# Energy Data Acquisition and Validation for a Large Office Building

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The automated data acquisition and validation processes being employed to assess the energy performance of the Phillip Burton Federal Building in San Francisco, CA are described. This 1.4 million square foot Federal Building and U.S. Courthouse, the second largest building in the city, has been extensively remodeled and outfitted with efficient lighting systems in coordination with Pacific Gas & Electric Company (PG&E). The General Services Administration (GSA) has contracted with PG&E to assist with the installation and evaluation of an energy management control system (EMCS) that complies with the BACnet standard. This standard was completed in 1995 by American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) members to facilitate the interoperability of automated building control systems from different manufacturers. The EMCS in this building will use equipment from several vendors and will be able to shed load, limit demand, and perform lumen maintenance, daylighting, and other functions in response to real-time pricing signals from the utility. It is expected to reduce energy consumption by approximately 25% and to reduce the building's peak electrical demand of 6.5 megawatts by approximately one megawatt.

To support the evaluation of energy efficiency measure savings, the building has been outfitted with eleven Synergistic Control Systems, Inc. data loggers and a suite of 100 temperature, flow, and energy measurement sensors. Fifteen minute interval data is accumulated in the logger memories for subsequent polling by a host computer in Bellevue, Washington. Immediately after polling, the host computer executes a series of validation checks, and automatically prints exception reports, verified data summaries, and plots of selected parameters.

This paper describes the measurement plan, metering equipment, and the data processing and validation system employed for this building. This project demonstrates how it is possible to improve data quality and reduce data validation labor by using off-the-shelf hardware and software in a routine and automated fashion.

## INTRODUCTION

The American Society of Heating, Refrigerating, and Air Conditioning Engineers has recently released the BACnet standard (ASHRAE 1995), a set of specifications to facilitate the interoperability of energy management control systems across various equipment vendors. This standard is of particular value to owners of large commercial buildings that employ sophisticated energy management control systems, because it allows them to select supplemental or replacement parts in a competitive arena, where various vendors can provide the necessary functionality. It is necessary, however, to test this protocol in actual application before it can be routinely relied upon.

This paper describes a project that uses state-of-the-art energy performance monitoring equipment to evaluate the effectiveness of the BACnet standard in actual application. The results of this project can have far reaching effects for the controls industry, since it will help formulate the government's specifications in implementing a new federal requirement for open-protocol building control systems. GSA manages approximately 265 million square feet of building space in the United States and has been ordered by President Clinton to reduce energy consumption in its facilities by 30% over a 1985 baseline by the year 2005.

We focus upon the energy performance measurement system and software developed to collect and validate large volumes of time series data in an automated fashion. We believe that facility operators and utility companies can benefit from this experience by implementing similar systems to better understand and manage energy use and serve the needs of their customers.

### Background

The collection of empirical energy performance data from commercial buildings has been demonstrated in numerous projects and applied for a wide variety of needs (Burch J.D. et al 1990, Claridge D.E. et al 1991, Mazzucchi, R.P. 1987, Subbarao, K. et al, 1986, SBW 1994). With the advent of micro-electronics, the capability of measurement systems has increased dramatically, reliability has improved, and unit costs have generally diminished. Although the hardware costs have shown impressive cost reductions over the past decade, labor expenses for installation, validation, and analysis have remained about the same, making labor a larger share of overall measurement project expenses. The work described in the paper controls these labor costs to a significant degree by employing automated data collection, validation, and basic analysis procedures that are applied as frequently as may be prudent.

The micro-electronics revolution has also enhanced the sophistication and capability of energy management and control systems, with numerous suppliers developing proprietary hardware and software to satisfy control requirements. While there has been a healthy competition among vendors to install new systems, the unique and proprietary nature of the EMCS equipment has forced owners to stay with a particular manufacturer for all hardware and software upgrades and replacements. This situation is on the verge of changing with the recent release of the BACnet standard, a set of consensus protocols developed by ASHRAE members to facilitate the interoperability of hardware from a variety of vendors.

At the federal building in San Francisco, PG&E has entered into a contract with the GSA to install and evaluate an energy management and control system using the new BACnet protocol. PG&E has installed metering equipment and to collect and validate energy performance data from the building in advance of the installation of the new control equipment. This allows the development of baseline levels of energy performance, which will be compared to performance after the system is commissioned to estimate energy savings and assess the efficacy of the measures installed.

## Scope

The scope of this paper is limited to a description of the measurement and data processing systems implemented to support the assessment of energy savings. Since the energy management system which is the subject of the BACnet protocol test has yet to be implemented, we can only anticipate the particular analysis requirement needed to assess performance. Hence the analysis methods, procedures, and estimated savings will be the topic of a future paper. In this paper we describe the measurement plan, the challenges confronted to date with its implementation, and the data processing system developed to validate the baseline data being collected.

# METHODOLOGY

The methodology employed for this effort consists of five principal components: (1) measurement planning, (2) equipment specification, (3) software development, (4) data processing, and (5) data validation.

## Measurement Planning

The measurement plan is comprised of the following types of measurements: (1) electrical power and power factor, (2) natural gas consumption, (3) water temperature, (4) air temperature, (5) relative humidity, (6) water flow, and (7) steam mass flow. All data are accumulated at 15 minute intervals using seven Synergistic Control System C-180E and four C-160E data loggers which are polled regularly by an IBM-compatible host computer. The specific measurement points, types, and equipment utilized are indicted in Figure 1. Each of these components is briefly described below.

**Electrical power and power factor.** Measurement of electrical power is made using split core current transformers and voltage transducers connected directly to the data loggers. The data loggers employ a high speed sampling method to capture the voltage and current waveforms and compute true power and power factor for each phase of electrical service. For balanced three-wire, three-phase delta configuration devices only two phases are measured to calculate true power readings and reduce channel requirements. Power measurements are made continuously, and the data loggers store the average kW and kVA for each 15-minute period.

**Natural gas consumption.** Natural gas provided to the boilers, the only gas load at the building, is measured using the utility revenue meter, outfitted with a pulse initiating head. We measure both corrected (for pressure) and uncorrected values as a validation check.

**Water temperature.** Temperatures are measured using two methods: (1) Hy-cal's stainless steel surface mounted 2 wire 1000 Ohm 375 Platinum resistance temperature detectors (RTD's) that are sensed directly by the C-180E analog input channels and (2) Burn's surface mounted 3 wire 100 Ohm 385 platinum RTD's attached to 4-20 ma current transmitters which have been factory calibrated for the specific application range. The current transmitters are powered by the data logger. The data loggers convert Ohms and current to temperature values using look-up tables.

**Air temperature.** Air temperatures are measured using two methods: (1) Vaisala's 2-wire 100 Ohm 385 platinum RTD's with current transmitter and (2) Minco's extended length averaging RTD's with current transmitters. The 4-20

*Figure 1-a.* *Instrumentation List*

| Point | Description | Type | Range/Units | Inst. Mfg. |
|---|---|---|---|---|
| | | | | |
| CHILLER #1 KW | Centrifugal Chiller #1 Power | 3ph/3W Electric Demand | kW | Synergistic |
| CHILLER #2 KW | Centrifugal Chiller #2 Power | 3ph/3W Electric Demand | kW | Synergistic |
| CHILLER #3 KW | Centrifugal Chiller #3 Power | 3ph/3W Electric Demand | kW | Synergistic |
| C1_IN_FLOW | Chiller 1 Evaporator Water Flow | Insertion Flow | 0- 5000 gpm | Onicon |
| C1_IN_TEMP | Chiller 1 Evaporator Input Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| C1_OUT_TEMP | Chiller 1 Evaporator Output Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| C2_IN_FLOW | Chiller 2 Evaporator Water Flow | Insertion Flow | 0- 5000 gpm | Onicon |
| C2_IN_TEMP | Chiller 2 Evaporator Input Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| C2_OUT_TEMP | Chiller 2 Evaporator Output Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| C3_IN_FLOW | Chiller 3 Evaporator Water Flow | Insertion Flow | 0- 3000 gpm | Onicon |
| C3_IN_TEMP | Chiller 3 Evaporator Input Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| C3_OUT_TEMP | Chiller 3 Evaporator Output Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| CCP_CHWST_1 | Chilled Water Supply Temp 1 | Surface Temperature | deg.F | Hy-Cal Eng. |
| CCP_CHWST_2 | Chilled Water Supply Temp 2 | Surface Temperature | deg.F | Hy-Cal Eng. |
| C1_CWIT | Chiller 1 Condenser Return Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| C2_CWIT | Chiller 2 Condenser Return Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| C3_CWIT | Chiller 3 Condenser Return Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| MAIN_ELEC_Y1108 | Electric Power Service 1108 | Billing Meter | x 7 kwh/pulse | PG&E mod. |
| MAIN_ELEC_Y1109 | Electric Power Service 1109 | Billing Meter | x 7 kwh/pulse | PG&E mod. |
| SS_SF | Steam Production Rate | vortex shedding | 0- 30000 lbs/hr | EMCO |
| SS_TCondF | Steam Condensate Return Rate | Insertion Flow (water) | 0- 436 gpm | Onicon |
| SS_CondT | Steam Condensate Temp | Surface Temperature | 131-221 deg.F | Burns Eng. |
| SS_CondT-Check | Steam Condensate Temp Check | Surface Temperature | deg.F | Hy-Cal Eng. |
| SSBW-2_KW | Supply Fan West #2 Power | 3ph/3W Electric Demand | kW | Synergistic |
| RSBW-3_KW | Return Fan West #3 Power | 3ph/3W Electric Demand | kW | Synergistic |
| RSBW-4_KW | Return Fan West #4 Power | 3ph/3W Electric Demand | kW | Synergistic |
| SSBW-2_OAT | Outside Air Temp to Supply #2 | Outside Air Temperature | -4-176 deg.F | Vaisala |
| SSBW-2_OARH | Outside Air Humidity to Supply #2 | OA Relative Humidity | 0- 100% | Vaisala |
| SSBW-2_ADMAT | Average Mixed Air Temp Supply #2 | Avg. Duct Temp.(mixed) (downstream supply fan) | 32-104 deg.F | Minco |
| SSBW-2_MARH | Mixed Air Relative Humidity Supply #2 | Duct Relative Humidity (downstream supply fan) | 0- 100% | Vaisala |
| SSBW-2_MAT | Mixed Air Temperature Supply #2 | Duct Temperature | -4-176 deg.F | Vaisala |
| SSBW-2_ADCSAT | Average Cooled Air Temp Supply #2 | Avg. Duct Temp.(cooling) | 32-104 deg.F | Minco |
| SSBW-2_CSARH | Relative Humidity of Cooled Air Supply #2 | Duct Relative Humidity (downstream supply fan) | 0- 100% | Vaisala |
| SSBW-2_CSAT | Cooled Air Temp of Supply #2 | Duct Temperature | -4-176 deg.F | Vaisala |
| SSBW-2_ADHSAT | Average Hot Air Temp Supply #2 | Avg. Duct Temp.(heating) | 32-104 deg.F | Minco |
| SSBW-2_HSARH | Relative Humidity of Heated Air Supply #2 | Duct Relative Humidity (downstream supply fan) | 0- 100% | Vaisala |
| SSBW-2_HSAT | Heated Air Temp Supply #2 | Duct Temperature | -4-176 deg.F | Vaisala |
| RSBW-3_RARH | Relative Humidy of Return Air #3 | Duct Relative Humidity | 0- 100% | Vaisala |
| RSBW-3_RAT | Temperature of Return Air #3 | Duct Temperature | -4-176 deg.F | Vaisala |
| RSBW-4_RARH | Relative Humidity of Return Air #4 | Duct Relative Humidity | 0- 100% | Vaisala |
| RSBW-4_RAT | Return Air Temp #4 | Duct Temperature | -4-176 deg.F | Vaisala |
| CR_CHLR #1 KW | Court Chiller #1 Power | 3ph/3W Electric Demand | kW | Synergistic |
| CR_CHLR #2 KW | Court Chiller #2 Power | 3ph/3W Electric Demand | kW | Synergistic |
| CRC_IN_TEMP | Court Chillers Input Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| CR1_OUT_TEMP | Court Chiller #1 Output Temp | Surface Temperature | 32-122 deg.F | Burns Eng. |
| CR2_OUT_TEMP | Court Chiller #2 Output Temp | Surface Temperature | 32-122 deg.F | Burns Eng. |
| CRCP_CHWST_1 | Court Chiller Supply Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| FBI_CHLR #1 Ph A | FBI Chiller #1 Power A Phase | 1ph Electric Current | Amps | Synergistic |
| FBI_CHLR #1 Ph C | FBI Chiller #1 Power C Phase | 1ph Electric Current | Amps | Synergistic |
| FBI_CHLR #2 Ph A | FBI Chiller #2 Power A Phase | 1ph Electric Current | Amps | Synergistic |
| FBI_CHLR #2 Ph C | FBI Chiller #2 Power C Phase | 1ph Electric Current | Amps | Synergistic |
| FBIC_IN_TEMP | FBI Chillers Input Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| FBI1_OUT_TEMP | FBI Chiller #1 Output Temp | Surface Temperature | 32-122 deg.F | Burns Eng. |
| FBI2_OUT_TEMP | FBI Chiller #2 Output Temp | Surface Temperature | 32-122 deg.F | Burns Eng. |
| FBICP_CHWRT | FBI Chiller Return Temp | Surface Temperature | deg.F | Hy-Cal Eng. |

***Figure 1-b.*** *Instrumentation List*

| Point | Description | Type | Range/Units | Inst. Mfg. |
|---|---|---|---|---|
| FBICP_CHWST | FBI Chiller Supply Temp | Surface Temperature | deg.F | Hy-Cal Eng. |
| SUPH-10_KW | Penthouse Supply Fan #10 Power | 3ph/3W Electric Demand | kW | Synergistic |
| XPH-10_KW | Penthouse Exhast Fan #10 Power | 3ph/3W Electric Demand | kW | Synergistic |
| PH_OAT | Penthouse Outside Air Temp | Outside Ambient Temp. | -4 to 176 deg.F | Vaisala |
| PH_OARH | Penthouse Outside Air Humidity | OA Relative Humidity | 0-100% | Vaisala |
| PH-10_MARH | Penthouse Supply #10 Mixed Air Humidity | Duct Relative Humidity | 0- 100% | Vaisala |
| PH-10_MAT | Penthouse Supply #10 Mixed Air Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| PH-10_SARH | Penthouse Supply Air Relative Humidty | Duct Relative Humidity | 0- 100% | Vaisala |
| PH-10_SAT | Penthouse Supply Air Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| PH-10_RARH | Penthouse Return Air Relative Humidity | Duct Relative Humidity | 0- 100% | Vaisala |
| PH-10_RAT | Penthouse Return Air Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| SSBE-2_OAT | Supply Fan #2 East Outside Air Temp | Outside Air Temperature | -4-176 deg.F | Vaisala |
| SSBE-2_OARH | Supply Fan #2 East Relative Humidity | OA Relative Humidity | 0- 100% | Vaisala |
| SSBE-2_ADMAT | Supply Fan #2 East Average Mixed Air Temp | Avg. Duct Temp.(mixed) (downstream supply fan) | 32-104 deg.F | Minco |
| SSBE-2_MARH | Supply Fan #2 East Mixed Air Humidity | Duct Relative Humidity (downstream supply fan) | 0- 100% | Vaisala |
| SSBE-2_MAT | Supply Fan #2 East Mixed Air Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| SSBE-2_ADCSAT | Supply Fan #2 East Average Cooled Air Tem | Avg. Duct Temp.(cooling) | 32-104 deg.F | Minco |
| SSBE-2_CSARH | Supply Fan #2 East Cooled Air Humidity | Duct Relative Humidity (downstream supply fan) | 0- 100% | Vaisala |
| SSBE-2_CSAT | Supply Fan #2 East Cooled Air Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| SSBE-2_ADHSAT | Supply Fan #2 East Average Heated Temp | Avg. Duct Temp.(heating) | 32-104 deg.F | Minco |
| SSBE-2_HSARH | Supply Fan #2 East Heated Humidty | Duct Relative Humidity (downstream supply fan) | 0- 100% | Vaisala |
| SSBE-2_HSAT | Supply Fan #2 East Heated Air Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| RSBE-3_RARH | Return Fan #3 East Relative Humidity | Duct Relative Humidity | 0- 100% | Vaisala |
| RSBE-3_RAT | Return Fan #3 East Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| RSBE-4_RARH | Return Fan #4 East Relative Humidity | Duct Relative Humidity | 0- 100% | Vaisala |
| RSBE-4_RAT | Return Fan #4 East Temp | Duct Temperature | -4-176 deg.F | Vaisala |
| SSBE-2_KW | Supply Fan #2 East Power | 3ph/3W Electric Demand | kW | Synergistic |
| RSBE-3_KW | Return Fan #3 East Power | 3ph/3W Electric Demand | kW | Synergistic |
| RSBE-4_KW | Return Fan #4 East Power | 3ph/3W Electric Demand | kW | Synergistic |
| MAIN _GAS/cor | Natural Gas Main - Corrected | Billing Meter | 1000 cf/pulse | PG&E mod. |
| MAIN _GAS/uncor | Natural Gas Main - Uncorrected | Billing Meter | 1000 uc cf/pulse | PG&E mod. |
| Lighting L7A KW | Lighting Power Floor 7A | 3ph 480v Elect. Demand | kW | Synergistic |
| Plug P7A KW | Plug Power Floor 7A | 3ph 208v Elect. Demand | kW | Synergistic |
| Lighting L7B KW | Lighting Power Floor 7B | 3ph 480v Elect. Demand | kW | Synergistic |
| Plug P7B KW | Plug Power Floor 7B | 3ph 208v Elect. Demand | kW | Synergistic |
| Lighting L7C KW | Lighting Power Floor 7C | 3ph 480v Elect. Demand | kW | Synergistic |
| Plug P7C KW | Plug Power Floor 7C | 3ph 208v Elect. Demand | kW | Synergistic |
| Lighting L7D KW | Lighting Power Floor 7D | 3ph 480v Elect. Demand | kW | Synergistic |
| Plug P7D KW | Plug Power Floor 7D | 3ph 208v Elect. Demand | kW | Synergistic |
| CT-1A | Cooling Tower 1 Fan A Power | 3ph 208v Elect. Demand | kW | Synergistic |
| CT-1B | Cooling Tower 1 Fan B Power | 3ph 208v Elect. Demand | kW | Synergistic |
| CT-1C | Cooling Tower 1 Fan C Power | 3ph 208v Elect. Demand | kW | Synergistic |
| CT-2A | Cooling Tower 2 Fan A Power | 3ph 208v Elect. Demand | kW | Synergistic |
| CT-2B | Cooling Tower 2 Fan B Power | 3ph 208v Elect. Demand | kW | Synergistic |
| CT-2C | Cooling Tower 2 Fan C Power | 3ph 208v Elect. Demand | kW | Synergistic |

ma current transmitters are powered by the data logger and have been factory calibrated for the specific application range. The averaging RTD typically has an associated single point RTD at the same duct location for comparison.

**Relative humidity.** Relative humidities are measured using Vaisala humidity 4-20 ma current transmitters that are powered by the data logger. They are housed in the same NEMA 4 enclosure as the related air temperature transmitter.

**Water flow.** Water flow is measured using Onicon's dual turbine insertion type flowmeters. The flowmeters are externally powered and provide 4-20 ma current transmitter outputs which have been factory calibrated for the specific application ranges.

**Steam mass flow.** Steam production was originally measured using an EMCO flow computer and insertion flowmeter rated at 0-24,000 pounds per hour. A turbine meter was chosen due to the required turndown ration of the application. However, due to turbine failure this meter was converted to a vortex shedding flowmeter rated at 0-30,000 pounds per hour.

**Host computer.** Data is acquired from the eleven data loggers using an IBM compatible desktop computer outfitted with a modem. The computer is networked to other desktop computers and printers running under Windows 95. The software used to operate the system includes: (1) Automite—to automatically execute keyboard commands on a scheduled basis, (2) Synernet—to set data loggers parameters and poll the data loggers, (3) SAS—to run validation checks and produce data summaries, (4) Pkzip—to compress and decompress data files, (5) DBMS copy—to translate SAS files into comma delimited files and other formats desired by the client, and (6) LPRINT—a utility to print out validation reports. All of this software is commercially available.

## Software Development

The heart of the data processing system is a set of SAS programs that manipulate and summarize the logger data. SAS is an integrated system of software providing complete control over data access, management, analysis, and presentation. These programs are fed with raw data files collected by the Synernet program provided with the data loggers. Approximately one hour following the polling of the loggers, a batch routine is executed to copy and move the data and call a series of SAS jobs to validate the data. A modular structure is implemented so that the system can be more easily debugged and modified. Each module, however, is automatically executed by the single batch job controlling the data processing. The following five validation modules were developed.

**Time-step validation.** This routine calculates the time interval between each time-series record. If the value is anything other than 15-minutes a validation flag is set, and the date and time of the previous and following record is printed-out.

**Range gate validation.** Each measurement is compared against an expected maximum and minimum value. These expectations are set based upon the capacity of particular equipment, or upon the experienced minimum and maximum values during the first month of operation (where capacity information is not available). Whenever the measured value does not lie within the minimum and maximum values set for the channel, a validation flag is set for that measurement, and the values of all measurements during that interval are printed out. The ranges are modified periodically when we are assured that the ''out-of-range'' values are in fact reasonable.

**Relational validation.** A variety of relational checks are carried out to see that cross-channel measurements and computed performance indicators are within expected tolerances. The relational checks include the following: (1) calculation of kW per ton of chilled water production for each of the three chillers, (2) comparison of the heat content of steam production and condensate return volume, (3) calculation of boiler efficiency, (4) calculation of percent outside-air provided to the building by the primary air handlers, and (5) calculation of enthalpy change across heating and cooling coils. The methods used to calculate and test each of these checks is briefly described below. The ranges of acceptable values are quite large since we apply these tests to each 15 minute data interval, where transient effects and lags associated with sensor response can be significant. The ranges are tightened as the time resolution of the calculation are reduced since transient and lag effects will have less impact on the calculations.

*Chiller efficiency.* The kW per ton of chilled water production is derived from measurement of the true-power consumed by each of three chillers and concurrent measurements of chilled supply and return water temperature and flow. The data logger integrates the temperature and flow measurements for each scan to calculate BTU. Using SAS, each 15-minute interval the BTU measurement is divided by 12000 (to convert to tons) and this value is divided into the average kW over the period to derive the kW per ton parameter. These values should fall between .5 and 1.0.

*Condensate return percentage.* The steam production measurement is compared to the volumetric flow rate of condensate return to develop the percentage of condensate returned to the boiler. These values should be between 70% and 100%.

*Boiler efficiency.* The heat content of steam produced by the boiler is divided by the heat content of the natural gas consumed by the boiler to develop a boiler efficiency parameter. These values should fall between 40% and 95%. This wide range is applied since the boilers are shut down each evening.

*Outdoor air percentage.* Measurements of the return, outside, and supply air temperatures for each of the primary air handlers are used to calculate the percentage of outside air provided using a standard temperature mixing equation. These values should fall between 25 and 100%.

*Calculation of enthalpy change across coils.* The temperature and humidity of the air supplied to and delivered from heating and cooling coils is used to calculate enthalpy on either side of the coil. The difference in these values time the volumetric flow rate of air over the coil indicates the heat added or removed by the coil, which should be within expected ranges. Although not yet implemented, these expected ranges can be set as a function of internal gains, air exchange rate, insolation, and building envelope conduction.

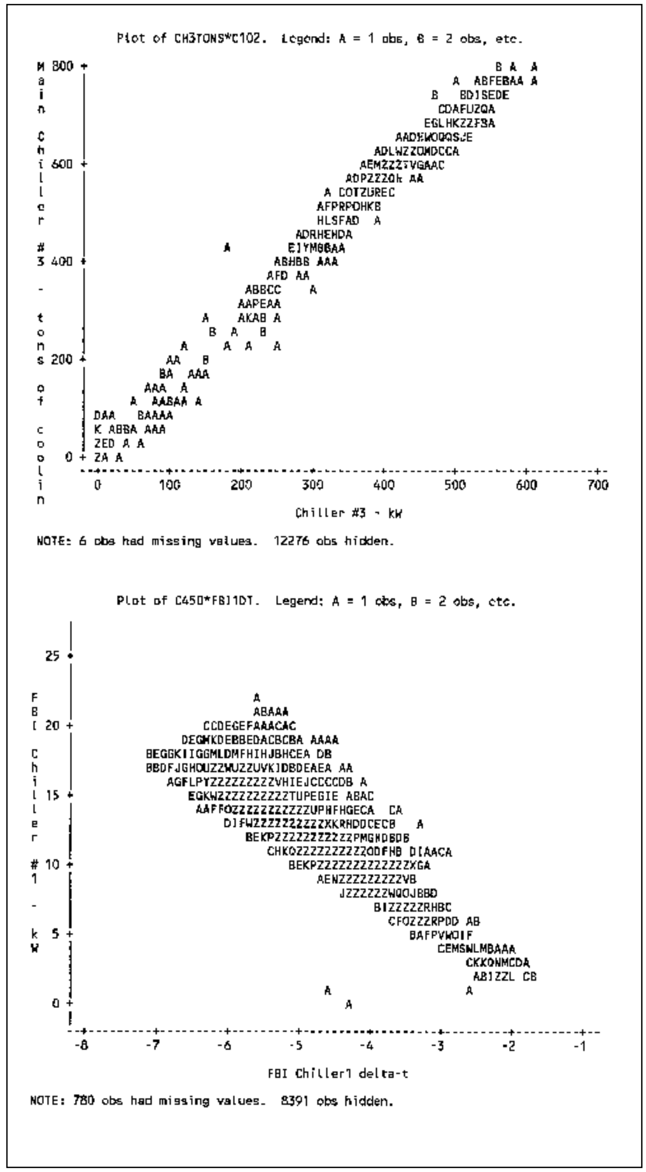
## Graphical validation

Selected variables are automatically plotted to show how they change with time or how they relate to one another. We do not routinely plot every measurement versus time since this would require an inordinate amount of skilled labor to review and interpret. Instead we plot key parameters against related parameters to validate that expected relationships hold true. For example, we plot chilled water production versus power and chilled water temperature change as shown in Figure 2. This figure displays the central tendencies of the data and any outliers. Letters from A to Y indicate one to 25 observations at the same point respectively, and Z indicates greater than 25 observations at that point.

Figure 3 shows another example plot of plug load versus lighting load for the seventh floor of the building (on top) and percent outside air provided by an air handler versus outdoor temperature (on bottom). For the upper plot we expect to see the curvature and limits shown as the plug load does not drop to zero (due to printers, computers, telephones etc. being on continuously) while the lighting load nearly does, and the plug load builds and drops gradually throughout the day, while the lighting load on these open floors is mostly all on or nearly all off. For the lower plot we expect the percent outside air to be less than 100% (except for transient driven outliers) and lower as temperatures diminish when heating is required.

These plots are automatically produced each time new data is introduced to the archive, so that the variations over time can be examined and problems can be identified with one

***Figure 2.*** *Graphical Validation of Chiller Performance*

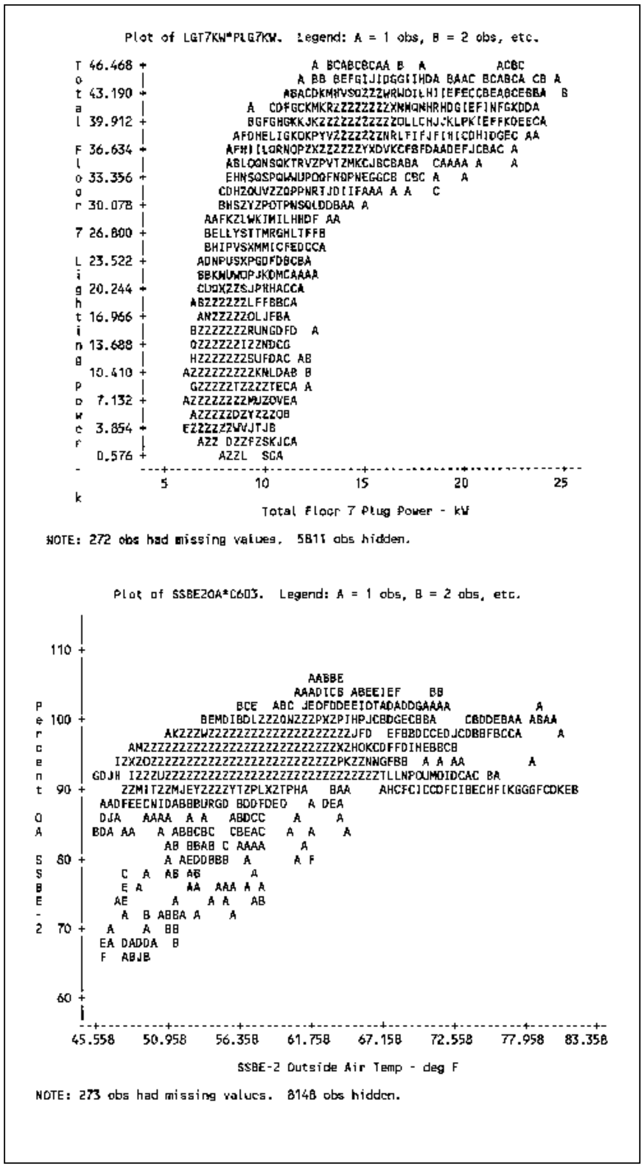



or more sensors feeding each of these parameters. Further investigation focuses on time series plots of individual channels to diagnose problem areas. These plots can be customized for presentation purposes, however they are shown here in their raw form to indicate what the analyst typically reviews.

## Statistical validation

Each time data is added to the archive the minimum, maximum, and mean values are tabulated as well as the standard deviation for all raw and computed channels. The values are scanned relative to the values for the entire archive to date to detect any large deviations or trends that exist. Figure 4 is sample page of the report produced by the statistical

*Figure 3. Graphical Validation of Lighting Versus Building Load and Percent Outside Air*




analysis package. Similar statistics are produced for each measured and computed channel every time the data loggers are polled, and from time-to-time for the entire data archive. These tables can be refined and customized for presentation purposes, however they are shown here in their raw form to indicate what the analyst typically reviews.

## Data Processing

At the start of the project we automatically polled the loggers each morning from 4am to 5am and automatically processed the data at 6am so that reports were ready for review when the analyst arrived at the office. After three months we converted to weekly interrogation since the system had proven to operate very reliably, and this reduced validation labor by a factor of five. The down side is that if a problem does develop, it may be several days before it is identified and corrected.

Validation flags are set for each parameter and observation. The flags indicate if everything is OK or if a parameter is missing, outside the established ranges, or fails a reasonableness check. When a flag is set the entire record for the time interval is printed in the validation report, so that the analyst is alerted to the problem and can see if other channels are affected as well. If there are no validation flags set, the program still prints out the results of the statistical analysis and the graphical analysis for review.

This has proven to be an effective method of keeping on top of the data flow, since voluminous validation reporting is provided only when problems exist. Otherwise the report is approximately 10 pages, allowing the analyst to validate the incoming data in as little as 5 minutes. When problems are identified it may take upwards of an hour to review and diagnose problems.

# RESULTS

To date the data capture rate has been excellent, approaching 99% of available time series records obtained in the first nine months of data collection. Five types of problems have occurred to make the capture less than perfect: (1) in three cases momentary power outages caused single 15 minute records to be lost for one or more of the loggers, (2) in one case two loggers were shut off for a week while HVAC equipment was being replaced in the penthouse, (3) in another case the power was inadvertently interrupted to two of the loggers by the operations personnel causing us to post large signs at these loggers to warn staff not to disrupt power, (4) one temperature channel failed and was corrected by moving the measurement to another logger channel, and (5) the insertion flowmeter for steam measurement failed by losing several of the fins on the turbine, this was corrected by installing a vortex shedding type meter that can handle possible slugs of water as the boilers are fired-up.

Approximately 5% of the time series records have validation flags set for one or more channels. This is felt to be an acceptable level of potential problem reporting. These records have been reviewed and found to be correct nearly all of the time, the flags being set due to transient or known data problems. The known data problems to date include: (1) the condensate return sensor was inadvertently installed on a pipe that employs a bypass system, making it impossible to rigorously compare the heat released by the condensate to the measured steam production rate, (2) the steam flow turbine meter was down for weeks for factory repair and

***Figure 4.*** *Sample Statistical Validation Report*

Federal Building All Data Summary

| N Obs | Variable | Label | N | Minimum | Maximum | Mean | Std Dev |
|---|---|---|---|---|---|---|---|
| 13645 | C580 | SUPH-10 - kVA | 13643 | 0 | 3.9465000 | 1.2338144 | 1.7635023 |
| | C581 | XPH-10 - kVA | 13643 | 0 | 2.4810000 | 0.7647104 | 1.0924336 |
| | C502 | Penthouse Outside Air Temp - deg F | 12881 | 44.9270000 | 82.0650000 | 57.9794052 | 5.0869753 |
| | C503 | Penthouse OA Relative Humidity - %RH | 12881 | 7.2750000 | 97.2910000 | 72.0568439 | 16.7190577 |
| | C504 | PH-10 Mixed Air Relative Humidity - %RH | 12881 | 12.4080000 | 91.9830000 | 59.4794102 | 15.5592579 |
| | C505 | PH-10 Mixed Air Temp - deg F | 12881 | 51.4170000 | 88.3750000 | 64.3993757 | 5.9304466 |
| | C506 | PH-10 Supply Air Relative Humidity - %RH | 12881 | 12.7590000 | 97.0910000 | 56.6496874 | 14.3745672 |
| | C507 | PH-10 Supply Air Temp - deg F | 12881 | 55.7440000 | 150.0310000 | 72.3008883 | 9.0048321 |
| | C509 | PH-10 Return Air Relative Humidity - %RH | 12881 | 12.4840000 | 90.2800000 | 57.2847836 | 14.6702524 |
| | C510 | PH-10 Return Air Temp - deg F | 12881 | 51.8680000 | 79.4510000 | 64.8996246 | 5.5378000 |
| | C599 | Resistance Check 3197 | 12881 | 2.9950000 | 2.9990000 | 2.9972577 | 0.000591858 |
| | C603 | SSBE-2 Outside Air Temp - deg F | 13638 | 45.5580000 | 81.7940000 | 57.5577162 | 5.0114303 |
| | C604 | SSBE-2 Outside Air Relative Humidity - % | 13638 | 7.7010000 | 98.8940000 | 74.5676447 | 16.0013183 |
| | C605 | SSBE-2 ADMAT - deg F | 13638 | 49.9660000 | 85.6800000 | 60.3942667 | 4.9280237 |
| | C606 | SSBE-2 MARH - %RH | 13638 | 7.3000000 | 94.9870000 | 67.4276763 | 14.3956356 |
| | C607 | SSBE-2 MAT - deg F | 13638 | 50.5150000 | 85.1300000 | 60.6943634 | 4.8067510 |
| | C608 | SSBE-2 ADCSAT - deg F | 13638 | 46.7210000 | 78.6130000 | 59.3380821 | 3.3311526 |
| | C609 | SSBE-2 CSARH - %RH | 13638 | 13.2100000 | 96.5900000 | 63.0030577 | 15.5399251 |
| | C610 | SSBE-2 CSAT - deg F | 13638 | 48.7130000 | 77.5580000 | 61.0862052 | 3.6148958 |
| | C611 | SSBE-2 ADHSAT - deg F | 13638 | 51.6070000 | 114.6690000 | 71.6205193 | 15.1137344 |
| | C612 | SSBE-2 HSARH - %RH | 13638 | 7.8760000 | 92.3830000 | 49.7311646 | 22.8371101 |
| | C613 | SSBE-2 HSAT - deg F | 13638 | 52.1380000 | 115.7770000 | 72.4186491 | 15.5030909 |
| | C614 | RSBE-3 RARH - %RH | 13638 | 11.2570000 | 85.9730000 | 53.4966180 | 14.2198904 |
| | C615 | RSBE-3 RAT - deg F | 13638 | 54.2110000 | 79.7210000 | 66.9887499 | 5.6478404 |
| | C616 | RSBE-4 RARH - %RH | 13638 | 12.2580000 | 85.8730000 | 54.0921957 | 14.2752975 |
| | C617 | RSBE-4 RAT - deg F | 13638 | 54.4820000 | 77.9180000 | 66.9711336 | 5.7555334 |
| | C699 | Resistance Check 3198 | 13638 | 2.9980000 | 3.0010000 | 2.9998210 | 0.000630441 |
| | C200 | Steam Mass Flow - lb/hr | 13643 | -14.5950000 | 27185.30 | 2072.92 | 3714.77 |
| | C201 | Condensate Water Flow - GPM | 13643 | -0.3750000 | 139.9090000 | 32.6694564 | 51.0749794 |
| | C202 | Condensate Water Temperature - deg F | 12280 | 128.0490000 | 218.7420000 | 175.4005594 | 32.7157836 |
| | C203 | Condensate Water Temperature Ck - deg F | 12280 | 81.1010000 | 219.4390000 | 170.9426673 | 39.9141754 |
| | V200 | Range check of c200 | 13006 | 0 | 0 | 0 | 0 |
| | V201 | Range check of c201 | 13006 | 0 | 0 | 0 | 0 |
| | V202 | Range check of c202 | 13006 | 0 | 2.0000000 | 0.3137014 | 0.7273478 |
| | V203 | Range check of c203 | 13006 | 0 | 2.0000000 | 0.3137014 | 0.7273478 |
| | C300 | Air Handler Fan SSBW-2 - kW | 13643 | 0 | 140.7260000 | 38.0702409 | 50.0640057 |
| | C301 | Air Handler Fan RSBW-3 - kW | 13643 | 0.2030000 | 43.2870000 | 10.7455674 | 15.0097236 |
| | C302 | Air Handler Fan RSBW-4 - kW | 13643 | 0.0900000 | 38.6140000 | 10.1636943 | 13.9403978 |
| | C380 | Air Handler Fan SSBW-2 - kVA | 13643 | 0 | 149.4330000 | 50.1268080 | 46.5202299 |
| | C381 | Air Handler Fan SSBW-2 - kVA | 13643 | 0.2940000 | 46.2530000 | 11.9137972 | 16.0950036 |
| | C382 | Air Handler Fan SSBW-2 - kVA | 13643 | 0.4150000 | 41.3140000 | 11.4829159 | 14.9891752 |
| | C303 | SSBW-2 Outside Air Temp - deg F | 13643 | 45.8280000 | 81.9750000 | 57.6809435 | 5.2207706 |
| | C304 | SSBW-2 Outside Air Humidity - %RH | 13643 | 7.4760000 | 97.8920000 | 73.5035878 | 16.0727598 |
| | C305 | SSBW-2 Duct Temp Mixed - deg F | 13643 | 50.0380000 | 85.0310000 | 60.6279370 | 5.0079210 |
| | C306 | SSBW-2 Duct Relative Humidity Mixed - %R | 13643 | 7.8010000 | 93.6850000 | 66.6881727 | 15.1764635 |
| | C307 | SSBW-2 Duct Temp Mixed- deg F | 13643 | 50.7860000 | 84.5890000 | 60.7663856 | 4.7001563 |
| | C308 | SSBW-2 Avg Duct Temp Cooling - deg F | 13643 | 51.0300000 | 80.0190000 | 61.5813081 | 3.2273664 |
| | C309 | SSBW-2 Duct Relative Humidity Cooling - | 13643 | 8.2270000 | 96.4900000 | 59.0135768 | 14.8545871 |
| | C310 | SSBW-2 Duct Temp Cooling - deg F | 13643 | 50.9660000 | 80.9830000 | 62.5748157 | 3.2913657 |
| | C311 | SSBW-2 Avg Duct Temp Heating - deg F | 13643 | 52.1120000 | 140.8460000 | 73.0519721 | 16.7599347 |
| | C312 | SSBW-2 Duct Relative Humidity Heating - | 13643 | 6.4490000 | 92.1830000 | 48.7907993 | 22.1054591 |
| | C313 | SSBW-2 Duct Temp Heating - deg F | 13643 | 53.4900000 | 142.6390000 | 74.8037233 | 16.8176842 |
| | C314 | RSBW-3 Duct Relative Humidity - %RH | 13643 | 13.4600000 | 88.6780000 | 54.1292131 | 14.2151134 |
| | C315 | RSBW-3 Duct Air Temp - deg F | 13641 | 52.6790000 | 79.0900000 | 67.9378816 | 6.0772179 |

subsequent replacement with a different meter, and (3) the temperature sensor for one of the condenser returns was out for five days due to an apparent problem with the data logger channel.

With weekly polling of the data loggers, the data validation labor is approximately 8 hours per month for the 100 measured channels and 170 computed parameters. The resultant data files are approximately 10 megabytes per month. Problem diagnosis and resolution has required approximately 16 hours per month, however this is expected to diminish as we learn from experience and become more aware of potential problem areas and mitigation methods.

## CONCLUSIONS

The software system implemented for this project is efficiently and effectively building an archive of verified data that establishes the baseline energy performance of the building's energy systems. The use of off-the-shelf applications software in a desktop computing environment has proven to be more than adequate to meet the ambitious data collection and validation goals. Having developed this system in a generic fashion, we expect the incremental costs of implementing it for other buildings to be very low, bringing data collection and validation costs in line with the costs of renting and installing the necessary metering equipment.

## ACKNOWLEDGMENTS

This work involves the contributions and efforts of many individuals and organizations. Steve Blanc of PG&E and Terry Pierce of GSA were instrumental in establishing and managing this project. Ken Gillespie of PG&E and Roger Lippman of New Horizon Technologies developed the measurement plan and selected and installed the metering equipment. Mike Baker and Rich Mazzucchi of SBW Consulting, Inc. designed and implemented the data processing and validation procedures. Finally we acknowledge the efforts of the ASHRAE members responsible for developing the BACnet standard that is the subject of this investigation.

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