

Field Monitoring and Data Validation for Evaluating the Performance of Cool Storage Systems

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ABSTRACT

This paper describes a general approach to validating measured data collected for the purpose of evaluating the performance of cool storage systems. The validation approach is a product of ASHRAE Research Project RP-1004, Determining Long-Term Performance of Cool Storage Systems from Short-Term Tests. Ensuring the quality of the data by field validation is preferable to post-processing. However, data validation is necessary to verify the accuracy of measurements, even when sensor accuracy has been verified in the field. Validation is critical if data collected by others are to be used for performance evaluation or if field verification capabilities are limited.

The paper presents several tests for verifying the accuracy and consistency of a data set. Tests are based on instantaneous energy balances, energy balances over time, flow balances, and temperature agreements where more than one sensor is measuring the same quantity. The general procedure for the tests is to calculate two or more quantities from selected subsets of the data and verify that they agree within a desired tolerance. Lack of agreement indicates that further analysis or on-site measurements are necessary to determine which sensor(s) are in error.

Appropriate tests for a given system generally depend on the specific configuration and operating strategy. This paper describes a number of tests that are applicable to many cool storage systems. The paper also describes two case study sites evaluated for ASHRAE Research Project RP-1004 and illustrates the use of these tests to validate the data from these sites. Recommendations for field monitoring are also provided.

The companion paper describes the details of the methodology development and its application to three case study sites (Reddy et al. 2002).

INTRODUCTION

This paper and its companion (Reddy et al. 2002) report the results of ASHRAE Research Project RP-1004, Determining Long-Term Performance of Cool Storage Systems from Short-Term Tests. The goal of this research project was to develop reliable and low-cost methods to evaluate the in-situ, long-term performance of cool storage systems.

Facility owners, public utilities, and energy service companies continue to invest in energy efficiency projects. To ensure the prudence of these investments, regulators, investors, and owners often require field monitoring to evaluate and verify the resulting energy and cost savings. These measurement and verification (M&V) efforts are needed because there is significant uncertainty regarding how well such projects perform relative to their design predictions. This has been especially true with non-steady-state systems, including HVAC systems and, in particular, those that incorporate cool storage. Many cool storage systems are completely or partially dependent upon field assembly of components that cannot be pre-rated or tested prior to assembly. The performance of this equipment is also highly dependent on how it is operated as a system. For these systems, field testing is the only way to verify that the installed systems meet the specified performance requirements. At present, there are no widely accepted standard methods or protocols to conduct long-term in-situ tests. Investigators must therefore develop custom measurement plans and analysis procedures for each project, increasing evaluation costs and diminishing quality assurance.

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ASHRAE Research Project RP-1004 has developed a methodology to evaluate the performance of cool storage systems in the field, based on models developed from short-term monitored data. Details of this methodology can be found in the project final report and companion paper (Reddy et al. 2001, 2002). This paper provides recommendations for validating monitored data and describes the application of the validation methods to two case study sites evaluated under Research Project RP-1004.

DATA MONITORING

The performance evaluation methodology of RP-1004 requires measurements of building loads, chiller loads, and cooling plant energy use. It does not require measurements of the thermal performance of thermal storage devices. However, measurements of storage device thermal performance are recommended for validating building load and chiller load data and for troubleshooting the operation of systems, controls, and storage components.

The following measurements are required at a minimum for the RP-1004 methodology:

1. Total building electricity use.
2. Cooling plant electricity use including chillers and auxiliaries. Auxiliaries include all pumps and cooling tower fans but not building AHU fans or any secondary circulating pumps not required to move fluid through the chillers and storage.
3. Building cooling load, calculated from the supply and return temperatures and flow rate of the chilled fluid serving the building load.
4. Chiller cooling load, for each chiller, calculated from the entering and leaving temperatures and flow rate.
5. Outdoor dry-bulb temperature.
6. If the thermal storage subsystem has a separate chiller and pump, their electricity use must also be monitored.

Glycol concentrations should also be measured periodically to ensure that the correct factors are used for energy calculations.

The following additional measurements are recommended for data validation and system evaluation:

1. Separate measurements of electricity use of chillers and auxiliaries.

2. Flow rate, entering temperature and leaving temperature for the storage tank(s).
3. Storage charge and discharge rates, calculated from the flow rate and entering and leaving temperatures.
4. Condenser water temperature entering each chiller.
5. Mechanical room temperature or temperature surrounding storage tanks.

Instruments should be installed in conformance with the requirements of *ANSI/ASHRAE Standard 150-2000* (ASHRAE 2000). The requirements for accuracy, precision, and resolution of the instruments are summarized in Table 1. Standard 150 also requires that practitioners field-verify the installed accuracy of temperature and flow instruments. The standard requires that temperature measurements be verified by a two-point calibration procedure. The procedure for verifying measurements of temperature difference involves subjecting the two sensors to fluid flow at the same temperature. Flow measurements are verified by confirming that the flow conditions in the field are consistent with the flow conditions that existed during the laboratory calibration. Practitioners should consult Standard 150 for details of the field verification procedures.

Electric power should be measured using instruments that yield true RMS power, based on measured current, voltage, and power factor.

An integrating energy meter (Btu meter) provides an output signal for energy transfer rate based on fluid flow and temperature measurements. The energy meter calculates instantaneous energy transfer rates at the scan rate of the data-logger, typically more than once per minute, then averages these readings over each recording interval of 15 to 60 minutes. These integrated measurements are normally more accurate than transfer rates calculated from average readings of flow and temperatures, especially in systems where flow rates or temperatures change quickly compared to the recording interval. Mathematically, the difference between the averages of two temperature measurements over an interval is equal to the average of the individual temperature differences. However, the product of the average temperature difference and the average flow rate is not necessarily equal to the average of the individual products.

**TABLE 1
Accuracy Requirements to Comply with ANSI/ASHRAE Standard 150-2000**

Measurement	Accuracy	Precision	Resolution
Temperature	± 0.3°F	± 0.2°F	± 0.1°F
Temperature Difference	± 0.2°F	± 0.15°F	± 0.1°F
Flow	± 5% of reading	± 2% of reading	± 0.1% of reading
Electric Power	± 2% of reading	± 2% of reading	± 0.5% of reading
Glycol	± 5% of concentration	± 5% of concentration	± 5% of concentration

Integrated energy meter measurements are preferred for monitoring energy transfer rates. However, flow and temperature data from these meters should be recorded as separate channels for data validation purposes.

Time series data should be recorded automatically by a data logger programmed with the appropriate channel parameters and recording intervals. Data should be downloaded from the site and checked weekly for missing and out-of-range data using standard data screening methods. Standard inspection plots that display each channel and calculated quantity also allow quick visual evaluation of a weekly data set.

Data recording at 15-minute intervals is recommended. Data for a recording interval that contains a change of operating modes are often not useful. Average temperatures, flow rates, and power measurements for an interval that contains two different operating modes generally do not reflect the actual conditions for either mode. Longer recording intervals are more susceptible to this effect, and more time is lost for each corrupted record.

UNCERTAINTY ANALYSIS

Evaluation of the uncertainty in measured data and calculated results is an essential part of the data validation process. The following references are recommended for information on uncertainty analysis: *1997 ASHRAE Handbook—Fundamentals*, Chapter 14, Measurement and Instruments (ASHRAE 1997); *ANSI/ASHRAE Standard 150-2000*, annex B (ASHRAE 2000); *ANSI/ASME Standard PTC 19.1-1985* (1990); Coleman and Steele (1989); and Dieck (1992).

DATA VALIDATION TESTS

Analysts may use a number of tests to evaluate the validity of system performance data. Ideally, sensor accuracy has been validated in the field, as discussed above. Post-processing of data for validation is then merely a formality to verify the accuracy of the measurements. However, these post-processing tests are often a valuable supplement to field verification of sensor accuracy. They are critical if data collected by others are to be used for performance evaluation or if field verification capabilities are limited for any reason.

In some cases, discrepancies caused by sensor errors can be resolved by informed analysis of the data. However, ensuring the quality of the data by field validation is nearly always preferable to post-processing.

Tests for data validity are generally based on the following principles:

- Instantaneous energy balance
- Energy balance over time
- Flow balance
- Temperature comparison

The general procedure for the tests is to calculate two or more quantities from selected subsets of the data and verify that they agree within a desired tolerance. Agreement is an

indication that the sensors involved in the test are reporting accurately. Lack of agreement indicates that further analysis or on-site measurements are necessary to determine which sensor(s) are in error. In some cases, previously collected data may need to be corrected if the errors can be adequately characterized.

Appropriate tests for a given system generally depend on the specific configuration and operating strategy. However, a number of tests are applicable to many cool storage systems. These common tests include the following.

- Calculate a flow balance from measurements of flow rates through chillers, storage, and load.
- Compare the temperature measurements at various points at times when they should be equal.
- Compare integrated energy meter measurements to energy transfer values calculated from temperature and flow measurements.
- Calculate an energy balance on the storage by comparing the energy added to storage with energy removed from storage over an extended period.
- Examine the running calculation of storage inventory.
- Calculate an energy balance on the entire system, including chillers, storage, and load, for each observation.
- Calculate an energy balance on the entire system over an extended period.

Performing the tests involves identifying the conditions that apply to a specific system, sorting the data to group the measurements to which the tests are to be applied, and comparing the measurements.

Considerations for each of these tests are discussed below. The following sections describe the data validation performed for the case study systems evaluated under RP-1004.

Calculate a Flow Balance

Many cool storage systems have operating modes for which the same flow rates are measured at different points in the system. For example, in the charging mode, the flow rate is often the same through chillers and storage. Likewise, in the chiller-only mode, the flow rate is often the same through chillers and load.

In many cases, a simple flow balance calculation is appropriate. For example, in discharge-and-chiller mode, the flow through the load may be equal to the sum of the flows through the chillers and the storage. A lack of agreement among the various flow sensors indicates a possible sensor error.

Compare Temperature Measurements

Cool storage systems typically have several operating modes or conditions when the same temperature fluid is measured at two or more points. This is true for any system that has two or more of the chiller, storage, and load measurements in series during any of its operating modes. The temper-

ature measurements should differ only by the amount of any heat gain to piping and equipment, which is normally a small fraction of a degree. A greater discrepancy is an indication of a sensor error. Depending on the specific system configuration, the temperature comparisons might include the following.

- During charging mode and discharge-and-chiller mode, the temperature leaving the chiller should equal the temperature entering storage.
- During chiller-only mode, the temperature leaving the chiller should equal the temperature entering the load.
- During chiller-only mode, the temperature returning from the load should equal the temperature entering the chiller.
- During discharge-only mode, the temperature leaving storage, downstream of any bypass, should equal the temperature entering the load.
- During discharge-only mode, the temperature returning from the load should equal the temperature entering storage.

Compare Energy Meter Readings to Calculated Energy Transfer Values

The energy transfer measured over a time period by an integrating energy meter (Btu meter) is not expected to be identical to the energy transfer calculated from average readings of flow and temperatures. However, in most cool storage systems, temperatures and flow rates change slowly enough that the measured and calculated values will agree fairly closely. A significant disagreement between these values indicates sensor error or meter malfunction.

If the same temperature and flow sensors are used for the energy meter and the calculation, a discrepancy indicates that the energy meter is not performing the required calculations correctly. Reasons for this may include incorrect scaling factors or erroneous specific heat formulas or data sampling errors. If different sensors are used for the calculation and the measurement, a discrepancy indicates that one or more of the sensors is in error.

Calculate an Energy Balance on the Storage Tank

Over an extended period of many charge-discharge cycles, the cooling capacity added to the storage tank (heat removed) by charging must be equal to the cooling capacity removed from storage (heat added) by discharging and losses. Over a large number of cycles, the difference between the beginning and ending tank internal energy is negligible compared to the total energy added and removed.

If a pump is located where its heat gain is included in the charge or discharge energy measurements, this gain should be included in the energy balance. Heat gain from a pump can be estimated from the measured energy input multiplied by the motor efficiency. This estimate assumes that losses from the

motor are not transferred to the fluid stream. The energy input to a constant-speed pump can be calculated from a measurement of pump power input and the run-time.

Losses from storage can be calculated from the area and insulation value of the storage tank and the inside and ambient temperatures. Storage losses are normally expected to be about 1% to 5% of the nominal storage capacity per day (Dorgan and Elleson 1993).

Investigators typically measure only the charging and discharging energy and ascribe the difference to losses. However, a difference between the charging and discharging energy that exceeds the expected losses is an indication that one or more sensors may be in error. Note that the possibility that unusually high losses are due to extreme ambient conditions, damaged or substandard insulation, or other causes should also be investigated.

Examine the Running Calculation of Storage Inventory

A running calculation of the storage inventory, based on charge and discharge energy, should yield values between zero and the total nominal capacity. The storage inventory is calculated as follows:

- Start at a known storage tank condition, typically fully charged or fully discharged. *ANSI/ASHRAE Standard 150-2000* (ASHRAE 2000) provides several options for determining the fully charged and fully discharged conditions.
- Based on the calculation of charge or discharge energy in the first measurement interval, add or subtract the appropriate quantity to or from the starting inventory.
- Subtract the estimated storage loss for the measurement interval.
- For each succeeding measurement interval, increment the preceding storage inventory value by the appropriate charge or discharge and loss.

A calculated storage inventory that falls well below zero or that exceeds the total nominal capacity is an indication of one or more sensors in error. Note that a negative storage inventory may be valid if the zero inventory point or fully discharged condition is defined as the point where all latent cooling capacity is removed from the tank. In this case, a negative inventory indicates that some sensible capacity has also been discharged.

Calculate an Energy Balance on the Chilled Fluid System for Each Observation

The total energy added to or removed from the chiller evaporator(s), storage tank(s), and load(s) should balance to zero in each measurement interval. A discrepancy in this energy balance is an indication of errors in one or more sensors.

Calculate an Energy Balance on the Entire System Over Time

The total cooling energy supplied by the chiller over a time period should be equal to the total cooling energy supplied to the load plus pump heat gains plus losses from storage.

The balance should be calculated over the entire analysis period and may also be calculated for shorter subsets of the data. The calculation should begin and end with the storage tank at the same state of charge. However, for periods of longer than one week, small differences in the state of charge can often be neglected as they are much smaller than the total building or chiller load.

If a pump is located between the building supply and return temperature sensors or the chiller entering and leaving temperature sensors, its heat gain is already included in the load measurement and should not be calculated separately.

The discrepancy in the energy balance calculation should be less than the combined uncertainty resulting from the uncertainties in each of the measurements. This is an indication that the errors in the measurements are within the assumed uncertainty levels. A larger discrepancy indicates that one or more measurements has an error greater than its assumed uncertainty.

CASE STUDY SYSTEMS

The savings analysis methodology of research project RP-1004 was applied to three case study sites. The data from

TABLE 2
Case Study Sites

	Site #2	Site #3
Location	Corpus Christi, Tex.	Austin, Tex.
Type of facility	Community college	Convention center
Number and size of chillers	1 × 800 ton 1 × 1000 ton	2 × 650 ton
Type of storage	Stratified chilled water	Internal melt ice-on-coil
Storage capacity	1.2 million gal	6000 ton-h
Storage cycle	Daily	Daily
Weekday on-peak period	12:30 – 19:30	14:00 – 20:00
Seasonal storage operation	Load-shifting from June-Sept. only	Year-round operation, constant electric rates
Data collection period	May 98 – Oct. 99	May 98 – Dec. 99
Data period used for analysis	June 99 – Sept. 99	Oct. 98 – Sept. 99
Time scale of data collection	1 h	1 h

site #1 had previously undergone extensive validation, both in the field and in post-processing. Therefore, additional data validation effort for this data set was not necessary.

Data from the other two sites required validation by the methods described above. The following sections describe the systems and the data validation procedures carried out for these sites. Table 2 summarizes some characteristics of the sites. Detailed descriptions of the case study savings analyses are provided in Reddy et al. (2001).

CASE STUDY SITE #2—COMMUNITY COLLEGE, CORPUS CHRISTI, TEXAS

Description of the Cooling Plant

Case study #2 evaluated the cooling plant at a 681,592 ft² community college campus in Corpus Christi, Tex. This system includes a 1.2 million-gallon stratified chilled water storage tank that provides partial cooling to the campus. The thermal storage tank was added to the cooling plant in 1992 to reduce electricity use during peak utility periods and to provide additional capacity to an overburdened system. At the time of this study, the cooling plant also included one 800 ton chiller and one 1000 ton chiller, each with a dedicated cooling tower. Chilled water is supplied from the plant to three separate chilled water loops that deliver cooling to the buildings on the campus.

Figure 1 is a schematic diagram of site #2 showing the configuration of the chillers, storage tank and campus load, and the locations of the monitoring points. Note that a number of essential control valves are not shown in this diagram.

In general, three operating modes are used at site #2. In the charge mode, one chiller charges the tank, and one chiller

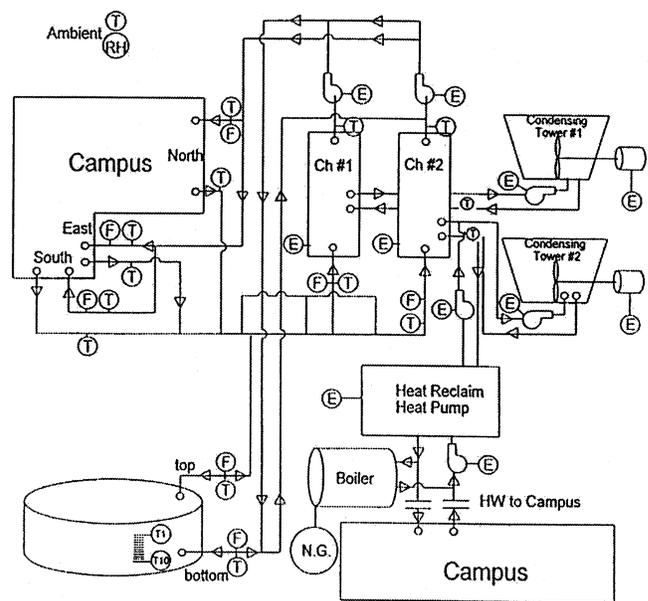


Figure 1 Schematic diagram of case study system #2.

TABLE 3
Data Channels for Case Study Site #2

Label	Units	Description
Month		Month
Day		Day
Year		Year
NE ChW	kBtu	Northeast loop chilled water load
NE ChW	gal/h	Northeast loop chilled water flow
NW ChW	kBtu	Northwest loop chilled water load
NW ChW	gal/h	Northwest loop chilled water flow
So ChW	kBtu	South loop chilled water load
So ChW	gal/h	South loop chilled water flow
OA T	°F	Outside air temperature
Stor Lwr T	°F	Storage lower inlet/outlet temperature
Stor Upr T	°F	Storage upper inlet/outlet temperature
Ch1 kWh	kWh	Chiller 1 kWh
Ch2 kWh	kWh	Chiller 2 kWh
Ch1	kBtu	Chiller 1 load
Ch1 flow	gal/h	Chiller 1 flow
Ch2	kBtu	Chiller 2 load
Ch2 flow	gal/h	Chiller 2 flow
Ch1 Lv T	°F	Chiller 1 leaving temperature
Ch1 Ent T	°F	Chiller 1 entering temperature
Ch2 Lv T	°F	Chiller 2 leaving temperature
Ch2 Ent T	°F	Chiller 2 entering temperature
Campus	kWh	Total campus electrical load
Dry bulb	°F	NWS outside air temperature
Dewpoint	°F	NWS outside air dewpoint
OA RH	%RH	Outside air humidity
Stor Chg	kBtu	Storage charging rate
Stor Chg	gal/h	Storage charging flow rate
Stor Disch	kBtu	Storage discharging rate
Stor Disch	gal/h	Storage discharging flow rate
Cond1 T	°F	Chiller 1 condenser entering temperature
Cond2 T	°F	Chiller 2 condenser entering temperature
ChWP1	KWh	Chilled water pump 1 kWh
ChWP2	KWh	Chilled water pump 2 kWh
CondP1	KWh	Condenser pump 1 kWh
CondP2	KWh	Condenser pump 2 kWh
CondFan1	KWh	Cooling tower fan 1 kWh
CondFan2	KWh	Cooling tower fan 2 kWh
ChWP1	KWh	Chilled water pump 1 kWh
ChWP2	KWh	Chilled water pump 2 kWh

carries the campus load. In the chiller-only mode, two chillers carry the campus load. In discharge mode, one chiller and cooling from storage carry the campus load during on-peak periods.

Instrumentation

The instrumentation at this site consisted of sensors and data loggers that had been previously installed, and additional sensors that were added to complete the measurement points needed for this analysis. Table 3 lists the data channels monitored at this site.

The datalogger at the site samples each data point approximately once every six seconds and records the average (or sum in the case of electric power channels) of the measurements into an hourly time series record. For temperature and flow rate channels, the datalogger records average values each hour. For electric energy channels, the datalogger records total energy for the hour in kWh, which is equal to the average power over the hour in kWh/h. For thermal energy channels, the total cumulative energy transferred in the hour is recorded each hour. The time stamp for each record is the ending time for the hour.

Data for this project were collected at this site between May 14, 1998 and October 6, 1999. However, some channels were not available for certain periods during this time. The channels that were added to the original installation were available beginning May 18, 1999. There were periods of one to two days when data logger malfunctions resulted in no data being recorded. There were also periods of several days to several weeks when one or more channels malfunctioned and were not available. In some cases, the missing data were reconstructed by calculation or modeling, as discussed below. In other cases, the system performance could not be evaluated for periods when data were missing.

The complete data required for the analysis methodology were available for May 14, 1998, through June 30, 1999, with a significant gap from March 12 to May 17, 1999, and with small gaps from June 26-28 to July 10-12, 1998. The analysis methodology and the data validation discussed below were applied to the data for the period from May 1998 through March 1999.

Data Validation

Because it was not possible to carry out field tests of sensor accuracy at site #2, we relied on extensive analytical checks to validate the data. The following sections discuss these tests as applied to site #2, the reconstruction of some data channels, and an overall evaluation of the data.

Flow Balance. The flow balance among chiller, storage, and load was not evaluated because of the limited number of hours when all the flow measurements were available.

The flow balance between chillers and load was evaluated for times when the plant was operating in chiller-only mode. During these times, the total flow to the load should be equal

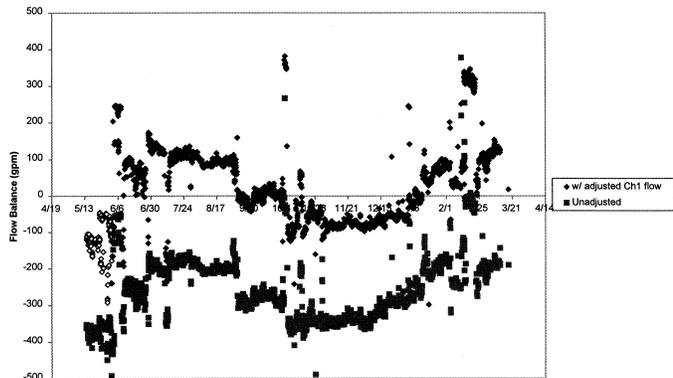


Figure 2 Difference between load flow and chiller flow in chiller-only mode for site #2.

to the total flow through the chillers. Comparison of the measurements suggested that the flow readings for chiller 1 were high, perhaps because of an inappropriate scaling factor in the flow transmitter. The flow balance, combined with a comparison of energy transfer measurements (discussed below), indicated that the chiller 1 flow reading should be adjusted by a factor of 0.864. Figure 2 shows the net flow balance before and after applying the adjustment. After adjustment, the average net flow is 18 gpm, with a standard deviation of 120 gpm. With an assumed 5% uncertainty in the flow readings, the average uncertainty in the flow balance calculation is ± 167 gpm. The fact that the imbalance in the flow measurements is less than this value indicates that the uncertainty in the adjusted flow measurements is less than 5%.

Compare Temperature Measurements. Several temperature comparisons were used to validate the sensor data. The measurements of chilled water temperature entering the two chillers were compared for times when water was flowing through both chillers. These temperatures consistently agree within 0.1°F.

The temperature measurement at the bottom of the storage tank was compared to the calculated charge temperature determined from the leaving temperatures and flow rates of each chiller. These temperatures, which should be the same during charge mode, typically agree within 0.8°F. This indicates very close agreement considering that the calculated charge temperature is determined from four measurements.

The temperature measurement at the top of the storage tank was compared to the chilled water temperature entering chiller 2. These temperatures should be the same during charge mode, when chiller 2 receives warm water directly from the top of the storage tank. The temperatures generally agree within 0.2°F.

The measurements of chilled water temperature entering and leaving the chillers were compared during times when the chillers were off but flow through the chillers continued. For chiller 1, the difference between entering and leaving temper-

atures readings was consistently about 0.15°F. For chiller 2, this difference was consistently about 0.3°F. Based on the excellent agreement among the sensor readings, the estimated uncertainty in the measurements of temperature and temperature difference is less than 0.3°F.

Compare Energy Measurements. The energy meter readings for chiller 2 compared very well with energy transfer rates calculated from flow and temperature measurements. The standard deviation in the difference between the meter readings and calculated values was 26 tons.

A comparison of the chiller 1 energy meter readings with the calculated values was used to help determine the correction to the chiller 1 flow measurement. After the correction to the flow measurements, the standard deviation in the difference between the meter readings and calculated values was 27 tons.

The energy meter readings for the three load loops could not be validated by this test because supply and return temperatures were not recorded. Furthermore, there were not sufficient data available to compare the storage energy meter measurements with calculated energy transfer rates.

Energy Balances. Because of the limited storage flow and energy transfer data available, it was not possible to perform detailed energy balance or storage inventory checks on the data set.

Over the entire analysis period, 4,580,000 ton-h were supplied by the chiller, with 4,106,000 ton-h delivered to the load. In addition, some chilled water capacity was lost to heat gain from the chilled water pumps and heat gains to the storage tank.

The average energy input to the chilled water pumps is 118 kWh per hour, of which 90% is assumed to appear as a heat gain in the chilled water. This results in an average heat gain of 30.6 ton-h per hour.

The heat gain to the storage tanks is assumed to be 3% of the total storage capacity per day, based on the typical range of 1% to 5%. For a nominal storage capacity of 12,000 ton-h, the tank heat gain is estimated to be 15 ton-hours per hour.

The total chilled water capacity delivered to the load and lost to pump and tank heat gains over the analysis period is approximately 4,445,000 ton-h. This agrees within 3% with the total 4,580,000 ton-h delivered by the chillers, with an average discrepancy of 18 ton-h per hour.

This discrepancy can be compared to an estimate of the uncertainty in the energy balance calculation to verify that the imbalance is within the expected error range. An estimate of 5% uncertainty in the energy meter readings results in total additive uncertainties of 124,000 ton-h in the total load and 192,000 ton-h in the chiller output. The root-sum-square of these uncertainties yields a total uncertainty in the overall energy balance of 228,000 ton-h. This is about 5% of the total chiller output, or an average of about 32 ton-h per hour. Since the energy balance discrepancy is less than this value, the uncertainty in the energy measurements can be considered to be within $\pm 5\%$.

Reconstructed Data. Several data channels were missing for periods of time but could be reconstructed using other available data channels. The outside air dry-bulb temperature at the site was unavailable for some time periods, so National Weather Service temperature data for Corpus Christi were reviewed to see if it could serve as a substitute. The National Weather Service data differed from the site data by 10°F or more for many observations. A regression of the site readings against the National Weather Service readings and the hour of the day yielded a model with a correlation coefficient of 0.80 and a standard error of 3.2°F, which was considered acceptable for this analysis. This model was used to fill in the missing data for times when the site measurement was missing. For times when neither the site measurement nor the National Weather Service measurement were available, readings were reconstructed by linear interpolation from the data values preceding and following the missing data points.

The chilled water load on the south loop was unavailable for three extended time periods. To adjust for this, a regression model was developed to fill in the missing data. The chilled water temperature rise for each loop was calculated from the respective energy meter reading and the flow measurement. The chilled water temperature rise in the south loop was then modeled as a function of the temperature rises in the northeast and northwest loops. This model had a relatively low correlation coefficient of 0.69 and a standard error of 43 tons, which is significant compared to the average south load of 150 tons and the average total load of 477 tons. However, this reconstruction of the south load was essential to obtain sufficient data to exercise the analysis methodology. The reconstructed data were used for the south load for the periods 6/28/98 to 7/10/98, 7/12/98 to 9/24/98, and 10/28/98 to 1/19/99.

Energy use data for the chilled water pumps, condenser water pumps, and cooling tower fans were unavailable for most of the selected analysis period. Models for total auxiliary energy in terms of kW/ton as a function of chiller load were developed for four modes of operation: charge, discharge, chiller-only, and weekend. The correlation coefficients of these models were quite good and ranged from 0.84 to 0.90. These models were used to determine the auxiliary component of the cooling plant energy use for the analysis methodology.

Quality of the Data Set. In spite of the difficulties with failed sensors and the resultant missing data, the validation tests indicate that, for the most part, the chiller load and chilled-water load data are reasonably robust. The flow balance and energy balance checks indicate that an assumed uncertainty of ±5% in the chiller load and cooling load readings is reasonable.

CASE STUDY #3—CONVENTION CENTER, AUSTIN, TEXAS

Description of the Cooling Plant

Case study #3 evaluates the cooling plant at a Convention Center in Austin, Tex. The thermal storage system at site #3 is

an internal melt, ice-on-coil, full storage system that was installed at the time the building was originally constructed. There are two chillers that each have a 650-ton cooling capacity in the chilled water mode (40°F) and a 425-ton capacity in ice-making mode (22°F). The system includes 42 modular ice storage tanks with a total nominal capacity of 6000 ton-h.

The chillers and the storage tanks are isolated from the building distribution loop by a plate-frame heat exchanger. The chiller-storage loop contains a nominal 25% solution of water and ethylene glycol, and the building loop contains water.

Figure 3 is a schematic diagram that shows the configuration of the chillers, storage tanks and building loop, and the locations of the monitoring points at site #3. Note that a number of essential control valves are not shown in this diagram.

The operating strategy at site #3 is to avoid operation of both chillers during on-peak hours. The chilled water pumps operate continuously to supply chilled water to building loads. The system uses three basic operating modes. In the charge mode, one or both chillers operate at a nominal 22°F glycol setpoint to charge the tank and meet the building load. In chiller-only mode, one or both chillers operate at a nominal 40°F setpoint to carry the building load. In the discharge mode, the storage tanks supply chilled glycol to the heat exchanger to carry the building load during on-peak periods.

Instrumentation

The instrumentation at this site consisted of sensors and dataloggers that had been previously installed and additional sensors that were added to the site to complete the measurement points needed for this analysis. Weather data were avail-

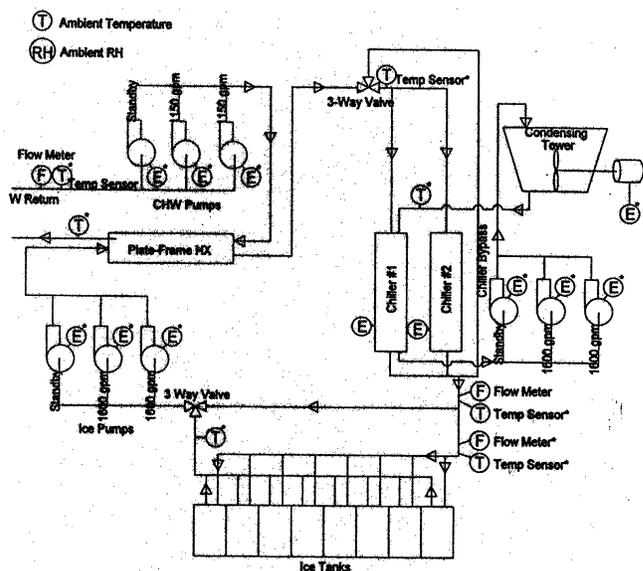


Figure 3 Schematic diagram of case study system #3.

able from the nearby NWS weather station located at the Corpus Christi airport, as well as being recorded on-site. Table 4 lists the data channels monitored at this site.

The datalogger at this site is the same type as installed at site #2. The datalogger samples each data point approximately once every six seconds. For temperature and flow rate channels, the data logger records average values each hour. For electric energy channels, the data logger records total energy for the hour in kWh, which is equal to the average power over the hour in kW. For thermal energy channels, the total energy

transferred is recorded each hour. The time stamp for each record is the ending time for the hour.

Data were collected at this site between May 1, 1998, and December 31, 1999. However, the measurement of the building load was unavailable for some time due to an error in installing the building chilled water temperature sensors. Complete data were available beginning September 10, 1998. A field recalibration was performed in July of 1999, resulting in the loss of one week of data, July 19-26, from the data logger memory.

TABLE 4
Data Channels for Case Study Site #3

Label	Units	Description
Month		Month
Day		Day
Year		Year
Hour		Hour
Chlr	gpm	Glycol flow through chillers
Chlr	kBtu	Total chiller load
Chlr	kWh	Total chiller kWh
Bldg	gpm	Chilled water flow to building
Bldg	kBtu	Total building load
Bldg	kWh	Total building electrical load
Chlr Lv T	°F	Chilled water temperature leaving chillers
Chlr Ent T	°F	Chilled water temperature entering chillers
Cond Ret	°F	Condenser water temperature entering chillers
Ice Lv T	°F	Glycol temperature leaving storage tanks
Ice Ent T	°F	Glycol temperature entering storage tanks
Ice Flow	gpm	Glycol flow through storage tanks
Charge	kBtu	Cooling load added to storage
Discharge	kBtu	Cooling load removed from storage
Bldg Ret	°F	Chilled water return temperature from building
Bldg Sup	°F	Chilled water supply temperature to building
TwrFan1	kWh	Cooling tower fan 1 kWh
TwrFan2	kWh	Cooling tower fan 2 kWh
CondP1	kWh	Condenser pump 1 kWh
CondP2,3	kWh	Condenser pumps 2 and 3 kWh
ChWP1	kWh	Chilled water pump 1 kWh
ChWP2,3	kWh	Chilled water pumps 2 and 3 kWh
Ice Pump1	kWh	Storage loop pump 1 kWh
Ice Pump2,3	kWh	Storage loop pumps 2 and 3 kWh
Mech Rm	°F	Mechanical room ambient temperature
OA	°F	Outside air temperature
OA	%RH	Outside air humidity

Data Validation

Sensor accuracy at site #3 was manually checked by the installation contractor during the installation. In addition, extensive analytical checks were used to validate the data. The following sections discuss these tests as applied to site #3, the reconstruction of some data channels, and an overall evaluation of the data.

Flow Balance. A comparison of the flow measurements through the chillers and the storage tanks during charge mode showed that the chiller flow measurements were consistently higher than the storage flow measurements. Normally, ice storage systems of this type direct the entire chiller flow through storage during charging, and the two flow measurements would be expected to be equal. However, site personnel indicated that the system operation had been modified to bypass approximately 20% of the chiller flow around the storage tanks to avoid overpressurizing the tanks.

The flow meter measurements are consistent with this description of system operation. For 74% of the charging hours, the chiller flow reading during charging was higher than the storage flow measurements by a factor of 1.25. For 16% of the hours, the chiller flow exceeded the storage flow by a factor of 1.35. For the remaining times, the ratios were evenly distributed across the range of 1.2 to 1.4.

There is no evidence to suggest that this pattern in the data is due to errors in the flow meters. The ratios between the readings are predominantly at one of two values, and the ratios are not correlated with the magnitudes of the flows. Therefore, the flow balance check offers no basis for correcting either of the flow meter readings.

Compare Temperature Measurements

Building Supply and Return Temperatures. There were about 15 periods, typically lasting 8-10 hours, when chilled water was flowing in the building loop, but the chillers were not operating and there was no cooling provided from storage. During these periods, the difference between the building supply and return temperature readings gradually approached zero. The temperature difference generally required two to three hours to fall below 1.0°F and another two to three hours to fall below 0.5°F. It appears that the slow convergence of temperatures is due to residual cooling capacity being removed from the system. However, the fact that the temper-

atures do converge indicates agreement between the two sensors.

Chiller and Storage Loop Temperatures. For this system configuration, the fluid temperature leaving the chillers must be equal to the fluid temperature entering the ice storage tanks when there is flow at both locations. However, the chiller leaving temperature measurement was consistently higher than the storage entering temperature measurement, typically by about 2°F. The difference between the two measurements, which has a mean value of 2.1°F and a standard deviation of 1.28°F, indicates a sensor error.

There were about 1200 observations when glycol was flowing through the chillers but the chillers were not operating. At these times, the glycol temperatures entering and leaving the chillers should both be equal to the fluid temperature entering storage. The chiller entering temperature measurement agrees very closely with the storage entering temperature measurement during these times, with a root mean square error of 0.32°F. However, the chiller leaving temperature measurement is consistently higher than both the other measurements. This indicates that the chiller entering and storage entering temperature measurements have small errors, and the chiller leaving temperature sensor has a significant error. This error is consistent with the surface-mounted chiller leaving temperature sensor being not in sufficiently close thermal contact with the pipe surface or not sufficiently insulated from the ambient temperature.

Analysis of the error shows that it is correlated with the temperature difference to the mechanical room ambient temperature. The following regression model was developed to correct the measured temperature:

$$T_{Corr} = T_{Meas} - \text{Max}[0, -0.5 + 0.053(T_{MechRm} - T_{Meas})]$$

where

T_{Corr} = corrected chiller leaving temperature,

T_{Meas} = measured chiller leaving temperature,

T_{MechRm} = mechanical room ambient temperature.

Figure 4 illustrates the fit of the model to the data. The model has a correlation coefficient of 0.21 and a root mean square error of 1.30°F. The low correlation coefficient is to be expected since the slope of the regression line is nearly horizontal. However, in spite of the poor correlation, the model is useful since it reduces the uncertainty in this measurement from 2.1°F to 1.3°F.

The model correction is necessary only when glycol is flowing through the chillers but not through the storage tanks, which occurs during 2593 or 29% of the 8931 observations. During other times, when the glycol is flowing through the storage tanks as well as through the chillers, the chiller leaving temperature can be set equal to the storage entering temperature.

The chiller entering and leaving temperature measurements are needed to calculate the chiller loads for the analysis methodology. The uncertainty in the entering temperature can

be estimated from the RMS error of 0.32°F between the entering temperature and the storage entering temperature. Assuming that the uncertainty in each of the sensors is the same, it is equal to $0.32/\sqrt{2} = 0.23^\circ\text{F}$.

The uncertainty in the chiller leaving temperature is assumed to be equal to the root mean square error in the regression model, or 1.30°F, when the temperature is determined from the model. The uncertainty is equal to the uncertainty in the storage entering temperature, or 0.23°F, when the chiller leaving temperature is set equal to the storage entering temperature.

Compare Energy Measurements

Energy Meter Corrections. A field check in July 1999 revealed that the energy meters supplied for the chiller and glycol loads had been set up for measuring loads in a 30% ethylene glycol solution. The actual concentration at case study site #3 was closer to 25%. Therefore, the meters were corrected by installing chips programmed for 25% glycol, and measurements recorded before July 19 were adjusted by a factor of 1.0315 to account for the correct density-specific heat product.

Building Load Energy Meter. For the period before July 19, 1999, the building load energy meter readings were generally within ± 50 tons of the values calculated from measurements of the building flow rate and the supply and return temperatures. These energy meter readings averaged 11 tons higher than the calculated values. This indicates that the temperature sensors used by the energy meter were in good agreement with those used by the temperature channels. The same flow meter is used by the energy meter and the flow channel.

An early energy balance test on the data (discussed below) implied that the building consumed more cooling capacity than was produced by the chillers. A field check in July 1999 showed that the building load energy meter used one

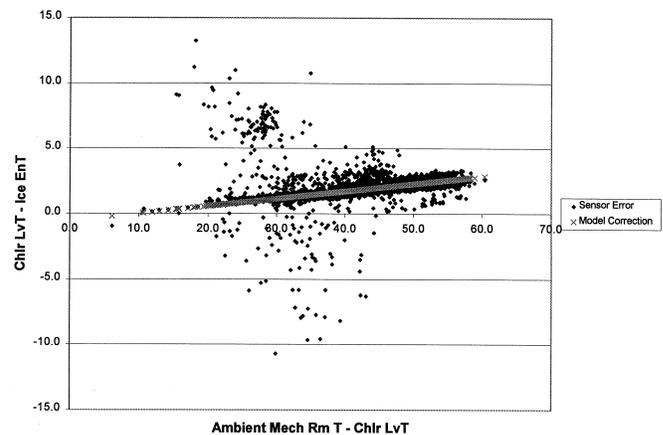


Figure 4 Error in chiller leaving temperature measurement.

well-mounted sensor and one surface-mounted sensor. In the original installation the building energy meter had two well-mounted sensors. However, when the heat exchanger was added to isolate the glycol loop in the mechanical room from the building load loop, the piping containing the sensor well was removed, and one of the well-mounted sensors was replaced with a surface-mounted sensor. After July 19, the surface-mounted sensor for the building supply temperature channel was moved, and one of the energy meter sensors was changed to a surface-mounted sensor to provide a better match with the other surface-mounted building return temperature sensor.

Unfortunately, moving the surface-mounted sensor for the building supply temperature increased the error in the calculated building load. For the remainder of the monitoring period, the calculated values were typically 50 to 110 tons lower than the energy meter readings, with an average difference of 75 tons. This error led to selection of the corrected energy meter readings for the analysis.

Chiller Energy Meter. When the chiller leaving temperature reading is corrected as described above, the calculated chiller Btu values are typically within ± 100 tons of the energy meter readings, with the energy meter typically 0-100 tons higher than the calculated values. There are many observations when power to the chillers was zero but the energy meter read 40-60 tons. There may be several reasons for this, including the fact that the energy meter “stores” the Btu reading and passes a pulse that is equal to a “stored” Btu value, which could occur after the power to the chiller has been switched off. Regardless, because of these spurious readings, and because of the possibility that a corresponding error occurs at nonzero values of chiller load, the calculated chiller loads were used for the analysis.

The uncertainty in the calculated chiller load can be determined from the estimated uncertainties in the flow and temperature readings. The uncertainty in the flow measurement is assumed to be $\pm 5\%$, which is a typical value for calibrated flow meters installed in good measurement locations. The estimated uncertainty in the entering and leaving glycol temperatures is $\pm 0.23^\circ\text{F}$ and $\pm 1.30^\circ\text{F}$, respectively, as discussed above. The resulting uncertainty in the chiller load averages ± 124 tons, about 22% of the average load of 560 tons.

This uncertainty in the chiller load measurement would be unacceptable for an actual savings evaluation of a thermal storage system. However, the values are reasonable and the data are still usable for the present purpose of demonstrating the evaluation methodology.

Energy Balances

Chiller and Building Load. An initial energy balance comparison showed the total building load over the analysis period was about 411,000 ton-h or 18% higher than the total chiller output prior to July 1999. As discussed above, this was caused by a surface-mounted temperature sensor that gave an

artificially high reading to the energy meter and caused the apparent increase in the building load.

To correct the readings, we compared the building load with the chiller load during chiller-only operation. At these times, the two loads should balance. We found that a constant correction factor of 0.68 applied to the building load readings prior to July 19, 1999, would minimize the discrepancies.

Storage Tanks. The total cooling capacity charged in the storage tanks during the analysis period should be equal to the total cooling capacity discharged plus losses due to tank heat gains and pump energy.

The heat gain to the storage tanks was assumed to be 3% of the total storage capacity per day, based on the typical range of 1% to 5%. For a nominal storage capacity of 6000 ton-h, the estimated tank heat gain would therefore be 7.5 ton-h per hour. While this heat gain could be expected to vary with the ambient temperature, a detailed analysis was beyond the scope of this project. For the purposes of data validation, the gain is assumed to be constant each hour. However, the heat gain does not appear as a load on the system when the ice tanks are bypassed, and it is not included in the energy balance analysis during chiller-only mode.

The energy input to the glycol pumps varies according to the operating mode. In discharge mode, the energy input averaged 7.5 kWh/h. In charge mode, the pump energy averaged 53 kWh/h, and in chiller-only mode, 17.3 kWh/h. The energy balance analysis assumed that 90% of the actual energy input in each observation appears as a heat gain in the system.

An energy balance on the storage tanks over the entire analysis period showed approximately 870,000 ton-h charged, 555,000 ton-h discharged, 68,000 ton-h lost to tank heat gains, and 47,000 ton-h lost to pump heat. Combining these totals leads to a discrepancy of 200,000 ton-h between the cooling energy stored in the tanks and the energy recovered. This shortfall, which amounts to 23% of the calculated charge energy, is much larger than could reasonably be ascribed to total system losses. This discrepancy is an indication of probable error in the storage charge or discharge measurements or an unidentified problem with the TES operation and/or equipment.

The cooling capacity added to or removed from storage during a given time period can also be evaluated from the difference between the building loads and the output of the chillers. During all charging hours in the analysis period, the net chiller output in excess of building loads and estimated tank and pump heat gains, which is an estimate of the total charging energy, was 915,000 ton-h. During all discharging hours, the chiller deficit, which is an estimate of the total discharging energy, was 772,000 ton-h. This check indicates that the actual discharge energy is higher than the measured value.

Unfortunately, tests to identify the source of the error were inconclusive. Adjustments to the temperature measurements that would correct the storage energy balance were not

supported by other data tests, and an exhaustive analysis was beyond the scope of this project.

Overall Energy Balance. Over the entire analysis period, the chiller load totals 2,261,000 ton-h, and the corrected building load totals 2,015,000 ton-h. The estimated storage tank and pump heat gains total 68,000 ton-h and 47,000 ton-h, respectively. These totals balance to within 131,000 ton-h, or about 6% of the total chiller load.

The uncertainty in the balance is $\pm 550,000$ ton-h or 24% of the total chiller load. The uncertainty is based on the following assumptions:

- Chiller load uncertainty calculated as discussed above.
- Building load uncertainty of $\pm 10\%$.
- Pump heat gain uncertainty of $\pm 5\%$. This is the estimated uncertainty in the assumption that 90% of the measured pump energy appears as a heat gain.
- Storage heat gain uncertainty of $\pm 100\%$, reflecting the estimate based on typical values for other installations.

The total additive uncertainty for each of these terms is summed over the analysis period, and the overall uncertainty in the balance is estimated as the root-sum-square of these totals.

Quality of the Data Set. The data tests showed that measured and calculated values of storage charge and discharge energy were not adequate to assess the storage tank performance in detail. However, detailed storage performance data are not required for the simplified savings calculation methodology demonstrated here. The uncertainties in the values of the chiller and building loads are unacceptably high for an assessment of the actual savings at this site. With an average uncertainty in the chiller load of 22% and building load measurements corrected to balance with the chiller load, it is difficult to assess how closely the data represent the actual loads at the site.

Even though an overall energy balance on the chiller and building loads, including estimated pump and storage tank heat gains, does balance to within 6%, the $\pm 24\%$ uncertainty in the balance diminishes the value of any conclusions regarding savings at the site. However, the internal consistency of the data set did give us enough confidence in the data set to demonstrate the savings evaluation methodology.

RECOMMENDATIONS FOR FIELD MONITORING

The case studies evaluated for this project used data from existing installations with limited on-site involvement by the investigators. Some on-site verification of sensor accuracy had been performed when the instruments at sites #2 and #3 were originally installed. However, the verification prescribed in *ANSI/ASHRAE Standard 150-2000* was not performed due to budget constraints. In retrospect, much of the extensive post-processing required to validate these data sets could have been avoided, at less expense, by on-site verification of sensor accuracy before monitoring began.

Fortunately, the monitoring plans at the sites included many more data channels than the minimum required to apply the analysis methodology. These redundant channels allowed us to correct or reconstitute much of the erroneous or missing data. If the data sets for these sites had included only the minimum channel list required to implement the analysis methodology, the post-processing tests and corrections would not have been possible.

The data validation procedures described in this paper should be applied when monitoring equipment is installed. Documentation of data validation should be a condition of the installation contract, along with documentation of field tests of sensor accuracy.

A recording interval of 15 minutes is recommended, rather than the hourly intervals used at the case study sites, to improve accuracy and reduce the loss of data when systems change modes.

The energy meters used at sites #2 and #3 receive inputs from flow and temperature sensors and provide pulse outputs for cumulative flow and energy use to the dataloggers. The temperature difference can be calculated from the flow and energy outputs, but the individual temperature readings are not available for recording unless a signal splitter is installed. The lack of access to the temperature data contributed to the difficulties in data validation at sites #2 and #3. To avoid these difficulties, energy meters used for evaluating cool storage system performance should provide flow and temperature outputs, or energy calculations should be performed on-board the datalogger.

Use of surface-mounted temperature sensors also led to unacceptable errors in the data. *ANSI/ASHRAE Standard 150-2000* allows the use of surface-mounted temperature sensors only under the following conditions:

- Heat conducting paste is utilized between the sensor and pipe.
- Closed cell insulation with a minimum insulation value of $2 \text{ m}^2 \cdot \text{K/J}$ ($12 \text{ ft}^2 \cdot ^\circ\text{F/Btu}$) isolates the pipe from ambient conditions for a distance of at least 15 cm (6 in.) from the sensor.
- The ambient temperature differs from the measured temperature by no more than 25°C (45°F).

These conditions could not be verified at the case study locations where surface-mounted sensors were installed. However, our experience with significant temperature errors from surface-mounted sensors indicates that surface-mounting should not be used when accurate field measurements of energy flows in cool storage or other chilled water systems are desired. Insertion-type sensors installed in thermo-wells should be used instead.

Insertion flow meters have been found to provide satisfactory flow measurement if installed properly and checked for calibration periodically. Flow meter readings should be validated on-site with secondary flow measurements or by analytical validation tests.

Data should be retrieved from sites regularly and inspected for problems. In this project, loggers were polled weekly and the data inspected, phone calls were made to confirm problems that were observed, and field crews were dispatched to fix sensors. Any serious monitoring project should anticipate the maintenance costs of the project in advance so that when sensors fail, resources are available to fix the sensors in a timely fashion.

RECOMMENDATIONS FOR FURTHER RESEARCH

Our experience with collecting and analyzing field data for this project leads to the following recommendations for further research.

- Evaluate the use of the measurement and analysis methods described in *ANSI/ASHRAE Standard 150-2000* (ASHRAE 2000) to quickly verify the capacity and system characteristics of thermal storage systems.
- Develop methods for verifying in-situ flow measurements, especially in situations where less-than-perfect flow meter locations must be used and flow correction is needed. These methods might include ultrasonic flow measurements, pitot traverses of pipes, use of oversized wet taps on thermo-wells to serve as flow verification ports, or other approaches.
- Develop public domain toolkits for gathering and manipulating time-series data. At present, each researcher is forced to develop their own method for polling, inspecting, archiving, and correcting data. Such tools should enable investigators to perform tasks, such as extracting columns of data from two different data files and merging the data into a third file, merging files that contain 15-minute data with files that contain hourly data, extracting data subsets that meet specified conditions, correcting for missing data, etc.

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