Impact Evaluation of 2006 Custom Process Installations - Part II

(Design 2000*plus* Application #511457 & Energy Initiative Application #511459)

EXECUTIVE SUMMARY

Submitted to

National Grid
55 Bearfoot Road
Northborough, MA 01532-1555

Submitted by

SBW Consulting, Inc.
2820 Northup Way, Suite 230
Bellevue, WA 98004

June 20, 2008

1. SUMMARY OF RESULTS

This report covers a Design 2000plus (D2000) Custom process project and an Energy Initiative (EI) custom process project that both affected two production lines at the same site. The D2000 project (Application 511457) resulted in the installation of two VSD-controlled chillers for each line and three cooling tower cells (one for one line and two for the other) with VSD-controlled fans. The EI project (Application 511459) involved the replacement of the primary-only chilled water system on each line with new primary chilled water pumps; the addition of six VSD-controlled secondary CHW pumps (two pumps for process loads on each system plus two pumps on one system to cover HVAC loads); the addition of booster pumps to one system to provide cooling to specific loads with condenser water; and replacement of five condenser water pumps with three smaller pumps on the system receiving the tower water booster pumps. Because these projects are very closely related, the Evaluation analyzed both of them together. Energy savings, however, have been calculated for each project separately. Table 1 summarizes savings estimates from the original Tracking Database and our Evaluation for both projects.

Table 1: Savings Summary

Savings Quantity	Tracking Estimate	Evaluated Savings	Evaluated/ Tracking %
Design 2000*plus* Project			
Annual Energy, kWh	1,012,709	1,090,038	107.6%
Percent Energy On-peak	37%	47.4%	128%
Summer Peak Diversified kW	68.8	225.4	327.6%
Winter Peak Diversified kW	105	37	35%
Summer FCM Peak Demand kW	N.A.	147	N.A.
Winter FCM Peak Demand kW	N.A.	123	N.A.
Energy Initiative Project			
Annual Energy, kWh	1,049,037	708,763	67.6%
Percent Energy On-peak	37%	48.5%	131%
Summer Peak Diversified kW	128	124	97.1%
Winter Peak Diversified kW	116	0.5	0.4%
Summer FCM Peak Demand kW	N.A.	124	N.A.
Winter FCM Peak Demand kW	N.A.	29.4	N.A.

1.1 Annual Energy Savings

Our estimate of annual energy savings is 108% of the Tracking estimate for the D2000 project. The models used to determine savings are quite complex with many interactions among the various influences on the system, so it is very difficult to ascribe specific impacts to individual causes. Nonetheless, we did identify two primary reasons for the difference. The first is a difference between the loads imposed on the modeled systems for the TA and Evaluation analyses. The Evaluation model of the A3 chillers showed a 5.8% reduction in annual ton-hours as compared to the TA model while there was a 34% reduction for the A4 chillers. Across both systems, the Evaluation annual ton-hours was 23% less than those modeled in the TA Analysis. The TA Analysis was constrained to estimating the loads that would be imposed on the systems, whereas loads were determined for the Evaluation based on a correlation between wet bulb temperatures and chiller loads calculated from actual trended data. In addition, the TA Analysis model was based on outside air dry-bulb temperatures as opposed to the Evaluation approach of using wet-bulb temperatures as the basis of load calculations. While the source of the temperature data used in the TA Analysis is uncertain, ambient wet-bulb temperature data for the Evaluation were obtained from a combination of on-site trended data and concurrent data obtained for a nearby (Quonsett Point) weather station. The distributions of ambient temperatures for the respective models influences the annual ton-hours for the two systems.

The second major difference in the two analyses has to do with the efficiencies of the chiller systems. The TA Analysis modeled the base case chillers at overall efficiencies 0.561 and 0.556 kW/ton for systems A3 and A4, respectively. The Evaluation analysis resulted in corresponding values of 0.770 and 0.745 kW/ton. The Evaluation values include the effect of adjustment factors developed to allow comparison of trended chiller kW data for the installed chillers to base case chiller kW values based on manufacturer's performance data. The adjustment factors increased Evaluation base case kW values, and thus kW/ton values, by approximately 20% (see Section 3.2c for a description of the adjustment factor derivation).

The difference in chiller efficiency (kW/ton) between the base cases for the TA Analysis and the Evaluation values did not vary significantly from one chilled water system to the other (approximately 37% for A3 and 34% for A4). Because the Evaluation models' base case chillers were less efficient, energy consumption for these chillers was greater than for the respective TA Analysis chiller models, given the same chilled water loads. In essence, this provided greater potential for energy savings in the Evaluation model on an absolute basis.

We estimate annual savings for the EI project at 67.6% of the Tracking estimate, primarily due to differences discovered in the operation of the systems as compared to the assumptions made in the TA Analysis. Energy consumption for the various pumps is predicated on the number of pumps that operate. For the Evaluation, the number of pumps in operation was determined from trended data for each type of pump addressed in the EI portion of the project. For the TA, the number of operating pumps was determined from assumed control strategies and always assumed an integer number of pumps within any temperature bin. The Evaluation used weighted average numbers of pumps within any bin, thereby accounting for the possibility of varying pump operations within any particular bin. This approach resulted in lower base case numbers of pumps and resulting kW, overall, as compared to the TA Analysis. At the same time, installed case numbers of pumps and kW were increased. Compared to the TA Analysis, the Evaluation's reduced baseline consumption and increased installed case consumption leads to reduced savings.

Annual energy savings summaries are provided by program and by equipment type in the Appendix. Figure A-28 provides values for the A3 chilled water system, Figure A-29 provides values for the A4 system and Figure A-30 provides results for both systems combined.

1.2 Percent Energy On-Peak Savings

For the D2000 project, we estimate on-peak energy savings at 47.4%, which is 128% of the Tracking estimate. Most of the difference in the increase in peak demand is likely due to the change in definition of the on-peak period of the Evaluation (6am to 10pm) versus what was used in the Tracking estimate (8am to 9pm). In addition the use of dry bulb temperature bins in the TA Analysis and wet bulb temperature bins in the Evaluation may contribute to the difference. The distributions of these two parameters may yield different frequencies of occurrence during the on-peak periods. The magnitude of the impact of this factor cannot be determined with the available data.

We estimate on-peak energy savings for the EI project at 48.5%, which equates to 114% of the Tracking estimate. The reasons for the difference between the evaluated and the Tracking estimate are similar to the D2 application discussed above.

1.3 Summer/Winter Peak Diversified kW Reduction

The Evaluation estimate of summer and winter peak diversified kW reductions for the D2000 project are 328% and 35% of the corresponding Tracking estimates, respectively. Summer and winter peak diversified kW reductions for the EI project are estimated at 96.7% and 0.4% of their respective Tracking estimates. The primary reason for the big differences in the savings is the difference in the definitions of peak savings between the Evaluation and Tracking analysis. The Tracking analysis used a method to determine the peak demand reduction that was based on summer and winter peak monthly averages while the Evaluation method used the demand differences on the hottest and coldest days. This tended to increase the savings in the summer when the chillers are more loaded and decrease the savings in the winter when free cooling was used and the cooling tower changes increased energy usage between the base and the proposed.

The TA Analysis modeled pump savings for the EI project based on derived flow rates, assumed flow rates, assumed temperature differences across chilled water loads and affinity laws. Without recorded data to inform their analysis, this is an acceptable approach. Our Evaluation based pump kW values on measured values and regressions against independent variables such as pump speed. As a result, the Evaluation average kW for the A3 chilled water base case pumps was 27% greater than the corresponding value for the TA Analysis. At the same time, the Evaluation installed case showed an increase of 46% over the TA Analysis value, leading to a decrease in available savings for the Evaluation A3 chilled water system pumping power. Similar analyses for the A4 chilled water and condenser water systems showed decreases of 11% and 5% for the respective Evaluation base cases and respective increases of 12% and 58% for Evaluation installed cases when compared to the TA Analysis. Decreased base case power draw and increased installed case power draw both result in reduced potential energy savings.

2. PROJECT DESCRIPTION

2.1 Efficiency Improvement

The Design 2000*plus* project installed two 450-ton water-cooled chillers with variable speed drives (VSDs) on each of two chilled water systems serving production lines A3 and A4 (four chillers total). One 2-cell cooling tower rated at 4,135 tons at 95/85/78 (warm water temperature/cooled water temperature/entering air wet bulb temperature, all in degrees Fahrenheit) and 3,000 gpm was installed on System A4 and one single-cell cooling tower rated at 940 tons at 95/85/78 and 2,263 gpm was added to two existing cooling towers of the same capacity for System A3. Each of the new cooling tower cells is equipped with a VSD-controlled 30-hp fan.

The Energy Initiative portion of the project included the installation of six 20-hp constant-volume primary chilled water pumps (3 installed in parallel for each production line); two pairs of 125-hp VSD secondary chilled water pumps (one pair on each production line) serving process loads; one pair of 75-hp VSD secondary chilled water pumps to serve HVAC loads met by the A4 chillers; three 40-hp constant volume condenser water pumps for the A4 line; and two 20-hp VSD booster pumps to circulate condenser water directly to process cooling loads on the A4 line.

2.2 Baseline/Pre-retrofit Equipment and Operation

The base case systems were assumed to include four new 450-ton centrifugal chillers in the same configuration as the installed chillers, but with inlet guide vane (IGV) capacity control instead of VSD control. Three new cooling tower cells of the same capacities and in the same configuration as the installed cells would have been installed with 2-speed fans as opposed to the installed VSDs. Base condenser water supply temperature (ECWT is the entering condenser water temperature for the condenser water that is entering the chiller) was assumed maintained at a setpoint of 72°F if possible. If 72°F could not be maintained, an approach of 10°F to OAT_{wb} was assumed to be $_{achieved}$ by cycling the fans between off, half- and full-speed. New piping would have been installed to serve the relocated A-Line loads.

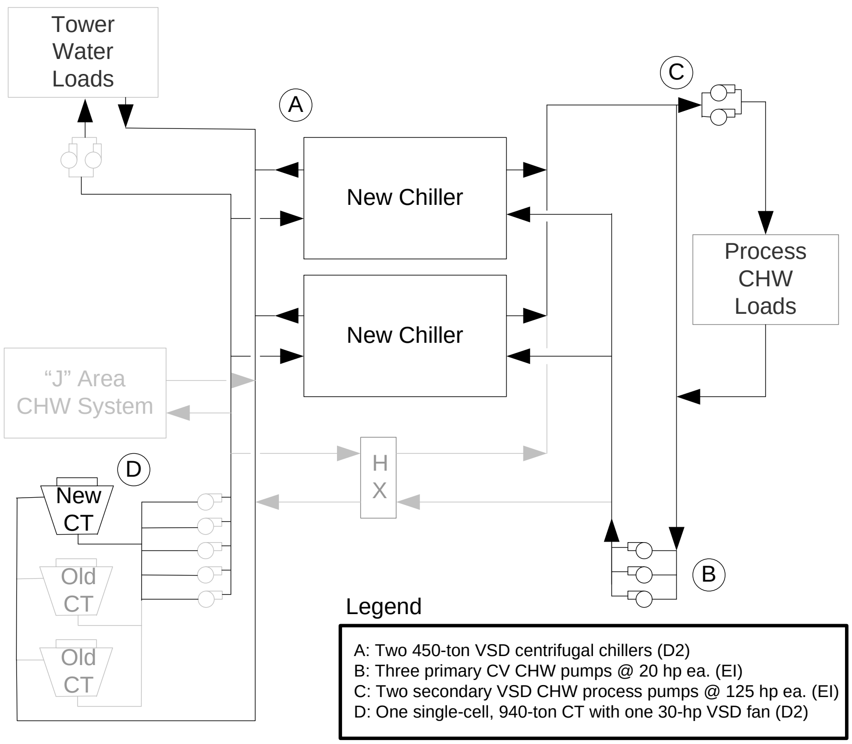
Power draw values measured by the TA analyst prior to pump replacements were assumed for each operating pre-retrofit primary chilled water pump. Similar measurements were assumed applicable to each condenser water pump on the A4 system. A set of five constant volume chilled water pumps were assumed to be available to serve chilled water loads for each of the A3 and A4 systems. Two pumps were assumed to run for each operating chiller plus one additional pump to ensure adequate chilled water flow. Condenser pumps were also assumed to stage on and off to meet loads. No changes were made affecting the condenser water pumps on the A3 system, so they are not included in the Evaluation. A pair of pumps on the A3 system circulates condenser water from the cooling towers directly to specific loads without being further cooled in the chillers. These pumps also were not affected by the project and are not included.

Heat exchangers existed in both chilled water systems allowing for “free cooling” when ambient conditions allowed. The TA Analysis assumed the chillers did not operate at wet bulb temperatures below 23.6°F.

2.3 Installed Equipment and Operation

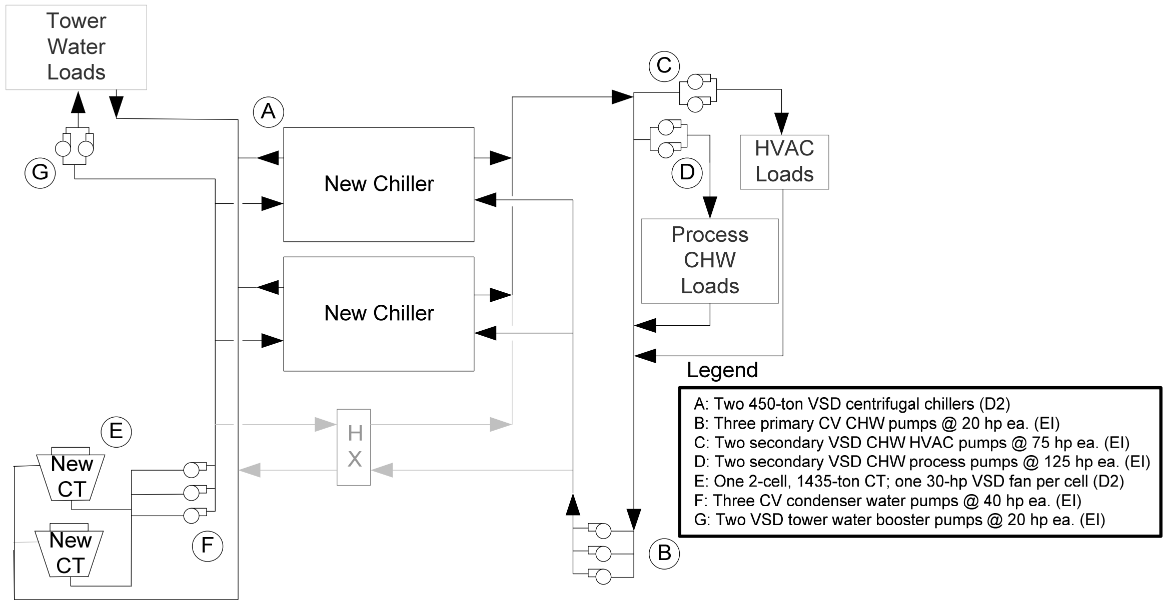
The installed case system includes two 450-ton VSD centrifugal chillers for each chilled water system. One 2-cell 1453-ton cooling tower was added to the chilled water system serving the A4 Line and a 1-cell 940-ton cooling tower was added to the system serving the A3 Line. Each of the cooling tower cells employs a single 30-hp fan that is VSD-controlled. Schematics of the A3 and A4 Line chilled water systems are provided in Figures 1 and 2, respectively,

Figure 1. Schematic of A3 Production Line Chilled Water System Following Implementation of the Design*2000* (D2) and Energy Initiative (EI) Projects.



Because primary/secondary pumping systems were installed instead of the assumed pre-retrofit primary-only chilled water pumping systems, smaller constant-volume primary chilled water pumps were installed (40' TDH/1080 gpm vs 140' TDH/1050 gpm) in each chilled water system, reducing the primary pumping energy. Both the A3- and A4-Line systems each received a pair of 125-hp VSD-controlled pumps (150' TDH/2160 gpm) to service both the process loads and some HVAC load. The A4-Line system also received a pair of 75-hp VSD-controlled secondary pumps (150' TDH/1200 gpm) to service HVAC loads that were transferred to this system to relieve another overloaded chilled water system (“J” system). A pair of VSD-controlled 20-hp booster pumps (75' TDH/650 gpm) was added to the A4-Line system to circulate condenser water directly (i.e. not mechanically chilled) to process loads for cooling purposes. The booster pumps allowed for three lower-head 40-hp constant-volume condenser water pumps (40' TDH/1500 gpm) to replace the existing higher-head condenser water pumps (139' TDH/1330 gpm). As with the base case, a heat exchanger in each chilled water system allows “free cooling” when ambient conditions are favorable.

Figure 2. Schematic of A4 Production Line Chilled Water System Following Implementation of the Design*2000* (D2) and Energy Initiative (EI) Projects.



The TA report assumed, when estimating installed case energy consumption, a constant chilled water temperature of 41°F. It also assumed that HVAC loads would be zero at outside drybulb air temperatures (OAT_{db}) of 45°F or lower, and that free cooling would be in effect whenever OAT_{wb} was below 23.6°F. Process loads were assumed constant throughout the year and HVAC loads were assumed to increase linearly with OAT_{db} greater than 45°F. Chilled water loop temperature differentials were assumed to be 9°F for determining chilled water loads based on assumed loop water flows. Cooling tower fan speeds were assumed to vary with load down to the VSD minimum 25% of capacity and to cycle on and off at lower loads.

3. EVALUATION METHODOLOGY

The Tracking analysis estimated project savings using a spreadsheet chilled water system analysis based primarily on equipment performance curves obtained from data provided by the manufacturers of the chillers and the cooling towers. One-time measurements were taken on several existing constant-speed pump motors.

The Evaluation used an analytical approach similar to the Tracking analysis, but inputs were enhanced through the use of extensive trend data captured by the equipment's control system, hourly weather data from a nearby weather station, short term monitoring carried out in parallel with trending and one-time measurements on installed equipment.

Spreadsheet models were developed for the respective components of the A3 and A4 systems in separate worksheets for the Design*2000* and Energy Initiative projects. For the former projects, summary pages for the calculation of chiller savings are provided in Figures A-1 and A-8 for systems A3 and A4, respectively. Similar summaries for the cooling tower energy savings calculations are provided in Figures A-5 and A-12, respectively. Summaries for the Energy Initiative projects can be found in Figure A-15 for the A3 chilled water pumps; in Figure A-18 for the A4 chilled water pumps; and in Figure A-23 for the A4 condenser water and tower water booster pumps.

Important steps in the Evaluation approach included:

a) A comprehensive installed case operations model, based on the model developed by the TA analyst, was created. Wet bulb temperature bins were established and the frequency of each was determined using hourly wet bulb temperatures obtained at Quonset Point, Rhode Island from March 1, 2007 to February 28, 2008. Impacts of production schedules on energy consumption are inherent in the trended data and are assumed to account for diversity in production.

b) Obtain actual performance data from the existing controls system, take one-time true-kW measurements of constant speed equipment and perform short-term metering of true RMS kW for variable speed equipment. Data were trended by the existing control system and were analyzed to determine relationships among various dependent and independent parameters, to verify various setpoints, and to determine when various modes of operation take effect. Short term metered data were correlated to concurrently trended equipment speed values to determine mathematical relationships between speed and power draw. The trended speed values, which reflect the diversity in production, were used as the basic input values for the models.

c) Develop regressions of chiller power as a function of entering condenser water temperature (ECWT) and chiller load using trended data for individual chillers. Similar regressions were developed for the base case chillers using manufacturer's part load performance data. Because these regressions were based on different types of data (projected performance data vs trended data), adjustment factors were developed to put the two sets of data on a similar basis. This was accomplished by comparing the trended chiller kW to kW values determined from a regression using manufacturer's part load performance data for the high-efficiency chillers. The resulting overall average ratio of trended data to manufacturer's data regression was then applied to each base chiller kW value that was calculated from the manufacturer based chiller kW regression. This approach allowed for the comparison of baseline and installed chiller kW values using a similar methodology.

d) Determine chilled water loads from trended chilled water supply and return temperatures and chilled water flow rates. Flow rates were obtained from pump performance curves and 1-time measurements of kW for the constant volume primary pumps. These data were analyzed to determine the average chilled water load in each of the OAT_{wb} bins.

e) Analyze trended chiller kW data to determine how many chillers were operating in each OAT_{wb} bin for the installed case. This analysis also provided the number of chillers operating in each OAT_{wb} bin for use in the base case cooling tower calculations (see *item h* below).

f) Calculate base and installed case chiller kW values from the regressions performed for the respective base and installed cases. ECWT values for the base case assumed a value of 72°F or an approach of 10°F, whichever yielded a greater value for ECWT. Installed case ECWT values were based on a correlation of trended ECWT values to OAT_{wb}. Chiller kW values were adjusted to account for the use of manufacturer's data in the base case (see *item c* above).

g) Determine power reduction and energy savings for chillers. Installed case kW values were subtracted from the respective baseline kW values for each bin and these values were summed to determine the kW reduction for the chillers. Annual energy consumption for the chillers was determined by summing the product of the calculated kW draw and the annual hours of occurrence from each bin. Energy savings was calculated for each bin by taking the difference between the baseline and installed case energy consumption and these values were summed for all bins to obtain total annual chiller savings.

h) Determine the kW draw of the baseline cooling towers. The analysis described in *item e* above was used in determining the leaving condenser water temperature in each OAT_{wb} bin. This value was then used to determine the potential and actual range of the baseline cooling tower and the ratio of these values yielded the fractional load on the cooling towers. Potential range values also took into account variations in condenser water flow rates based on the number of chillers operating. Fan load was then determined assuming the 2-speed fan would cycle as necessary to match the fractional load on the cooling tower.

i) Determine power draw for the installed cooling towers. A correlation between monitored cooling tower fan kW and trended cooling tower fan speed was established (see Figures A-6 and A-13 in the Appendix for systems A3 and A4, respectively) and the average fan speed within each OAT_{wb} bin was determined from trended data (see Figures A-7a & b and A-14 in the Appendix for systems A3 and A4, respectively). Average kW values for each bin were then determined from the average speed and the correlation that was established.

j) Calculate cooling tower savings. Cooling tower savings were calculated in the same manner as described for the chillers in *item g* above.

k) Calculate total savings for the *Design2000* projects. Chiller and cooling tower savings were summed to determine overall annual savings for the *Design2000* projects.

l) Determine baseline chilled water pump power draw. Baseline pump power draw was based on 1-time measurements taken by the TA analyst. The number of operating pumps was assumed to be 2 for each operating chiller plus one pump. The weighted average number of pumps in operation was determined based on the number of chillers operating to meet the chilled water load. Total kW for each bin was taken as the product of these two values.

m) Determine installed case chilled water pumping power draw. The weighted average number of installed primary pumps operating within each OAT_{wb} bin was determined from trended data (see Figures A-16 and A-19 for systems A3 and A4, respectively). This value was multiplied by the 1-time measurement of primary chilled water pump power draw to determine the average primary pump power draw for each bin. Monitored kW data for the process secondary pumps were compared to concurrent trended speed values with the result that kW and speed values did not correlate as the affinity laws would dictate (see Figure A-17 for the A3 process pump, Figure A-20 for the A4 process pump and Figure A-21 for the A4 HVAC pump). An average kW value was used as a constant for these pumps. The trended speed data for the secondary HVAC pump on system A4 showed essentially no variation with time, and it's value was taken as a constant, also (see Figure A-22 in the Appendix). Installed case chilled water pumping power was determined by summing the individual pump kW values for each bin, then summing those values across all bins.

n) Calculate condenser water (CW) pump savings for system A4. Baseline condenser water pump power draw was obtained as a constant from measurements taken by the TA analyst. The number of condenser water pumps operating for each OAT_{wb} bin was taken as the number of operating chillers plus 1 pump. For the installed condition, the number of operating CW pumps in each OAT_{wb} bin was taken as the weighted average number of operating pumps based on analysis of trended pump status data (see Figure A-24 in the Appendix). The power draw per pump was obtained from 1-time measurements. Tower booster pump power draw was obtained from a correlation of short-term monitored kW and concurrent trended OAT_{wb} data (see Figures 25a & b in the Appendix). Demand reductions and energy savings were calculated in a manner similar to that described for the chiller savings, comparing the baseline CW pumps to the installed CW pumps and tower water booster pumps combined.

o) Calculate total Energy Initiative kW reduction and annual kWh savings. Savings for the A3 pumping systems took into account the baseline primary chilled water pumps and the installed case took into account both primary and secondary chilled water pumps. Pumps serving the same functions for the A4 system were also accounted for in addition to the HVAC secondary pumps and tower water booster pumps, neither of which had corresponding base case pumps. Both base case and installed case CW pumps were also taken into account.

Equipment trend logs provided essentially all data required for the Evaluation. Short term (approximately four weeks) of true RMS power draw data were obtained in parallel with trended data for variable speed loads so a relationship could be established between kW and equipment rotational speed. Pump curves were also obtained for all the pumps installed as part of the EI project. In addition, plant staff was interviewed regarding operation of the systems to establish normal operating procedures.

Downloads of trended data were obtained for several multi-week periods beginning September 7, 2007 and ending March 9, 2008. Instantaneous values of parameters were recorded at 15 minute intervals.

Short-term and one-time measurements are summarized in Table 3. Architectural Energy MicroDataLoggers (MDLs) and Veris kW transducers were used for all these measurements. Average values were recorded at 5-minute intervals.

Table 3. Evaluator's Short-term Monitored Points

Short Term Measurements (kW)	
Duration:	2/6/08 to 3/3/08
Recording Interval	5 Minutes
Line	**Variable Speed Loads**
A3	Clg Tower Fan 1
A3	Secondary CHW (PROC) Pump2
A3	Chiller1
A4	Clg Tower1 Fan
A4	Secondary CHW (PROC) Pump2
A4	Secondary CHW (HVAC) Pump3
A4	Tower Booster Pump1
A4	Chiller2
One-time Measurements (kW)	
A3	Primary CHW Pump (constant speed)
A4	Condenser Water Pump (constant speed)
A3	Chiller2 (verification of trend readings)

4. RECOMMENDATIONS FOR IMPROVING EVALUATIONS

The following recommendations are based on the experience obtained from evaluation of the projects addressed in this report. They are intended to make future evaluations easier to perform and lead to more accurate results. Recommendations are provided for both the development of the tracking estimates of savings and the evaluation process.

Recommendations for the TA Analysis are:

a) Annotations in cells of Excel models could be used to explain some of the assumptions and rationales that are not immediately obvious (e.g. the cooling tower increased flow adjustment)

b) Clear labeling of parameter values from any data collected for the TA Analysis or M&V efforts would help make that information more useful, although those data sets may be less robust than those obtained for the evaluation.

Recommendations for the Evaluation are:

a) The Evaluator should submit a scheme for cleaning the data and obtain approval from the Reviewer before finalizing the data set. This may require multiple iterations as planned approaches do not always work out and different sets of input variables may require different reasons for accepting or rejecting data.

b) For large projects with many facets, any analysis plans should be expected to evolve. While evaluation models can be better informed than ex ante models due to larger data sets, they can also be more difficult because the data constrain the assumptions that might otherwise be made.

c) As modeling progresses, a set of tests should be developed to ensure all facets of any models make sense in relation to each other. These tests should be run each time a significant adjustment is made to the model.