Use of EMCS Recorded Data to Identify Potential Savings Due to Improved HVAC Operations & Maintenance(O&M)

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ABSTRACT

In most chiller and boiler central plants, the energy management and control systems (EMCS) monitor and record key operation parameters and energy production continuously. A method was developed to identify potential O&M savings by using the EMCS recorded data. This method was applied to a central plant which supplied heating and cooling to a University Campus with a total building floor area of 3.5 million square feet. It was found that the potential savings from improved O&M were $2,651,000/yr which included $1,934,000/yr from improved AHU operation on the campus, $673,000/yr from improved chiller operation, and $44,000/yr from improved boiler operation.

The improved AHU operations were fully or partially implemented in a number of buildings. The measured O&M savings ($610,000/yr or 22.5%) were consistent with predicted savings in five buildings where the LoanSTAR program measured both pre-O&M and post O&M energy consumption on a hourly basis. The savings from implemented chiller and boiler O&M improvements need to be evaluated using the EMCS data.

INTRODUCTION

Energy retrofit projects are often identified through pre-screening visits and energy audits performed by consulting engineers. Audits often cost from $0.05/ft^2$ to $0.12/ft^2$ [Nutter et al., 1990]. This requires spending a large sum of money, say $175,000 to $420,000 for a facility of 3.5 million ft^2. Facility operators often have difficulty obtaining funds before knowing how much energy cost can be reduced and how much additional investment will be. Consequently, energy audits are often performed on only selected buildings in a large facility. Whole campus energy projects are typically performed in multiple phases which are largely independent. These, in turn, create the following problems: (1) retrofitted systems are often retrofitted again a short time later; (2) newly installed retrofit systems are removed or disabled; and (3) retrofit systems create operating problems in other systems.

The quality of information used is also very important for audits. Unfortunately, it is very expensive to collect actual system performance information since field tests have to be performed by auditors. Due to budget and time limits, the potential retrofit and O&M savings are often evaluated using design information which is no longer valid.

In most chiller and boiler central plants, energy management and control systems (EMCS) record key operating parameters and energy production continuously with a certain time interval, say every 2-minutes or every hour. These recorded data represent the system performance. A method has been developed to identify potential O&M savings by using the EMCS recorded data combined with field data collection. This method was applied to a central plant which supplied heating and cooling to a University Campus with a total floor area of 3,500,000 ft^2.

This paper presents the methodology, results from application to the case study campus, and measured results from partial O&M implementation.

METHOD

Heating and cooling energy systems consist of plants, distribution networks, and AHUs. The method has been developed for plants (chillers and boilers) and AHUs. It needs to be extended to distribution networks.

Method for AHUs

The basic approach is first to calibrate AHUs models using measured data. Then, these models are used to optimize operating schedules and to estimate the energy consumption under the optimized schedules. The potential energy savings are taken as the difference between the measured consumption and the model simulated consumption under the optimized operating schedules. The basic procedures are listed below:

Step 1: Prepare daily measured heating, cooling energy consumption data from the plant.

Step 2: Generate bin weather data (dry bulb and dew point temperature) for the same period of time as the available energy consumption data.

Step 3: Collect the following information for each building: (1) Conditioned floor area; (2) HVAC type; (3) Total air flow rate; (4) Outside air intake fraction; (5) Deck control schedules; (6) HVAC operating schedule; (7) Internal gain level; (8) Building envelope heat transfer coefficient; and (9) Interior zone fraction.

Step 4: Simulate building heating and cooling energy consumption using an appropriate model [Liu 1995, Liu and Claridge 1995] with the bin weather data for each building.

Step 5: Calculate the campus consumption as the sum of consumption of all buildings.

Step 6: Compare the simulated and the measured consumption. If the simulated consumption does not agree with the measured heating and cooling energy consumption within 10%, fine tuning is suggested. If the simulated consumption agrees with the measured value within 10%, the models are considered calibrated. If the model predicted consumption values are higher than the measured value, the conditioned floor area and/or the air flow rate are probably higher than the actual values. If the model predicted values are lower than the measured values, the difference may be taken as potential maintenance savings provided that the difference is due to one or more of the following reasons: (1) the actual cold deck temperatures are lower than the model assumed; (2) the hot deck temperatures are higher than the model assumed; and/or (3) the actual air flow rates are higher than the model assumed or design values.

Step 7: Develop optimized operating schedules or energy conservation retrofit measures (ECRM).

Step 8: Simulate building heating and cooling energy consumption with different ECRMs implements and/or improved O&M measures. The potential savings are determined as the difference between the base model prediction and the model prediction incorporating the ECRMs and improved O&M measures.

Method for Chillers

The basic approach is to identify the correlation between kW/ton with the key influencing parameters, such as chilled water temperature and condenser water temperature using measured data first. Then, these correlations are used to predict the "potential" electricity consumption under the optimized chilled water reset schedules. The basic procedures are listed below:

Step 1: Prepare the daily or hourly data for the following parameters: compressor electricity consumption; whole plant electricity consumption; chilled water production; chilled water supply temperature; chilled water return temperature; condenser water supply temperature; and condenser return temperature.

Step 2: Determine the kW/ton as the ratio of the compressor electricity consumption to the chilled water production. The whole plant electricity consumption may replace the compressor electricity consumption provided that the compressor electricity consumption is over 80% of the plant electricity consumption.

Step 3: Identify the correlation of kW/ton with chilled water supply and return temperature using measured data.

Step 4: Identify the correlation of kW/ton with condenser water temperature using measured data.

Step 5: Identify the correlation of kW/ton with load ratio.

Step 6: Develop improved chilled water and condenser water reset schedules.

Step 7: Determine the kW/ton under the improved schedule using the identified system characteristics.

Step 8: Determine the potential savings as the difference between the measured consumption and the simulated consumption under the improved operation schedules.

Method for Boilers

The boiler efficiency depends on air/fuel ratio, load ratio, stack flue gas temperature and other parameters. The basic procedures are listed below:

Step 1: Prepare the daily or hourly data for the following parameters: gas consumption; hot water or steam production; steam or hot water pressure and temperature

Step 1: Determine the boiler efficiency based on the steam or hot water production and the gas consumption:

$$\eta = 0.971\frac{E_{steam}}{MCF_{gas}}$$

where η is the boiler efficiency, E_{steam} is the steam production (MMBtu/hr), and MCF_{gas} is the gas consumption (MCF/hr). Note that the impact of makeup water on the boiler efficiency is neglected and the gas was assumed to have a heat content of 1030 Btu/CF_{gas}.

Step 2: Plot boiler efficiency against with load ratio and/or date to identify factors which impact the efficiency.
Step 3: Identify the improved operating schedules and set points.
Step 4: Determine the boiler efficiency under the improved schedules and set points.
Step 5: Determine the potential savings.

APPLICATION

A case study was performed in a central plant which supplied chilled water and steam to a university campus. The plant had seven chillers with a total capacity of 19,400 tons, and two boilers.

The campus had 49 buildings with a total conditioned floor area of 3,500,000 ft^2 which included medical research buildings, hospital buildings, teaching buildings, administration buildings and a library. The constant volume systems were used in 48 buildings, which had a total floor area of 3,300,000 ft^2. VAV systems were used in one of the medical research buildings, which was built in 1993.

The primary objective of the case study was to identify potential savings due to improved plant and HVAC operations. The plant and HVAC operating schedules were first obtained from the control system and/or identified from the measured data. Then, the system characteristics were identified using the measured energy consumption and operation parameter data. Finally, the potential energy savings were determined as the difference between the measured energy consumption and the predicted energy consumption under the improved operation schedules. This preliminary study investigated the potential savings from: (1) Improving the outside air reset schedules; (2) Improving the boiler efficiency; and (3) Improving chiller operations.

Results for AHUs

From April 1, 1993 to March 30, 1994, the central plant supplied 906,560 MMBtu ($6,418,000) chilled water and 301,270 MMBtu ($1,530,000) hot water and steam to the campus. The annual thermal indices were 0.3385 MMBtu/ ft^2 yr, or $2.32/$ft^2$ yr for the campus.

Table 1. Summary of Building and AHU Parameters Used in the Model Simulations

Bldg	AC area sq ft	System type & numbers	Total CFM	O.A. frac.	Temperatures (measured & set points)							
					Pre-heat		Pre-cool		Hot		Cold	
					mea.	sp.	mea.	sp.	mea.	sp.	mea.	sp.
1	191,476	dcvp-5,scv-1	222,360	0.29	73.5	45	61.7	57	89.9	#3	53.9	55
2	312,392	dcv-1,scvp-4,scv-17	380,780	0.39	78.3/67,79.5*	45	57	57	89.2	#4	61.4	55
3	163,337	dcvp-7,scvp-6,scv-2	158,958	0.45	63.6	52	57.4	58	81.5	#3	55.4~	55
4	90,310	dcvp-2,scv-2	134,400	0.13			66.5	60	84.5	#3	66/55.6	55
5	206,560	dcvp-3,scv-5,fcu-13	161,440	0.26	72.6	53	68.4	58	86	#5	57.8~	55
6	215,855	fcu-20	17,400	0.00								55
7	98,219	scvp*-3,scvp-5,scv-1	132,490	0.22			63.6	60			67.3/55	55
8	214,116	dcvp-4,scv-2	210,770	0.15	45	45	66	56	92	#7	54.5~	55
9	148,880	dcvp-4,scv-3	197,373	0.17			67	60	88.7	#8	63.2/55	55
10	280,614	scvp-10	60,900	1.00	67.1	52		60			55.7	55

Note: 1. Control schedule for Thd:
No.#1: if Ta>85 then Thd=75 else Thd=min{90,90-0.38(Ta-45)}
No.#2: if Ta>95 then Thd=80 else Thd=min{100,80+0.33(95-Ta)}
No.#3: if Ta>95 then Thd=75 else Thd=min{95,75+0.33(95-Ta)}
No.#4: if Ta>94 then Thd=95 else Thd=min{102,95+0.16(94-Ta)}
No.#5: if Ta>90 then Thd=80 else Thd=min{93,80+0.25(90-Ta)}
No.#6: if Ta>80 then Thd=80 else Thd=min{100,80+0.5(80-Ta)}
No.#7: if Ta>80 then Thd=80 else Thd=min{95,80+0.375(80-Ta)}
No.#8: if Ta>80 then Thd=87 else Thd=min{102,87+0.375(80-Ta)}
No.#9: if Ta>80 then Thd=85 else Thd=min{100,85+0.375(80-Ta)}
2. "^ " site visit measured value
3. "~" Average temperature from part data measured
4. "*" Tph for mixed or return air of scv system.
5. "T/T" Tmax/Tmin.
6. scvp*: single duct constant valume with by-pass
7. scv: single duct constant valume
8. dcvp: dual duct constant volume with out side air pre-treatment unit
9. dcv: dual duct constant volume

The building and system characteristic parameters were collected building-by-building. Table 1 lists typical results for 10 buildings. The building floor areas, the AHU information, such as types, schematic diagrams, outside air intakes and total flow rates, were collected from design drawings, air balance reports, and site measurements. The EMCS system controlled the cold deck temperature at 55°F or less and reset the hot deck temperature from 80°F to 100°F according to the outside air temperature. We also measured the cold and hot deck temperatures for a number of AHUs to compare the setpoints with the actual temperature.

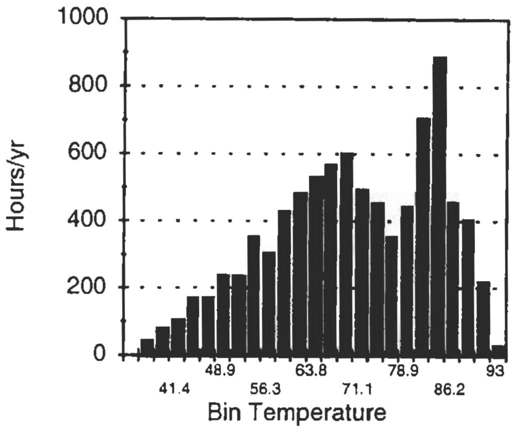

Figure 1: Bin Temperature Data Generated Using the National Weather Service Measured Hourly Temperature from April 1, 1993 to March 30, 1994

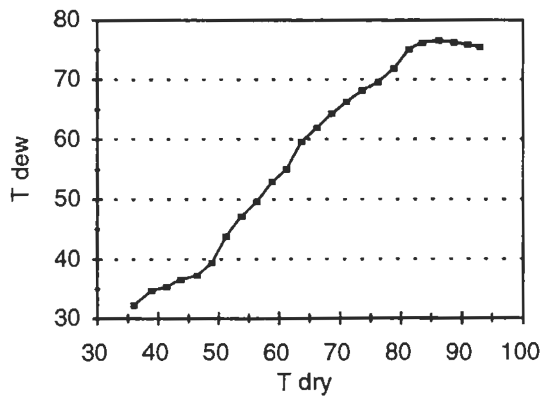

Figure 2: Mean Coincident Dew Point Temperature Versus the Dry Bulb Temperature

The bin weather data was developed using the National Weather Service dry bulb and dew point temperatures from April 1, 1993 to March 30, 1994 at the city where the University was located. Figure 1 presents the number of hours the drybulb temperature was within each bin. Figure 2 presents the mean coincident dew point temperature versus the dry bulb temperature.

The heating and cooling energy consumption was simulated by using two zone models for each building and the bin weather data. The simulated campus energy consumption was determined as the sum of consumption of all buildings. Figure 3 compares the central plant measured and the simulated daily average hourly heating and cooling energy consumption. The simulated heating and cooling energy consumption were smaller than the measured consumption when the ambient temperature was lower than 55°F, because the EMCS could not maintain the setpoints under such conditions.

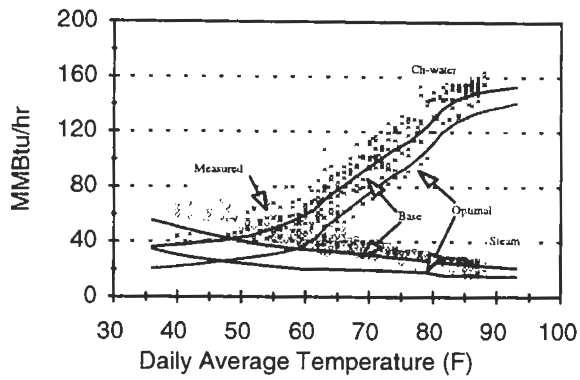

Figure 3: Heating and Cooling Energy Consumption for Measured, Simulated (Base), and Predicted Under Improved Reset Schedules as Function of the Ambient Temperature

Table 3 compares the measured and simulated total heating and cooling energy consumption from April 1, 1993 to March 30, 1994. The simulated cooling energy consumption was 54,500 MMBtu or 6% smaller than the measured consumption. The simulated heating energy consumption was 32,670 MMBtu or 11% smaller than the measured consumption. Since the requested set points were often not maintained due to a number of mechanical problems, such as unbalanced water loops and control valve problems, which were observed during site visits, this difference, which corresponds to $523,000/yr, was considered as the potential maintenance savings which can be achieved by correcting the problem noted.

The improved hot and cold deck operating schedules were developed based on our experience at similar buildings [Liu et al., 1993]. These improved operating schedules are summarized in Table 2. The optimized schedules reset the cold air temperature from 55°F to 60°F according to the outside air temperature, and are higher than the "existing" set points of 52°F or 55°F. The optimized schedules reset the hot air temperature from 75°F to 85°F according to the outside air temperature, and are lower than the "existing" reset ranges of 80°F to 110°F.

Note that, although these operating schedules were used to determine the potential O&M savings for the entire campus, they could not be regarded as the optimized operating schedules for specific buildings. Truly optimized operating schedules would have to be developed for each building by a detailed engineering analysis.

Table 2: Summary of the Improved Hot and Cold Deck Operating Schedules

System	Deck	Schedule
Dual Duct	Cold	Min(60, 60-0.125(T_a-60))
	Hot	If T_a>80°F then off If T_a<80°F then Min(85, 85-0.25(T_a-60)
Pretreat	Preheat	If T_a<40°F then 40°F If T_a>40°F then off
	Precool	If T_a<60°F then off If T_a>60°F then Min(57, 57-0.125(T_a-60))
Single Duct	Cold	Min(61, 61-0.09(T_a-58))

Table 3: Summary of Thermal Energy Consumption at 49 University Buildings from April 1, 1993 to March 30, 1994

	Consumption MBtu/yr		Potential Savings		
	Ch-water	Steam	Ch-water MMBtu/yr	Steam MMBtu/yr	Total $/yr
Measured Consumption	906,500	301,300			
Improved maintenance	851,700	268,600	54,500	32,700	$523,000
Improved operation	717,900	169,000	135,700	99,600	$1,411,000
Total					$1,934,000

Note: Chilled water price is $7.08/MMBtu, steam price is $4.524/MMBtu

The optimized heating and cooling energy consumption was determined by introducing the optimized reset schedules into the building models. The potential savings were considered as the difference between the model predicted consumption under the "existing" operating schedules and the predicted consumption under the "optimized" operating schedules (See Table 2). The simulation results showed that improved operation could reduce chilled water and steam consumption by 135,700 MMBtu/yr and 99,600 MMBtu/yr, respectively. The potential cost savings were $1,411,000/yr. The combined potential savings from improved operating and maintenance were $1,934,000/yr, or 25% of the current annual cost of $7,781,000.

Results for Boilers

The central plant had two boilers which supplied steam to the campus buildings. These two boilers were each operated during alternate months. The total steam production was 301,300 MMBtu with a total gas consumption of 437,600 MMCF from April 1, 1993 to March 30, 1994. The average annual boiler efficiency was about 0.67.

The daily average boiler efficiency was also calculated using daily average gas consumption and steam production data. Figure 4 presents the daily average boiler efficiency and steam pressure in time series. The boiler efficiency varied from 0.55 to 0.75 and the steam pressure varied from 125 psi to 145 psi. When the steam pressure was approximately 125 psi, the boiler had an efficiency near 0.72. When the steam pressure was near 145 psi, the boiler efficiency dropped to a range of 0.60-0.66.

It appears that the boiler efficiency depends on the steam pressure. To confirm this, Figure 5 presents the steam production and steam pressure as time series. During March 1994, the steam production was similar during November 1993. However, the boiler efficiency was much lower.

Based on these observations, it appears that the boilers would have an average annual efficiency near 0.72 which was the measured average efficiency in January 1994, if operated at 125 psi. The gas consumption, assuming 125 psi operating, was then calculated as:

$$MCF_{gas} = 0.971 \frac{E_{steam}}{0.72}$$

Table 4 presents the steam production, gas consumption and boiler efficiencies. If the boiler efficiency was increased to 0.72 by setting steam pressure to 125 psi, the gas consumption would have dropped to 405,500 MCF/yr. Consequently, the annual potential gas savings were 32,100 MCF/yr, or 7% of the current annual consumption. The cost savings would be $82,000/yr with a gas price of $2.57/MCF,

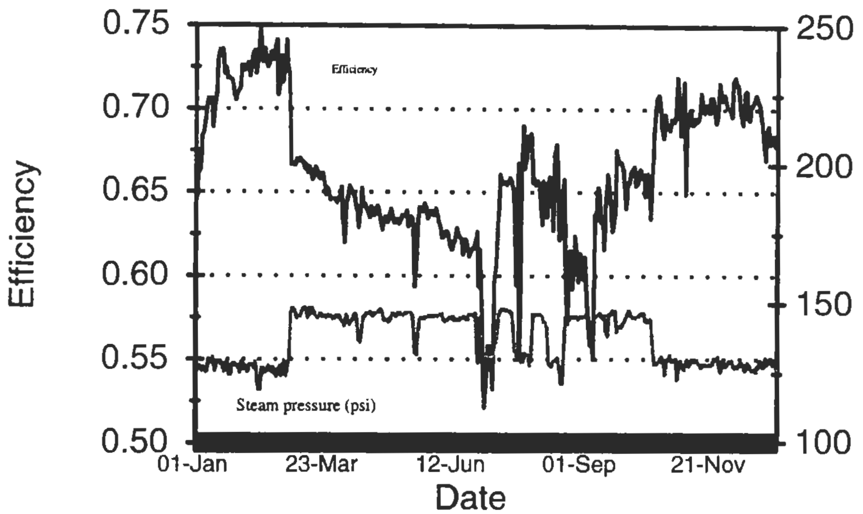

Figure 4: Measured Boiler Efficiency and Supply Steam Pressures

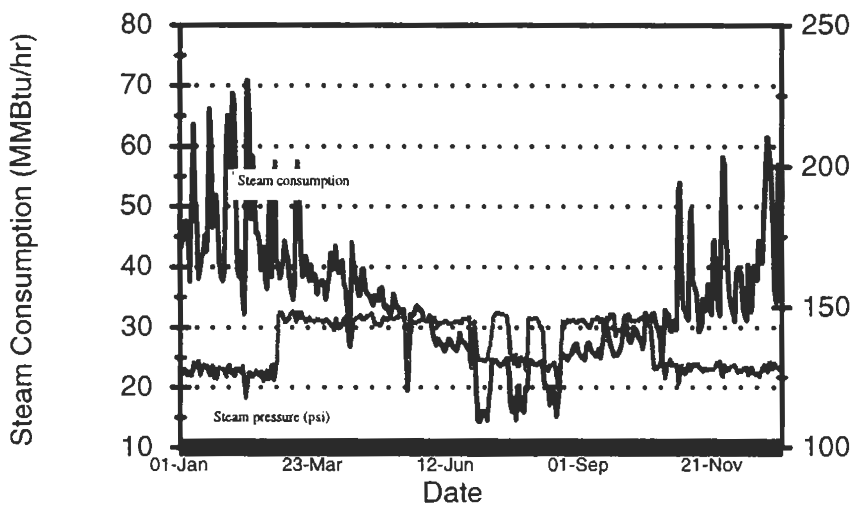

Figure 5: Measured Steam Consumption and Supply Steam Pressure

Table 4: Summary of Boiler Efficiency Analysis

	Steam	Gas	Efficiency	Savings %
	MMBtu/yr	MCF/yr		
Current	301,300	437,600	0.67	
Improved	301,300	405,500	0.72	7

Results for Chillers

The central plant had 7 chillers with a total capacity of 19,400 Tons. The chilled water production was 906,540 MMBtu or 75,545,000 Ton-hr from April 1, 1993 to March 30, 1994. The central plant consumed 69,700 Million kWh during the same period. Since the majority of the electricity was used to drive chiller operation, the plant electricity consumption data were used to investigate the chillers' efficiency.

The Energy Management and Operations Department at the university supplied the following hourly data: central plant electricity consumption, chilled water production, chilled water flow, chilled water supply and return temperatures, cooling tower water flow, and cooling tower supply and return temperatures. The daily average data were produced using these hourly data.

The electricity consumption per ton-hr was calculated as the ratio of the central plant electricity consumption to the chilled water production. The kW/ton was, then, correlated with the average water temperatures at the condenser and evaporator by a linear regression. The average water temperature at the evaporator was taken as the average value of chilled water supply and return temperatures. The average water temperature at the condenser was taken as the average value of cooling tower supply and return temperatures.

Figure 6 shows the measured kW/ton and average condenser water temperature as functions of the evaporator water temperature. It shows that the kW/ton tended to decrease linearly (from 1.1 to 0.92) with an increase of the average evaporator water temperature (from 42°F to 44.8°F) when the condenser water temperature was constant. When the condenser water temperature increased, the kW/ton increased. Both characteristics are consistent with normal chiller performance. Hence, the kW/ton was linearly regressed against the average evaporator water and condenser water temperatures. The regression formula determined is:

$$kW / ton = 1.27665 - 0.02356 T_{evap} + 0.008481 T_{cond}$$

Based our engineering experience [Liu et al., 1994], we suggested that the chilled water supply temperature be reset linearly from 45°F to 41°F when the ambient temperature changes from 40°F to 90°F. Figure 7 compares the current chilled water supply temperature with the suggested reset schedule.

Figure 8 compares the measured condenser water supply temperature and the suggested supply water temperature plotted against the wet bulb temperature. The results show that the condenser water supply temperature was about 72°F when the ambient wet bulb temperature was lower than 60°F. The condenser temperature was about 7°F higher than the wet bulb temperature when the ambient wet bulb temperature was higher than 60°F. We suggested that the condenser temperature be controlled at 65°F when the ambient dew point was lower than 60°F, and the condenser temperature be 5°F higher than the wet bulb temperature when the ambient wet bulb was higher than 60°F. This reset schedule had a lift at least 30°F for chillers.

After an improved cooling tower supply temperature schedule and an improved chilled water supply temperature schedule were developed, the average water temperatures at the condenser and evaporator were again determined. These temperature values were introduced into the regression formula obtained above to calculate the kW/ton under these improved schedules. The difference between the electricity consumption at this kW/ton and measured kW/ton represents the potential savings from improved operation schedules. Figure 9 presents the measured and predicted kW/ton using the improved operating schedule. The suggested reset schedules would decrease the kW/ton to a range of 0.6 kW/ton to 0.8 kW/ton.

Table 5 summarizes the potential savings due to the improved chilled water supply and cooling tower return water temperatures. The improved cooling tower and chilled water temperatures could reduce compressor electricity consumption by 15,221,000 kWh, or 22% of the current central plant electricity consumption. The annual potential electricity savings were $852,000/yr with a electricity price of $0.056/kWh (ratio of bill cost to the electricity consumption kWh from April 1993 to March 1994).

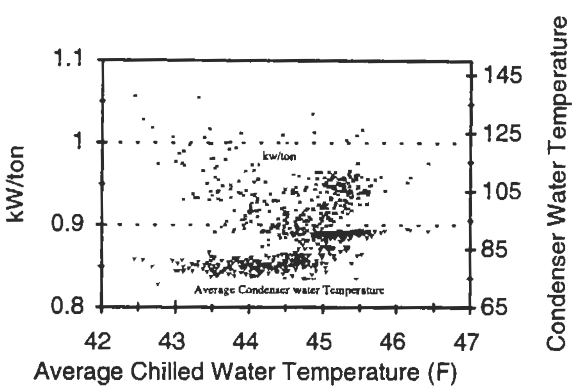

Figure 6: Measured kW/ton and the Average Condenser Water Temperature Against the Average Chilled Water Temperature

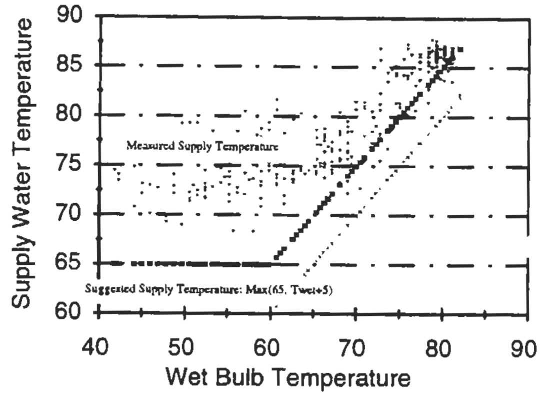

Figure 8: Measured and Suggested Condenser Water Temperature

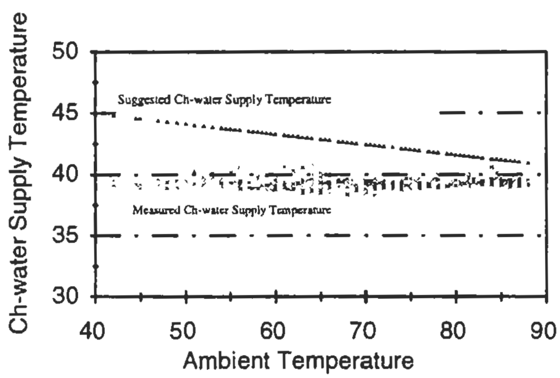

Figure 7: Measured and Suggested Chilled Water Supply Temperatures

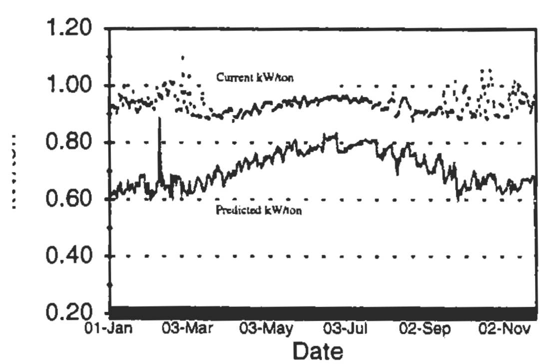

Figure 9: Measured and Would Be kW/ton under the Suggested Chilled Water Supply and Condenser Water Supply Reset Schedules

Table 5: Summary of Chiller Efficiency Analysis

	Electricity (MkWh)	kW/ton	Savings	
Current	69,711	0.92	Electricity	%
Improved	54,489	0.72	15,222	22

Table 6: Summary of Potential Savings for each O&M Measure

Item		Consumption	Savings	Percent Savings	$ Savings (Independent)	$ Savings (Corrected)	Notes
Buildings	Steam (MMBtu)	301,300	132,300	44%	$598,000	$598,000	Improved operation Optimized schedule
	Ch-water (MMBtu)	906,500	188,700	21%	$1,336,000	$1,336,000	Improved operation Optimized schedule
Central Plant	Electricity (MkWh)	69,700	15,200	22%	$852,000	$673,000	Increase chilled water temperature
	Gas (MCF)	437,600	32,000	7%	$82,000	$44,000	Increase boiler efficiency
Total					$2,868,000	$2,651,000	

Note: Gas price $2.57/MCF; Ch-water price $7.08/MMBtu ($0.085/ton-hr); Steam price $4.524/MMBtu; and Electricity price $0.054/kWh.

SUMMARY

In the study case, three major improved O&M measures were identified:

- Improving the outside air reset schedules of AHUs;
- Controlling the steam pressure at 125 psi; and
- Improving the chilled water and cooling tower water temperature set points.

The potential O&M savings were estimated independently. However, when the heating and cooling consumption was reduced, the potential savings due to improved plant operation would be smaller than estimated based on the current production. Therefore, the plant potential savings were corrected according to the potential energy reduction in the buildings. The results are summarized in Table 6.

The potential heating savings were estimated as $598,000/yr or 44% of the steam consumption. The potential cooling savings were estimated as $1,336,000/yr or 21% of the cooling energy consumption. The total potential thermal energy savings were 27% of "existing" heating and cooling energy consumption.

The improved O&M measures were fully or partially implemented by facility staff after this study. Both heating and cooling energy consumption were measured on a hourly basis in five buildings (779,000 ft^2) by the LoanSTAR program. The measured O&M energy savings ($610,000/yr) varied from 14% to 33% with an average of 22.5% in these five buildings [Claridge et. al. 1996]. It appears that the actual measured savings were consistent with the predicted savings.

The potential gas savings were estimated as 32,000 MCF/yr or $44,000/yr. This measure was implemented in 1994. The measured savings will be evaluated at a future date using the EMCS data.

The potential chiller electricity savings were estimated as 15,200 MkWh/yr or 22% of the "existing" electricity consumption in the plant. The savings were due to increased chilled water supply and decreased condenser water temperature. The chilled water supply temperature has been increased to a range of 44°F to 45°F. The realized savings will be evaluated using the EMCS measured data at a future date.

CONCLUSIONS

A method was developed to identify the potential reductions in central plant and campus wide energy use by utilizing EMCS measured data combined with the data collected from field tests and design documents. This method provided reliable savings estimates since it used the real energy performance data. This method also reduced the audit cost due to reduced labor for the data collection effort.

The O&M measures were fully and partially implemented in the plant and the buildings respectively. The measured savings due to improved HVAC operations in five buildings were consistent with predicted savings. The boiler steam pressure was decreased to 125 psi in 1994. The chilled water supply temperature was increased to a range of 44°F to 45°F in 1995. The realized savings will be evaluated using the EMCS data.

It is important to emphasize the preliminary nature of this study. Although boiler efficiency can be improved by simple set-back the steam pressure to 125 psi, other potential savings can be achieved through additional investigation and necessary engineering work.

It should also be noted that the building simulation program, used for this project, played an important role in keeping the project cost down since it provided a tool to simulate and optimize the building HVAC systems with minimum time investiment.

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