REPLACING INEFFICIENT EQUIPMENT --- AN ENGINEERING ANALYSIS TO JUSTIFY PURCHASING A MORE EFFICIENT CHILLER

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ABSTRACT

Chiller energy consumption in commercial buildings accounts for about 40% of HVAC system energy consumption, and about 30% of the total energy use in the whole building. Being the largest energy component in the building, the chiller energy use is the greatest contributor to the cost of utilities. The Connally Building is an office building, with a total floor area of approximately 123,960 ft^2. Field studies indicated the need to evaluate the existing chiller plant's economic performance. Specifically how well the plant, as a whole system, met cooling loads of the building, and how this affected their use.

This paper reports our findings from an engineering analysis of the Connally Building, aimed at improving the energy efficiency of a conventional chilled water plant during the commissioning activity. Utility bills (electricity and gas) and one-year trended data for chillers' operation were analyzed for the chiller plant evaluation of different energy conservation opportunities. The commissioning measures for the chiller plant optimization have been specifically recommended to improve chiller plant operation performance.

Key words: chiller plant, engineering analysis, evaluation, optimization

INTRODUCTION

Continuous Commissioning is a process of optimizing building HVAC systems and reducing overall energy consumption, without sacrificing and often improving occupant comfort (Claridge, et al. 2000a; Claridge 2000b; Deng, etc. 1998; Turner, et al. 2001). This is accomplished by optimizing the building's EMCS HVAC control sequences and schedules in addition to identifying and repairing malfunctioning HVAC system components (Chen, et al. 2003). Although the Continuous Commissioning process is directed towards the entire building HVAC operation, the most substantial savings can be found by focusing on the highest energy consumption systems. As a part of the CC activity on the Connally Building, a chiller assessment was conducted. The following will describe the recommendations that resulted from the chiller assessment.

The John B. Connally Building is a 7 story, 123,960 ft^2 office building. Chilled water for the building is provided by two 280-ton York water-cooled chillers and one 30-ton McQuay air-cooled chiller. Only one of the 280-ton chillers is required to meet the maximum cooling needs of the building; the other chiller is used as a backup in case of mechanical failure. The lead operating chiller is cycled between the two 280-ton chillers on a weekly basis to keep both chillers in a good working condition.

There is a third 30-ton chiller. Chiller #3 is the 30-ton McQuay air-cooled chiller. It was initially intended to operate during unoccupied periods and low load conditions. The chiller was found to be undersized for this application limiting the amount of time it was used. In addition, there were many mechanical problems causing it to be out of service for long periods of time. Because of these problems, the 280-ton chillers ran during unoccupied times and low load conditions. Since the 280-ton chillers were used during very low load conditions, problems such as surging occurred. Also as a result, these big chillers would occasionally set off low load alarms.

A replacement for chiller #3 that would increase energy efficiency was investigated. This paper gives an investigation for replacing chiller #3 with a properly sized chiller that will save energy and protect the 280-ton chillers from further damage. Studies of the energy usage of the current chillers and proposed future chiller were conducted. The information in this investigation provides an estimate for the energy savings and simple payback time of installing a new chiller.

EXISTING CHILLER PLANT INFORMATION

The building plant currently consists of two 280-ton York centrifugal water-cooled chillers (#1 and #2) and one 30-ton air-cooled McQuay chiller (#3). Only one of the 280-ton chillers is required to meet the maximum cooling needs of the building; the other chiller is used as a backup in case of mechanical failure. The lead operating chiller is cycled between the two 280-ton chillers on a weekly basis to keep both chillers in a good working condition. The 30-ton McQuay chiller is scheduled to run at nighttime and during low building cooling loads. It runs only when the tonnage of chiller #1 or chiller #2 becomes less than or equal to 20 tons for a certain length of time, and if there are three or less AHUs ON in the building. These conditions only occur during the night, weekends, or holidays. There are three parallel chilled water pumps, one is 1.5 hp, and two are 20 hp. The smaller pump only runs when chiller #3 is ON and the larger pumps run when their associated chiller is running. A schematic for the chilled water system is provided in Figure 1. There are two cooling towers that serve the chillers. Each tower has a 15 hp fan that is controlled by a VFD. A schematic for the cooling towers is given in Figure 2.

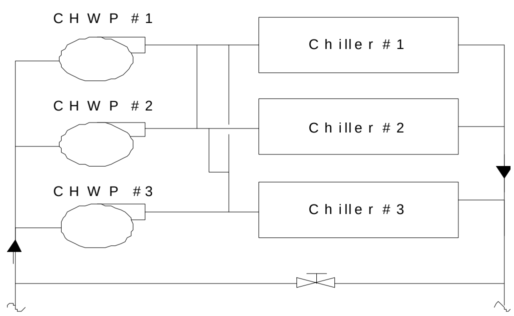

Figure 1: Chilled Water Schematic

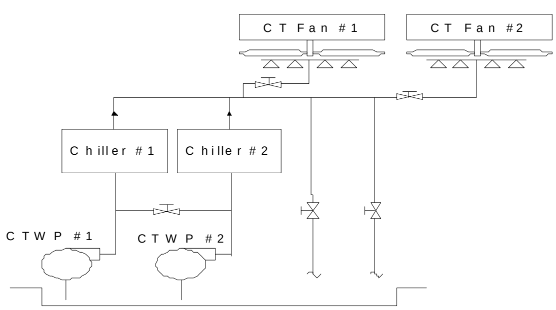

Figure 2: Condenser Water Schematic

Every night from 11:30 pm until 6:00 am, the building goes into the unoccupied mode and most of the AHUs are turned off. Four AHUs and three FCUs remain ON during unoccupied periods because they serve computer rooms that must be conditioned at all times. The building is also equipped with thermostats that have override switches that cause the AHU serving them to turn ON when pressed, even if they are in unoccupied mode. When the number of operating AHUs in the building becomes greater than three, the 30-ton chiller shuts down and one of the 280-ton chillers starts running. This causes the 280-ton chillers to run at low cooling loads.

ANALYSIS OF CHILLER LOAD AND PERFORMANCE

Chiller Operation and Minimum Cooling load

The existing chiller #3 is a 30-ton McQuay air-cooled package chiller. Due to mechanical problems, this chiller is often out of service and in need of repairs. When the chiller is in service, it cannot be used as much as originally intended because unoccupied cooling needs are often above the maximum 30-ton capacity of the chiller.

The 280-ton chillers run most efficiently at loads at or above approximately 112 tons. It is very inefficient and energy consuming for one of the 280-ton chillers to operate with less than 84 tons of load. There have been some occasions when one of the 280-ton chillers has had to run at loads less than 15% of their maximum load (40 tons). When the unit runs at such low loads, it causes internal damage and puts excessive strain on the chiller. When the load is too low, it causes the chiller to trip off on a Low Load Alarm. The 280-ton chillers have a time delay of 10 minutes after being shut off; this could lead to building HVAC system control and stabilization problems during the time delay period.

Existing Load Profile and Demand Distribution

Measured hourly data was used to develop typical day profiles. These day profiles are basic for identifying energy usage, energy use pattern, and potential savings. The most important purpose of the identification process is to optimize the building and chiller plant's energy consumption.

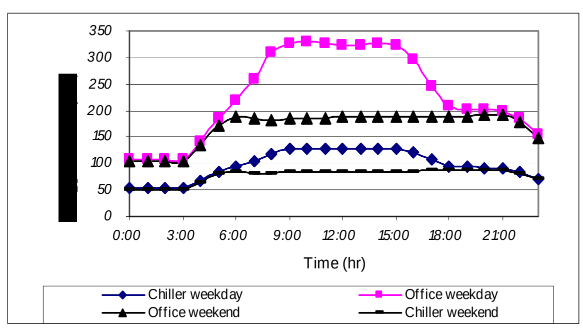

Figure 3: Average chiller and office energy use vs. hour of the day for weekdays and weekends

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Figure 3 above shows the average energy consumption pattern for both weekdays and weekends for the period between Sept 2001 and Aug 2002. There is an obvious increase in energy demand between the hours of 8am and 5pm that correspond to the normal working office hours for the building personnel. Office energy consumption is determined by the summation of all office equipment (including all of the AHUs).

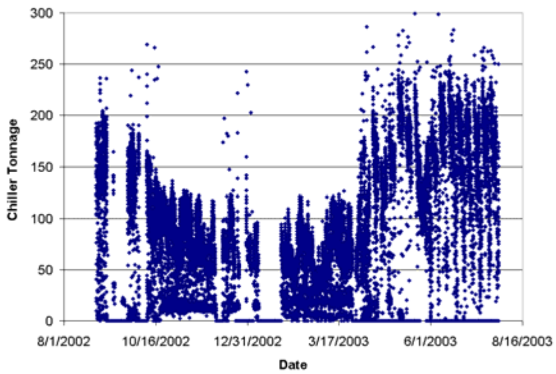

Figure 4: Time-series Graph of Chiller Tonnage

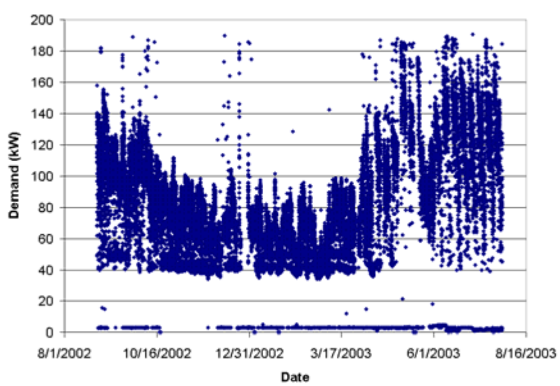

Figure 5: Time-series Graph of Chiller Demand

It can be seen that some AHUs were operating during the weekend. There is also some evidence of other equipment running such as computers, refrigerators and other office type appliances. The average energy use per day during the weekend for the chiller shows that it was running at 48% of its capacity. Also, during the weekend, the amount of energy used by the chiller decreased. This is due to a decrease in the building-cooling load. It can also be determined that during the weekend chiller #3 is not the primary chiller.

This analysis indicates that the best determinate of office building and chiller energy use, is the building schedule and office temperature that is maintained within the space. Thermostat control (day and night settings for cooling and heating within the terminal electronic controller) is also important.

Trends of the tonnage and electrical demand for the chillers in the Connally Building were taken in 15-minute intervals from August 2002 to August 2003. Graphs of the chiller tonnage and demand during this period are given in Figures 4 and 5 respectively.

Figure 4 shows the data pattern of the trended chiller tonnage versus time. The chiller tonnage was below 100 tons most of the time during the period of late October, 2002 to late March 2003 and was as high as 250 tons during the warm and hot weather period (April to September). The trended demand data pattern in Figure 5 is the same as the tonnage's pattern in Figure 4. The tonnage required periods at or below 100 tons in the winter and begins to vary widely during the summer. Demand use follows the same pattern as the tonnage since demand is a function of the cooling required and the efficiency of the chillers.

During the period of middle October 2002 to late March 2003, the chiller demand was at or below 80 kW most of the time, and the chiller demand peaked at 180 kW during the high temperature weather data period of March to September. Figures 4 and 5 shows the chiller's input and output. Figure 5 also represents the building load value and pattern during the period of August 2002 to August 2003.

Chiller Operating Frequency Versus Tonnage

Figure 6 shows the load profile for chillers #1 and #2 during the same period (August 2002 ~ August 2003). The bar chart is based on one-year 15 minute interval data for both chillers #1 and #2. It can be seen from the figure that the majority of the time the chillers run at 120 tons or below. The amount of time the chillers run below 30 tons is very small. The full 280 tons is very rarely used, showing that the chiller size was chosen to meet the maximum load conditions.

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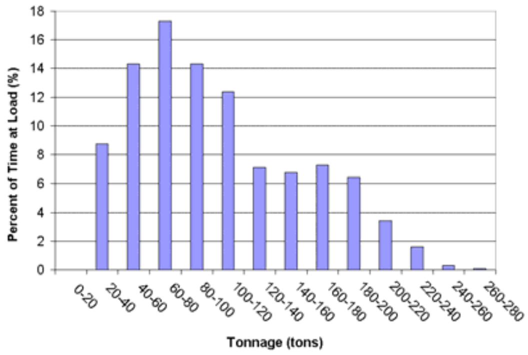

Figure 6: Chiller Operating Frequency vs. Load

Figures 7 and 8 show the percentage of time chillers 1 and 2 spend above and below 120 tons. The chillers spend a combined 67% of their run time at loads below 120 tons. Therefore, a new 120 ton chiller can be used the majority of the time. A new 120 ton chiller would be able to supply all the cooling needs of the building for about 67% of the time. This would leave the 280 ton chillers to run only about 33% of the time, and while they are running, they would operate close to their peak efficiencies.

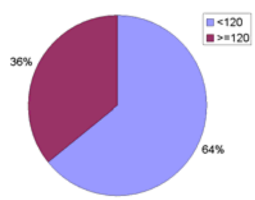

Figure 7: Chiller 1 Tonnage Distribution

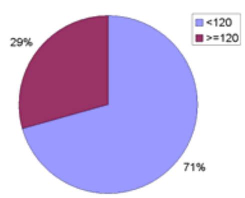

Figure 8: Chiller 2 Tonnage Distribution

Existing Chiller's Performance

The full-load energy usage or efficiency of a chiller represents an important design point. It determines the sizes of the motor, starter, and electrical wiring of the system. But to only use full-load efficiency to make chiller comparisons is inappropriate and even misleading.

The Integrated Part-Load Value (IPLV) performance calculation is recommended by ASHRAE to evaluate energy efficiency as a basis for chiller comparisons. Table 1 shows minimum water-cooled chiller (centrifugal) efficiency requirements from ASHRAE standard 90.1 – 1999. The existing two chiller's capacity is 280 ton. Table 1 shows its minimum peak load COP is supposed to be 5.55 and 0.634 for IPLV (kW/ton).

Table 1. Minimum water-cooled Chiller Efficiency Requirement (ASHRAE/IESNA Standard 90.1-1999)

Capacity (tons)	Peak load COP	IPLV (kW/ton)
<150	5.00	0.703
151-299	5.55	0.634
>=300	6.10	0.576

A graph of the chiller efficiency (demand per ton) in relation to the tonnage output over a year is given in Figure 9.

At 120 tons and higher, the demand per ton is the lowest and it remains relatively constant. As the load goes below 120 tons, the demand per ton begins increasing. The energy efficiency is inversely related to the demand per ton, so as the demand per ton increases the efficiency decreases. From looking at this figure and the chiller load distribution, it can be seen that the chillers are operating in their lower efficiency ranges the majority of the time. For a 280-ton chiller, the efficiency should be at least 0.634 kW/ton (Table 1). Data taken from the current chillers in Figure 6 shows that at high loads the efficiencies are near the ASHRAE standards. When the loads decrease, the chillers become less efficient and cannot meet the standard. All new chillers are required to meet or exceed the minimum ASHRAE standard value; therefore a new chiller would be more efficient at lower loads than the current chillers.

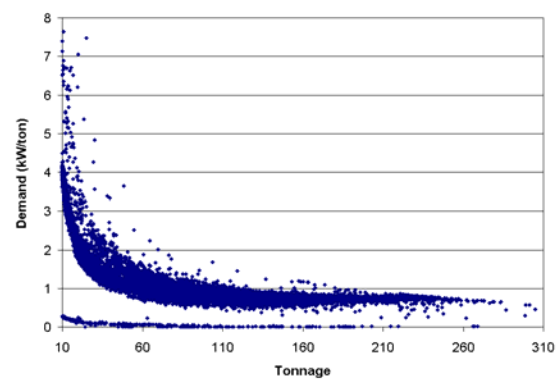

Figure 9: Chiller Demand vs. Tonnage Output

Integrated Part-Load Value calculation is performed according to the one-year 15-minute interval trend data. For this rating, chillers are categorized at 100%, 75%, 50% and 25% loads. The result is a single-number estimate of a chiller's part-load energy use, weighted for the number of hours the units might spend at each part-load point. Lower IPLV indicates

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lower energy use. The IPLV rating multiplied by annual operating hours and by local energy costs produces a comparison figure for operating costs.

Table 2: Actual IPLV Calculation

Load %	Weight %	kW/ton	Weighted ton/kW
25	0.623	1.39	0.448
50	0.256	0.75	0.341
75	0.118	0.73	0.162
100	0.002	0.40	0.005
IPLV = 1/0.956 = 1.046kW/ton			0.956

Table 2 shows an actual IPLV calculation. The kW/ton values in the table are actual average trend data and the weight % values are chiller operating relative frequency at different load points. This calculation is a rough estimation, but it is good enough to show the existing chiller's operating costs and performance. The actual IPLV (kW/ton) in table 2 is 1.046, which is higher than the ASHRAE minimum efficiency requirement value at 0.634. As a result, we can count on reducing kW/ton to minimize the existing operating costs.

NEWLY IMPLEMENTED CONTROL STRATEGIES

The original design sequences operated on local control. If the lead centrifugal chiller system was equal to the full capacity of that chiller, the lag system would be energized. After the minimum on time has expired, the lag chiller would be de-energized when the load is less than 40% of the capacity of the lead chiller. The chillers were then updated to DDC remote control.

Chilled water temperature set points were based on local programs. The set point settings were not based on actual building cooling load and the chiller plant's optimization. Presently, chilled water temperature is reset with optimal supervisory override using the cooling plant optimization package (CPOP) software (Braun, 1990; Cascia, 2000; Chen, 2003; ASHRAE 2003).

PROPOSED NEW CHILLER

Chillers are most efficient when running above 40% of their maximum loads; for a 120-ton chiller that load is 48 tons and for the 280-ton chiller it is 112 tons. Table 3 shows the tonnage output for a 280-ton chiller and a 120-ton chiller as a percentage of their peak loads. For the chiller load profile given in Figure 5, the 120-ton chiller will spend more time in its most efficient range than the current chillers. Below 15% of maximum load, chillers begin to experience problems. The smaller chiller is able to go down to 18 tons and remain above 15% while the larger chillers reach 15% at 42 tons.

Table 3: Percentage of Peak Load And Minimum Cooling load

PLV %	15%	30%	40%	80%	90%	100%
280-ton	42	84	112	224	252	280
120-ton	18	36	48	96	108	120

A replacement for chiller #3 needs to have a capacity of approximately 50% of the 280-ton chillers so that it will be able to handle the building load the majority of the time. The new chiller must also be more efficient at the loadings seen most often. Initial equipment cost is another factor to be considered. A 120-ton chiller will meet requirements for replacing chiller #3. Using a 120-ton chiller would cause a substantial reduction of electrical consumption for loads below 120 tons.

A new chiller will be able to run as low as 18 tons (15% of maximum) without any damage and there will rarely be a need for the chiller to run below 18 tons. Therefore, replacing chiller #3 with a 120-ton chiller will also reduce the amount of maintenance required due to running at low loads.

Figures 10, 11 and 12 compare the demand and cost/KWh for the 280-ton chiller with the estimated demand and cost/KWh for the 120-ton chiller. The comparison is based on times during one-year trended data when the building load was less than 120 ton. A new chiller model (demand versus capacity) was developed to predict the demand for a 120 ton chiller during the period of August 2002 to August 2003. By utilizing the 120-ton chiller during these times, an estimated annual savings of $11,000 could be achieved. A new chilled water pump would need to be installed to replace the existing chilled water pump for chiller #3 because the existing pump is too small (GPM: 64; Head: 40 ft; HP: 1½). The cost of the new chiller and new pump, including installation is estimated to be $60,000. If the 120-ton chiller were to be utilized, the payback time would be approximately 5.5 years, therefore, it is recommended that a 120-Ton chiller replace the existing 30-Ton chiller #3.

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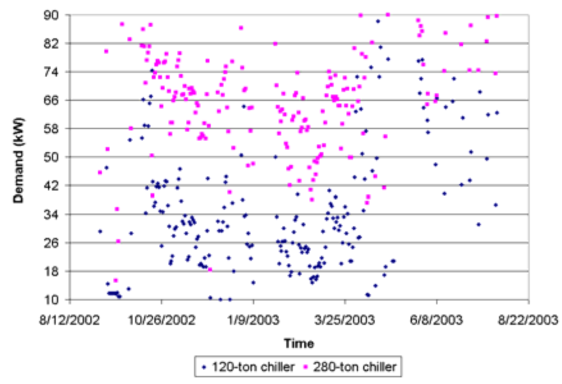

Figure 10: Demand Comparison of Existing 280-ton Chiller to Proposed 120-ton Chiller (<120 ton)

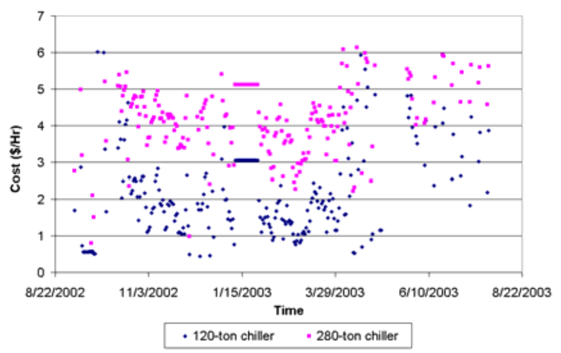

Figure 11: Cost Comparison of Existing 280-ton Chiller to Proposed 120-ton Chiller (<120 ton)

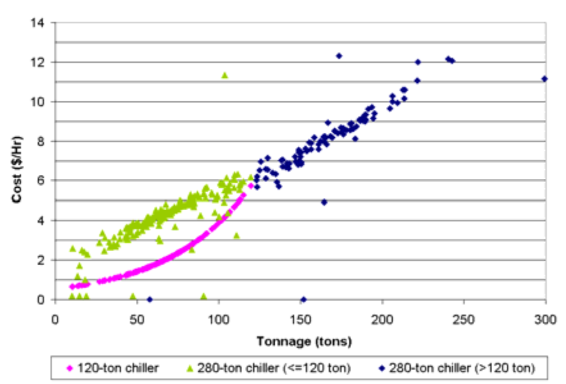

Figure 12: Cost Comparison of Existing 280-ton Chiller to Proposed 120-ton Chiller

Because of the unreliability and incapability of the 30-ton chiller to meet a majority of off-peak cooling loads, it is recommended that a more functional chiller replace the 30-ton chiller. The proposed chiller is a 120-Ton water cooled screw compressor chiller. The chiller's demand under design condition (122.5 ton) is 87 kW and its refrigerant is HFC 134a.

CONCLUSION

Trend data from the building shows that from August 2002 to August 2003, the chiller tonnage needed was below 120 tons for 64% of the operating hours for chiller #1 and 71% of the time for chiller #2. Using a 120-ton chiller instead of a 280-ton chiller during these times would have saved $11,000 per year. Additionally, there will also be a reduction in the damage caused by running the 280-ton chillers at very low loads.

The cost of retrofitting the chilled water system with a new 120-ton chiller is estimated to be $60,000. If the 120-ton chiller were to be used when the load is 120 tons or below, the estimated payback time would be 5.5 years. It is recommended that a 120-ton chiller replace the existing 30-ton chiller #3.

REFERENCES

ASHRAE, 2003 --- HVAC Applications, Chapter 41 "Supervisory Control Strategies and Optimization". Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

Braun, J. E. and G.T. Diderrich. 1990. Near optimal control of cooling towers for chilled water systems. *ASHRAE Transactions, 96(2): 806 -13*

Cascia, Mark A. 2000. "Implementation of a Near-Optimal Global Set Point Control Method in a DDC Controller", ASHRAE Transactions, Vol. 101, Part 1, pp. 249 - 263.

Chen, Hui, Homer L. Bruner, Jr., Deng Song, 2003, "Achieving Better Building Performance and Savings Using Optimal Control Strategies," *International Conference For Enhanced Building Operations*, Berkeley, California, October 13-15, 2003.

Claridge, D.E., Culp, C.H., Deng, S., Turner, W.D., Haberl, J.S., and Liu, M., 2000a. "Continuous Commissioning on a University Campus," *Proc. of 8th National Conference on Building Commissioning*, Kansas City, MO, May 3-5, pp. 12.1-12.9.

Claridge, D.E., Culp, C.H., Deng, S., Turner, W.D., Haberl, J.S., and Liu, M., 2000b. "Campus-Wide

Proceedings of the Fifth International Conference for Enhanced Building Operations, Pittsburgh, Pennsylvania, October 11-13, 2005

Continuous Commissioning[SM] of University Buildings," *Proc. of ACEEE 2000 Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA, Aug. 20-25, pp. 3.101-3.112.

Deng, S., Liu, M. and Turner, D., 1998. "Reducing Pump Power Consumption by 40% (1000 kW) through Improved Pump Management in a central Plant", *33rd Intersociety Engineering Conference on Energy Conversion*, Colorado Springs, CO, August 2-6, 1998.

Turner, W.D., Claridge, D.E., Deng, S., Cho, S., Liu, M., Hagge, T., Darnell, C., Jr., and Bruner, H., Jr., 2001. "Persistence of Savings Obtained from Continuous Commissioning[SM]," *Proc. of 9th National Conference on Building Commissioning*, Cherry Hill, NJ, May 9-11, 2001, pp. 20-1.1 - 20-1.13.