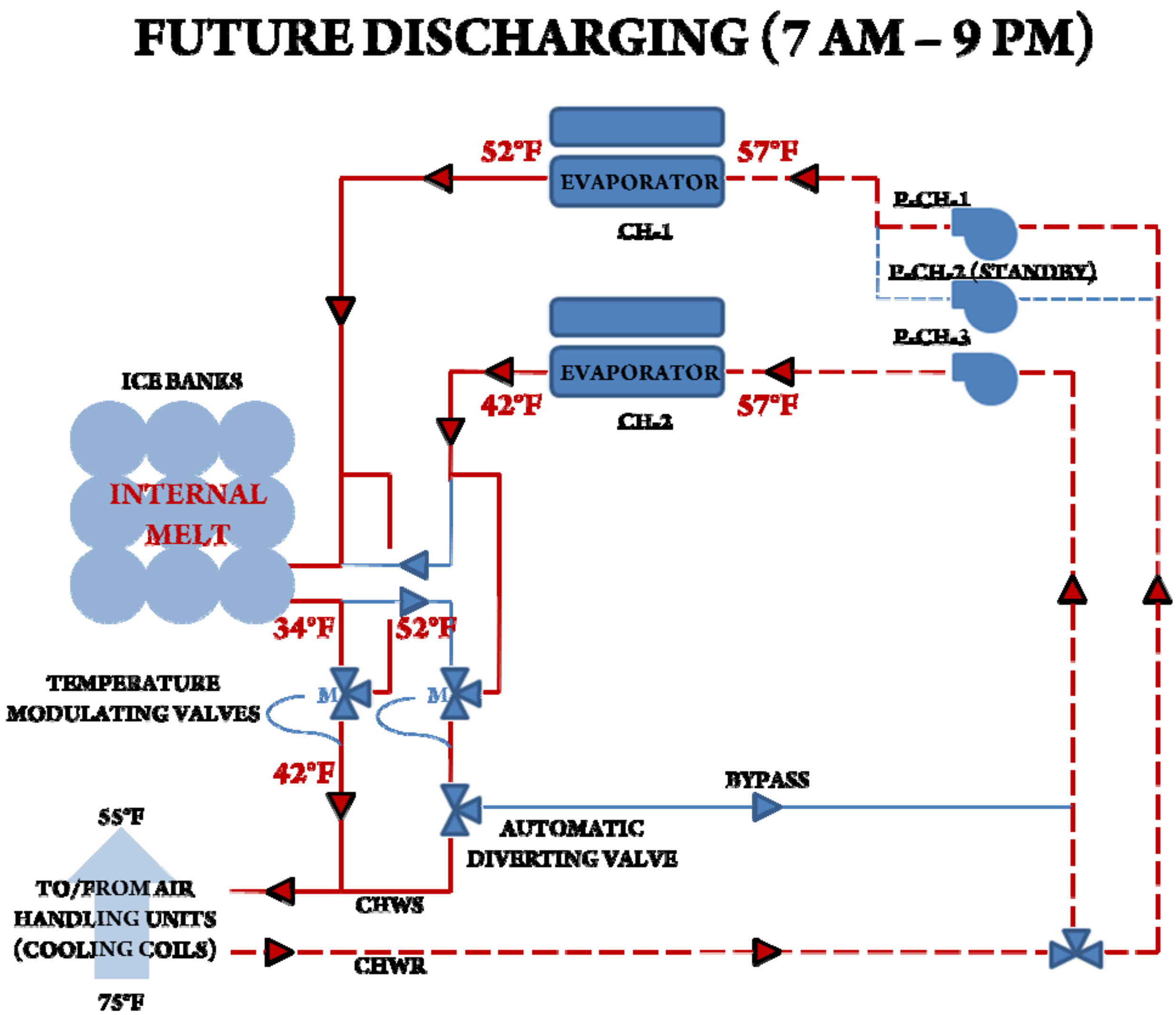

FIGURE 3.13

COST ANALYSIS

The main benefit of thermal energy storage is to operate equipment during off-peak hours when electric utility rates are low. The chiller specified for the South Tower Vertical Expansion operates at 1,255 kW at full load, so shifting loads will significantly reduce costs.

Using cooling load profiles from TRACE 700, it is possible to determine part load ratios for each month, and consequently, the chiller's average energy consumption. Once again, this procedure will only evaluate the three additional floors and the link and lobby of the South Tower Vertical Expansion.

Full Load Kilowatts =	1,255
Maximum Cooling Capacity/Month [ton-hr] =	1,440,000

Month	Cooling Capacity [ton-hr]	Part Load Ratio	Hourly Part Load Kilowatts
1	38,909	0.0270	33.91
2	32,167	0.0223	28.03
3	88,668	0.0616	77.28
4	129,875	0.0902	113.19
5	215,357	0.1496	187.69
6	278,891	0.1937	243.06
7	336,441	0.2336	293.22
8	295,990	0.2055	257.96
9	233,580	0.1622	203.57
10	141,332	0.0981	123.18
11	110,467	0.0767	96.27
12	70,351	0.0489	61.31

TABLE 3.9

The part load kilowatts for each month do not accurately represent the daily variations in energy consumption. However, they will be used to simplify the economic analysis while remaining on the conservative end for estimates. For example, the part load kilowatts is around 400 during off-peak hours while being close to 550 kW during peak hours on the cooling design day rather than a consistent value for the entire day.

TIME-OF-USE ELECTRIC UTILITY RATES

Electricity is provided to the South Tower Vertical Expansion from Baltimore Gas & Electric. They offer rate discounts based on time of electricity use. Figure 3.14 summarizes those rates.

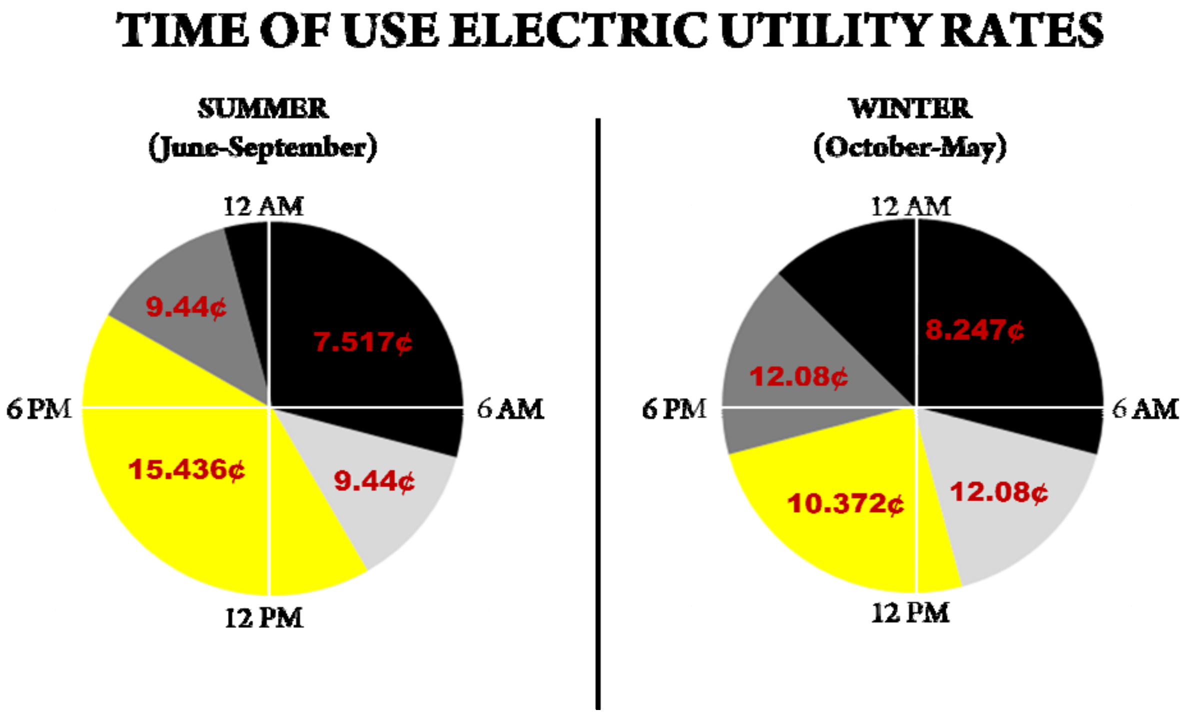

FIGURE 3.14

These rates compare to non-time-of-use rates, which do not fluctuate during the day. Those rates are given in Table 3.10.

Summer Non-TOU Rate:	11.526¢/kWh
Winter Non-TOU Rate:	9.945¢/kWh

TABLE 3.10

ELECTRIC UITLITY SAVINGS

CURRENT DESIGN

Using the part load kilowatts required for chiller operation listed in Table 3.9, it is possible to estimate the electric utility costs for the cooling equipment.

**Assume 720 operating hours per month*

Month	Hourly Part Load Kilowatts	kWh	Rate	Cost
1	33.91	24,415	$0.09945	$2,428
2	28.03	20,185	$0.09945	$2,007
3	77.28	55,639	$0.09945	$5,533
4	113.19	81,497	$0.09945	$8,105
5	187.69	135,137	$0.09945	$13,439
6	243.06	175,004	$0.11526	$20,171
7	293.22	211,117	$0.11526	$24,333
8	257.96	185,734	$0.11526	$21,408
9	203.57	146,571	$0.11526	$16,894
10	123.18	88,686	$0.09945	$8,820
11	96.27	69,318	$0.09945	$6,894
12	61.31	44,146	$0.09945	$4,390
				$134,423

TABLE 3.11

Without thermal energy storage, the cost to operate the chiller annually for the South Tower Vertical Expansion is $134,423.

REDESIGN

The same procedure will be performed for the redesign's cost analysis with thermal energy storage being accounted for. This is shown in Table 3.12.

**For capacity met by chilled water directly, assume 300 operating hours per month (by CH-1)*
**For capacity met by thermal energy storage, assume 300 operating hours per month (by CH-2)*

Month	Hourly Part Load Kilowatts	Hours	kWh	Rate	Cost
1-CHW	33.91	9 PM - 7 AM	10,173	$0.08247	$839
1-TES		9 PM - 7 AM	10,173	$0.08247	$839
2-CHW	28.03	9 PM - 7 AM	8,410	$0.08247	$694
2-TES		9 PM - 7 AM	8,410	$0.08247	$694
3-CHW	77.28	9 PM - 7 AM	23,183	$0.08247	$1,912
3-TES		9 PM - 7 AM	23,183	$0.08247	$1,912
4-CHW	113.19	9 PM - 7 AM	33,957	$0.08247	$2,800
4-TES		9 PM - 7 AM	33,957	$0.08247	$2,800
5-CHW	187.69	9 PM - 7 AM	56,307	$0.08247	$4,644
5-TES		9 PM - 7 AM	56,307	$0.08247	$4,644
6-CHW	243.06	9 PM - 11 PM	14,584	$0.09440	$1,377
		11 PM - 7 AM	58,335	$0.07517	$4,385
6-TES		9 PM - 11 PM	14,584	$0.09440	$1,377
		11 PM - 7 AM	58,335	$0.07517	$4,385
7-CHW	293.22	9 PM - 11 PM	17,593	$0.09440	$1,661
		11 PM - 7 AM	70,372	$0.07517	$5,290
7-TES		9 PM - 11 PM	17,593	$0.09440	$1,661
		11 PM - 7 AM	70,372	$0.07517	$5,290
8-CHW	257.96	9 PM - 11 PM	15,478	$0.09440	$1,461
		11 PM - 7 AM	61,911	$0.07517	$4,654
8-TES		9 PM - 11 PM	15,478	$0.09440	$1,461
		11 PM - 7 AM	61,911	$0.07517	$4,654

**For capacity met by chilled water directly, assume 300 operating hours per month (by CH-1)*
**For capacity met by thermal energy storage, assume 300 operating hours per month (by CH-2)*

Month	Hourly Part Load Kilowatts	Hours	kWh	Rate	Cost
9-CHW	203.57	9 PM - 11 PM	12,214	$0.09440	$1,153
		11 PM - 7 AM	48,857	$0.07517	$3,673
9-TES		9 PM - 11 PM	12,214	$0.09440	$1,153
		11 PM - 7 AM	48,857	$0.07517	$3,673
10-CHW	123.18	9 PM - 7 AM	36,953	$0.08247	$3,047
10-TES		9 PM - 7 AM	36,953	$0.08247	$3,047
11-CHW	96.27	9 PM - 7 AM	28,882	$0.08247	$2,382
11-TES		9 PM - 7 AM	28,882	$0.08247	$2,382
12-CHW	61.31	9 PM - 7 AM	18,394	$0.08247	$1,517
12-TES		9 PM - 7 AM	18,394	$0.08247	$1,517

$82,976

TABLE 3.12

Figure 3.15 shows the difference in annual electricity costs.

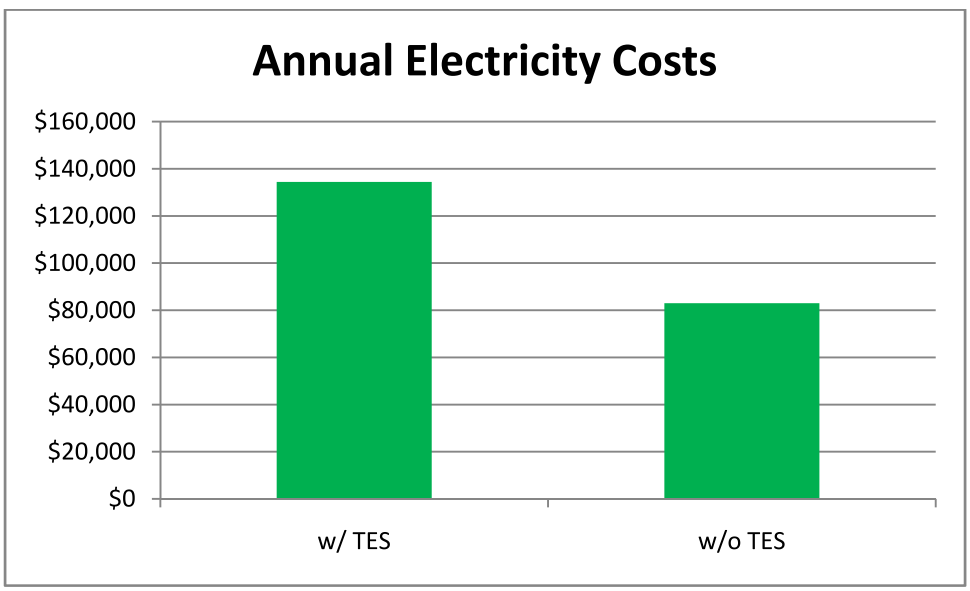

FIGURE 3.15

SAVINGS

Table 3.13 summarizes the annual savings by dollars per year, dollars per square foot, and dollars per kWh.

w/ TES	w/o TES	Annual Difference
\$134,423	\$82,976	**\$51,447**
\$1.12/ ft²	\$0.69/ft²	**\$0.43/ft²**
\$0.10863/kWh	\$0.08046/kWh	**\$0.02817/kWh**

TABLE 3.13

SIMPLE PAYBACK PERIOD

According to CALMAC, the installed cost of thermal energy storage is around \$100/ton-hour. This figure will be used to determine the payback period of the system. The storage capacity required for the South Tower Vertical Expansion is 7,613 ton-hr. Future storage will not be evaluated. In addition, the cost of the future chiller and associated equipment will not be taken into account; they have already been proposed.

$$Simple\ Payback\ Period = \frac{\frac{\$100}{ton - hr} \times 7{,}613[ton - hr]}{\$51{,}447}$$

$$\boldsymbol{Simple\ Payback\ Period = 14.8\ years}$$

CONCLUSIONS

Objective 1: Shift loads during peak hours of operation to off-peak hours ✓

As displayed in Figure 3.4, full storage was implemented, and 7,613 ton-hr of cooling capacity was shifted from peak hours in the current chiller to off-peak hours in the future chiller.

Objective 2: Achieve economical benefits ✓

As a result of load shifting, economical benefits were achieved. Baltimore Gas & Electric offers lower electric utility rates during off-peak hours, and because both chillers generate cooling capacity only during those times, there was a savings of approximately $0.03 per kWh. This resulted in an annual electric utility savings of $51,447.

Objective 3: Increase plant flexibility ✓

By using the future chiller for thermal energy storage applications, flexibility in the chilled water plant increased. Both chillers can meet current and future loads while still taking advantage of off-peak time-of-use rates. Furthermore, the future chiller could potentially be downsized by implementing partial storage for any additional loads.

Objective 4: Perform a feasibility study of locating storage equipment on-site ✓

The storage required to support the shifted cooling capacity for current loads would be a feasible amount. 7,613 ton-hr of cooling capacity would need approximately 17,000 ft^3 of space, which is available on the roof. However, the addition of 77 ice tanks for future storage may be more difficult to locate since it requires an additional 28,000 ft^3 of space.

Objective 5: Attain a reasonable payback period ✓

After performing the redesign and cost analysis, it was determined that the payback period of the thermal energy storage addition would be 14.8 years. This is a fairly long length of time, but the system still remains a viable option. CALMAC Ice Banks require very little maintenance and come with a 10-year warranty, so achieving reimbursement of the initial investment seems very likely, especially with a hospital lifespan of at least 30 years.