The Texas Medical Center in Houston is the largest medical center in the world. Thermal Energy Corporation (TECO) provides thermal utilities (chilled water and steam) to many of the buildings in the medical center, and in 2007 TECO had an 80,000 ton (281 MW) chilled water system serving the medical center. Master planning indicated that the cooling load demand for the campus would double to 160,000 tons (563 MW) over the next decade, so TECO sought the most cost-effective way to provide the increased quantity of chilled water to the medical center while maintaining a high level of reliability to serve critical campus needs.
Installing new chilled water production and thermal energy storage (TES) system were evaluated as methods to meet the increasing demand. A lifecycle cost analysis determined that installing TES in a load leveling scheme was the most cost-effective first step to meet the increasing chilled water demand, even without factoring in Electric Reliability Council of Texas’s (ERCOT’s) current pricing strategy (see Real-Time Pricing at right). This resulted in the selection of an 8.8 million gallon (33.3 million L) stratified chilled water storage tank that is 100 ft (30 m) in diameter and 150 ft (46 m) tall. To meet the increasing demand, the TES system was required to be in operation for the 2010 cooling season, followed by the operation of the first phase of the new East Chiller Plant for the 2011 cooling season (Figure 1).

To meet the requirement of being operational a full year before the new east chiller plant and to operate with the existing plants, the TES system had to function independent of the east chiller plant operation, eliminating the possibility of using a primary-secondary chilled water plant pumping scheme where the TES tank is located in the hydraulic bridge between the primary and secondary systems. Finding a way to connect the TES tank to the TECO system would become the most challenging aspect of the project.

Innovation

The reason this project is unique is twofold. First is the height of tank at 150 ft (46 m), making it the tallest stratified chilled water storage tank in the world. Second is a result of integrating such a tall tank that is open to the atmosphere into a closed chilled water distribution system.

The tall tank height creates 65 psig (448 kPa) of pressure at the bottom of the tank on both the chilled water supply (CHWS) and chilled water return (CHWR) lines connected to the tank. TES tanks normally use a pump on either the CHWS or CHWR line and take advantage of gravity and the pressure differential between the TES tank and the chilled water system to drive water into or out of the tank. Table 1 shows the current system pressures, as well as the results if the system pressures were modified to allow for single direction pumping.

If the chilled water system pressure were raised, the system pressure would greatly exceed the pressure rating of the existing 40-year-old distribution piping, which was estimated to be 115 psig to 125 psig (790 kPa to 860 kPa). If the chilled water system pressure was lowered, the return system would be required to operate at approximately 5 psig initially, and under a vacuum as system loads increase. Therefore, for this installation, as result of the height of the chilled water tank, the connection of the tank into the system and the resulting chilled water system pressures the pumps are required to operate simultaneously (at least in some operating conditions) on both the CHWS and CHWR.

Using simultaneous dual pumping of CHWS and CHWR on a TES tank had been tried previously on other TES systems, but in each instance we studied, it was not successful. To connect this TES tank to the existing chilled water system, the design team needed to accomplish something that hadn’t been previously accomplished.

The system in Figure 2 shows the TES tank, the CHWS and CHWR pumps as well as the chilled water production facilities at the existing central plant and the future east chiller plant. One method of pump control considered was to measure the flow rate into and out of the TES tank. One pump speed would be lead and the other would follow the first pump by matching the flow rate. This is the solution that other installations had unsuccessfully applied in the past.

### Real-Time Pricing

One way the Electric Reliability Council of Texas (ERCOT) manages demand on the grid that serves most of Texas is to use real-time pricing for power. A customer using this pricing scenario will experience a varying price of power for every 15 minutes of the year. This varying rate is based on the hourly operating cost of generation assets and grid congestion. During times of peak demand, the price of electricity can rise dramatically. In 2010 the ERCOT peak rate was approximately $2,200 per MWh, in 2011 it was $3,500 per MWh and in 2012 the peak rate is $4,500 per MWh. These rates are high when compared to an average cost of $50 per MWh. The large difference provides a strong incentive for large electric users to reduce their electrical energy consumption during the high demand periods. One way that district energy providers can do this is to use thermal energy storage to shift the demand to the evening.

### TES System at a Glance

#### TES Tank

**Location:** Houston  
**Owner:** Thermal Energy Corporation  
**Principal Use:** Chilled Water Storage  
**Volume (gross):** 8,800,000 gallons  
**Capacity:** 64,285 ton-hours  
**Discharge Rate:** 27,000 gpm (maximum)  
**Heat Gain:** 1.33% per 24 hours (maximum)  
**Pressure Drop:** 5 psi (maximum)

#### TES Supply and Return Pumps*

- 16,000 gpm;  
- 146.2 ft of head; and  
- 600 hp

*The system is designed to have the pumping capacity increased in the future to two pumps at 16,000 gpm each.
A reason for failure is the inaccuracy of the flow meters. A small difference of 1% of the flow (160 gpm [10 L/s] in this case) would result in the pumps attempting to push a large volume of water into (or out of) the closed chilled water system (with its fixed volume) to or from the TES tank. This situation would raise (or drop) system pressure, possibly causing pumps to cavitate, the tank to overflow, or pull air into the system. Causing the chilled water system pressures to rise very quickly would raise the system pressure above the rated capacity of the piping system, greatly increasing the chances of pipe failure.

To solve the problem and control both pumps without either damaging the chilled water system or overflowing the tank, we explored a concept that used the fixed chilled water system volume to our advantage. This solution has the CHWS pump being controlled either based on a fixed flow rate selected by the operator, or controlled by the differential pressure out in the chilled water system. This control strategy is fairly simple and straightforward. However, the second pump is required to be controlled by a variable that would react quickly to a differential in flow rate between the supply and return (more quickly than tank level). It was determined that the CHWR pressure for the entire system could be the variable used to control the pump. As more water is pumped into or out of the chilled water system, the system pressure raises or lowers, causing the CHWR pump to adjust its speed (and volume of chilled water) to maintain a constant return pressure.

Prior to the installation of the TES system the existing chilled water system had experienced frequent rapid swings of 20 psi to 30 psi (140 kPa to 200 kPa) on both the supply and return sides of the system. After the installation of the TES tank and pumping system, the return side pressure is now stable (normally around 40 psig) with the supply side pressure varying based on chilled water load changes (Figures 3 and 4). The installation became the first TES tank with successful dual directional pumping known to the author.

**Energy Efficiency**

Conventional wisdom would indicate that a TES system uses more energy than an equivalent non-TES system. After all, there are losses associated with getting the energy/water into and out of storage, plus heat gain while in storage. However, TES systems use slightly less energy (Btu or kWh) by shifting chilled water production from the middle...
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of the afternoon when the highest wet-bulb temperatures of the day are experienced to the evening when wet-bulb temperatures are lower. The lower wet-bulb temperatures yield lower condenser water temperatures, which allow the chillers to operate more efficiently during the night hours when the tank is being charged. In addition, the TES system allows chillers to operate at their most efficient point, increasing the energy savings. Table 2 shows a summary of the energy information for various months throughout the first year of operation.

There are three pieces of information to be extracted from the data in Table 2. First, during the first year of operation the operators were learning when to use the TES system to provide a positive benefit to the system. Second, the energy-saving potential is reduced during the winter. Finally, when the east chiller plant came on-line in 2011, it increased the overall system efficiencies during the day and night operation, decreasing the day/night efficiency differential and lowering the TES energy savings. (Note that during 2011, the chiller capacity increased by 40%, allowing TECO to reduce the operating hours of its less efficient chillers. As loads increase, the hours of operation of the less efficient chillers will increase, resulting in increased energy savings due to the TES system.)

### Operation and Maintenance

The TES system provides the owner with several operational and maintenance benefits. When looking at the maintenance, the cost to maintain a stratified chilled water storage tank is much lower than that for equivalent chilled water production capacity. In essence, the TES tank is a large piece of pipe in the chilled water system, requiring a similar level of maintenance. Additional chillers and cooling towers would otherwise be required to be installed and maintained for the new production capacity. With the TES system, only the temperature and level sensors in the tank require maintenance, while both TES and non-TES systems would have approximately the same number of pumps to be maintained.

The TES system provides the owner important operational flexibility with regard to when to make chilled water and when it is best to discharge the tank and send

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>August 2010</th>
<th>September 2010</th>
<th>November 2010</th>
<th>January 2011</th>
<th>July 2011/August 2011</th>
</tr>
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<tbody>
<tr>
<td>Amount of Storage Used</td>
<td>ton/h</td>
<td>1,274,770</td>
<td>1,345,796</td>
<td>751,813</td>
<td>140,976</td>
<td>1,707,715</td>
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<td>Full Discharge</td>
<td>days</td>
<td>22</td>
<td>24</td>
<td>15</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>Partial Discharge</td>
<td>days</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Energy Saved</td>
<td>kWh</td>
<td>104,893</td>
<td>92,688</td>
<td>–18,685</td>
<td>814</td>
<td>38,751</td>
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<td></td>
<td>8.61%</td>
<td>7.18%</td>
<td>–2.75%</td>
<td>0.64%</td>
<td>2.54%</td>
</tr>
<tr>
<td>Energy Cost Saved*</td>
<td>$</td>
<td>$101,159</td>
<td>$46,195</td>
<td>$9,435</td>
<td>$452</td>
<td>$506,837</td>
</tr>
</tbody>
</table>

*On peak and off peak energy rates vary greatly based on real-time pricing.

### Table 2: Energy use data.
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the energy to their customers. This allows them to take advantage of the real-time electric pricing in the deregulated electric utility market.

In addition, the nearly 9 million gallons (34 068 690 L) of chilled water when the tank is fully charged provides nearly an hour of total system peak chilled water demand in the event of a catastrophic failure of the plant. This is vital for the Texas Medical Center, which has many multiyear temperature-critical experiments. A one-hour buffer might be enough to keep those experiments intact during an outage. The TES can provide a longer period of backup cooling capacity if used at a lower flow rate to meet only the most critical loads.

The TES system also allows the operators to minimize the chilled water return pressure fluctuations. Figures 3 and 4 show the chilled water system pressures for a week (168 hours) both prior to and after implementation of the TES system. The chilled water return pressures flatten out. The remaining fluctuations were when the TES system was not in operation.

Cost Effectiveness

Cost is where the TES tank really shines. When analyzed without real-time pricing (RTP), installing the TES system was more cost effective than installing equivalent new chilled water production on both a first cost ($13 million vs. $19.1 million) and when analyzed on a life-cycle cost basis (approximately $9 million lower life cycle cost). Since that initial decision, TECO is now using RTP from ERCOT for its electrical costs. Using RTP generally has a lower average cost, but for certain hours on peak days, costs can rise dramatically.

During the first 23 days of August 2011, TECO experienced 16 hours when the price of electricity was $3,000/MWh. The TES system was operating each of those hours, saving an average of $24,750 per hour for a total savings of $395,000! These 16 hours account for 78% of the $506,000 in energy cost savings during those 23 days.

Summary

Integrating a TES system into the existing chilled water system provided many benefits including a lower first cost, lower operating costs, lower energy use, lower emissions, increased operational flexibility and increased reliability. However, none of those benefits could have been realized without first solving the problem of controlling a dual directional pumping system. Dual directional pumping had been tried previously, each time with an unsuccessful result. Using system pressure to control the flow of the pumps resulted in a successful control scheme for the TES pumps and allowed all of the benefits of the TES system to be realized by TECO.