# HARVEY MUDD COLLEGE CLINIC PROJECT – LEED BUILDING RECOMMISSIONING

*HT10SCE2100 Report*

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Southern California Edison's Design & Engineering Services (DES) group is responsible for this project. It was developed as part of Southern California Edison's HVAC Technology and Systems Diagnostics Advocacy (HTSDA) program under internal project number HT10SCE2100. DES project manager Brian James conducted this study with overall guidance and management from Jerine Ahmed. For more information on this project, contact brian.james@sce.com.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ° | Degree |
| AHU | Air handler unit |
| CAV | Constant air volume |
| Cfm | Cubic feet per minute |
| $CO_2$ | Carbon Dioxide |
| F | Fahrenheit |
| HTSDA | HVAC Technologies and Systems Diagnostics Advocacy |
| HVAC | Heating, ventilating, and air condition |
| LEED | Leadership in Energy and Environmental Design |
| MHz | Mega Hertz |
| Ppm | Parts per million |
| Rpm | Revolutions per minute |
| SCE | Southern California Edison |
| USGBC | US Green Building Council |
| VAV | Variable air volume |

# FIGURES

# TABLES

# CONTENTS

# EXECUTIVE SUMMARY

The main objective for this project is to gain a better understanding of the degradation of high performance buildings over time through the process of recommissioning. Recommissioning is the systematic investigation process for improving or optimizing a building's operation and maintenance.

The project consists of leading a team of students at Harvey Mudd College through the recommissioning process of the Hoch-Shanahan Dining Hall at Harvey Mudd College. The dining hall was constructed in 2005 as a Leadership in Energy and Environmental Design (LEED) Silver Certified building. Work was performed through Harvey Mudd College's Clinic Program, which seeks to provide senior-level students with real world work exposure by collaborating on a project with a company looking to leverage the students to assist in solving real-world applications.

Review of utility bills indicated a slight decrease in the building's historical energy consumption from 2005 to 2007, down as much as 2.2% from 2006 to 2007. However, the utility bills indicates a steady increase in energy consumption from 2008 to 2010, raiing 3.0% in the 2008-2009 school year and 5.7% in the 2009-2010 school year relative to the inaugural school year in 2005-2006. However, the building's actual energy consumption has been consistently more than double the predicted energy consumption from the design phase. This is due in large part to the fact that the design phase tool modeled the building's energy consumption without kitchen equipment.

The team performed the following tasks in order to identify potential building equipment and operational inefficiencies:

- Collected power demand and energy consumption data on 16 building components,
- Performed a lighting audit of the facility,
- Identified and itemized the kitchen equipment,
- Conducted an analysis of the building management system,
- Tested the functionality of the $CO_2$ sensors, and
- Performed a partial air and water balance of the heating, ventilation, and air conditioning (HVAC) system.

The systematic process of recommissioning was used to assess the current operating conditions of the Hoch-Shanahan Dining Commons. Due to the lack of availability of historical building performance data, no concrete conclusions could be made about the degradation of the building's performance. It is clear that the building consumes more energy than predicted during the design phase and seems to be trending upward when analyzing the historical utility bills. This upward trend may be also due to the increase occupancy of the dining hall. Regardless, the Clinic team developed several recommendations to the building's current operations that will undoubtedly improve the overall performance of the building.

In light of the findings of this project, the team has developed a list of recommendations for improving building comfort, operation and efficiency. Since the project was focused on the HVAC system, most of the improvements impact the HVAC system. Below is the list of recommendations as well as details on how it will affect the building.

1. Perform air volume balance of all air handling units
2. Tune control sequence to better respond to building state by hiring a contractor familiar with current Andover systems, or replace existing control system
3. Raise carbon dioxide ($CO_2$ setpoint in software to 800 parts per million (ppm)
4. Replace $CO_2$ monitors
5. Update kitchen hoods to demand controlled technology
6. Clean or replace exhaust fans
7. Ensure air handler unit 2 (AHU 2) supply fan turns off completely at night
8. Purchase more energy efficient kitchen appliances
9. Continuous software/power monitoring

The team expects that implementing changes to the entire building could lead to a 10% reduction in energy usage, resulting in approximately $6,000-$7,000 annually in energy cost savings.

# INTRODUCTION

The project consists of leading a team of students at Harvey Mudd College (HMC) through the recommissioning process of the Hoch-Shanahan Dining Hall at Harvey Mudd College, a Leadership in Energy and Environmental Design (LEED) Silver Certified building. Work was performed through Harvey Mudd College's Clinic Program, which seeks to provide senior-level students real world work exposure by collaborating on a project with a company looking to leverage the students to assist in solving real world applications. Southern California Edison (SCE) tasked the Harvey Mudd Clinic team to recommission the Hoch-Shanahan dining hall building in order to gain a better understanding of the degradation of high performance buildings over time. The project was constrained to the two semester school year.

Recommissioning can be defined as the systematic investigation process for improving or optimizing a building's operation and maintenance. It may or may not emphasize bringing the building back to its original intended design. The goal of the process most often focuses on dynamic energy-using systems with the goal of reducing energy water, obtaining energy cost savings, and identifying and fixing existing problems[i]. The process of recommissioning and retrocommissioning is typically the same except retrocommissioning is applied to a building that was never commissioned.

This project aims to determine how the building is operating with respect to original design and as-built specifications. Power meters were installed to measure the overall building's energy consumption and power demand as a means to determine the building's current performance level. Additional meters were also installed to measure energy consumption and power demand of the kitchen, lighting system, and heating, ventilation, and air conditioning (HVAC) system. The demand profiles from the meters were analyzed for anomalies and operational deficiencies.

The students were instructed by SCE staff to emphasize their analysis on evaluating and optimizing of the building's unique HVAC system, highlighted by a displacement ventilation system that provides cool air to the dining occupants. The result was a detailed analysis of each of the five air handler units (AHUs), analysis of the building management system software, an air and water balance report to determine the current "as is" building operation, and a survey of building occupant comfort.

The projects overall goal is to provide the necessary recommendations to bring the building back to its original intended design.

# BACKGROUND

The Hoch-Shanahan Dining Commons was designed by Mazzetti & Associates and constructed in 2005. The building was built to follow the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) for New Construction Green Building Rating Supply System.

The 26,500 square feet (sf) facility includes five AHUs, photosensor-controlled lighting in the atrium, a white ENERGY STAR™ roof, and carbon dioxide sensors for enhanced indoor air quality. As designed, the building was projected to save 44.1% over a standard Title 24 building. The floor plan of the facility is depicted in Figure 1.

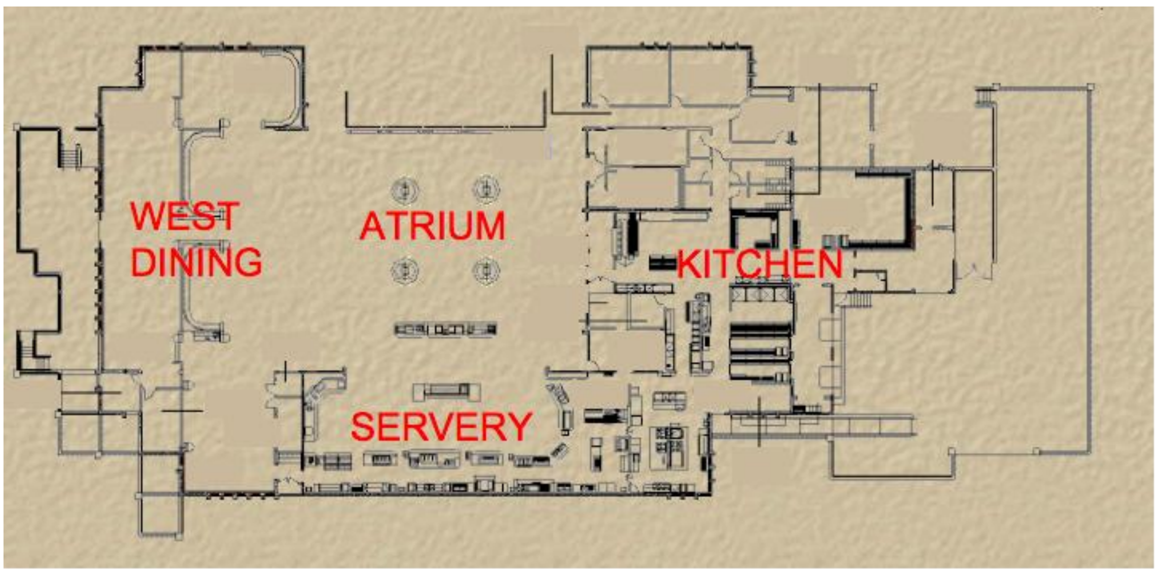



**FIGURE 1 HOCH-SHANAHAH DINING COMMONS FLOOR PLAN**

The dining hall provides ample opportunities to allow SCE to gauge how a high performance building has degraded in the few short years after its inception. Also, the project provides avenues for SCE to educate and train future members of the workforce on sustainable and integrated building design, energy efficiency, and building diagnostics and to provide them with real world work experience and tools that can be used in their future careers.

# OBJECTIVES

The main objective for this project is to guide the Clinic team through the process of recommissioning to gain a better understanding of the degradation of high performance buildings over time. To accomplish this, the following objectives were established:

- Collect historical building information, including
    - Previous air balance reports
    - Previous commissioning reports
    - LEED certification documents
    - As-Built building drawings
    - Building energy model
    - Historical energy consumption data
- Develop monitoring plan
- Install monitoring equipment
- Conduct an air and water balance study
- Analyze building performance data
- Make recommendations to bring the building back to its as-built specifications

# TECHNICAL APPROACH

The technical approach to this project is to follow a systematic process of recommissioning in order to evaluate the Hoch-Shanahan Dining Commons. The team was provided the Portland Energy Conservation, Inc. *Retrocommissioning Handbook for Facility Managers* as a basis for the technical approach for this project. The handbook states that there are six steps to retrocommissioning; project selection, planning phase, investigation phase, final adjustment, and project hand-off. The Clinic team revised these steps as follows to better fit this individual project:

1. Gather Information
2. Set Goals and Define Scope
3. Monitoring and Analysis
4. Recommendations
5. Final Adjustment and Re-monitoring
6. Final Documentation

Recommissioning begins with a rigorous collection of building information. This includes construction documents, control system information, building modeling, LEED certification documentation (if applicable), and hardware specifications. After this information is collected and reviewed, the scope of the project can be defined and the objectives identified.

The most crucial step in the process is the monitoring and analysis stage. The appropriate data must be collected so that inefficiencies and anomalies can be identified and investigated. From this analysis, a possible list of improvements and recommendations can be made. The next step in a systematic recommissioning process is to make appropriate changes and re-monitor to see if the desired results were obtained. Because of the limited timeline of this project, this step was outside of the scope for the team. Instead of making changes and re-monitoring, the team decided to provide recommendations to the college's Facilities and Maintenance Office (F&M) based on the findings from the analysis, feasibility of implementation, and economic analysis. Therefore, step 5 was not included in this report. The following sections detail the recommissioning process performed by the team as well as document observations and recommendations.

## GATHERING INFORMATION

Once the site was selected, the recommissioning process began with gathering information about the building. To initiate this process, the team contacted Harvey Mudd College's F&M to gather any information about the Hoch-Shanahan Dining Commons. The team also contacted the building's design-build firm Mazzetti & Associates, the original commissioning agent CTG Energetics, and the Hoch-Shanahan Dining Commons staff to get further building documentation. The process was not trivial as multiple attempts were made to establish contact with these entities. Some of the documentation did not arrive until the end of the first semester. The following list shows the information the team was able to obtain throughout the course of this Clinic project with the sources in parentheses:

- LEED Scorecard (HMC F&M) – See Appendix C
- Control System Sequence of Operation (Mazzetti & Associates)
- Lighting Schedules (HMC F&M)
- Building energy model output file (CTG Energetics)
- LEED certification submittal (CTG Energetics)
- List of kitchen inventory (Hoch-Shanahan Commons staff) – See Appendix D
- HVAC Analysis Test (HMC F&M)
- HVAC Control software applet (HMC F&M)
- Historical energy consumption data (HMC F&M)

This information was useful in defining the scope and executing the recommissioning process. There was, however, some documentation about the building energy model that was missing in the analysis and would have been helpful in comparing the building to its original state. The team had access to the output file for the energy simulation; however, the team did not have access to the necessary input files to analyze the parameters of the modeled building. The results from the output file are broken down into lighting, space cooling, pumps, exhaust fans, and miscellaneous equipment.

# SET GOALS AND DEFINE SCOPE

The information gathered in the first step was used to define the scope and set the goals for the project. Refer to the Introduction and Objectives sections for further details.

# MONITORING AND ANALYSIS

The primary tasks for this step were to understand how and why building systems were being operated and maintained, and to identify deficiencies and potential improvements. A Master List of Findings was developed in this step. The Clinic team was then tasked with determining final recommendations based on the most the projected cost savings. The Clinic team established a monitoring plan to examine the following areas for analysis: Power Monitoring of Building Components, Lighting Audit, Air and Water Balance, Control Software Monitoring, and $CO_2$ Sensor Testing.

## POWER MONITORING OF BUILDING COMPONENTS

Several circuits in the building were monitored over a period of 9 to 16 weeks. The monitoring period fluctuated due to equipment availability. This data was useful in evaluating building operation and checking for broken or malfunctioning equipment. Based on observations, building drawings and discussions with the building manager and SCE engineers, the team chose 16 building circuits to monitor. These circuits were categorized into four main categories: Whole Building (1 circuit), Lighting (3 circuits), Kitchen (1 circuit), and HVAC (11 circuits). All 16 circuits were accessed in the main electrical room on the east side of the building, allowing for the monitors to be placed in a centralized location for easier installation and access. There were approximately 225 circuits that could have been monitored. The majority of these were captured by monitoring the entire panel that encompassed the circuits (i.e.

Kitchen panel). The remaining circuits were captured by monitoring the main switch to the building.

The Whole Building circuit was important to monitor to track miscellaneous loads not captured through the other 15 circuits. The entire lighting panel was monitored to compare the original lighting specifications to current performance. Two other lighting circuits, both in the sun-lit atrium area, were chosen to evaluate the effectiveness of the photosensors that control the atrium lights. The kitchen panel was selected since the kitchen was predicted by the team to be a major fraction of the building's power consumption. Sub-metering individual appliances would have been useful to evaluate the efficiency of the appliances and develop detailed savings potential for the kitchen, but the team emphasized their monitoring tactics on the HVAC system and relied on the nominal power rating to estimate appliance power consumption. Nominal power ratings are given in the HVAC and Kitchen Equipment list in Appendix D.

Once the monitoring plan was established, the team hired a qualified electrical contractor to install 10 Dranetz PowerVisa® monitors. The PowerVisas were chosen due to their accuracy (0.15%), ability to handle high harmonic environments, and for their physical differential inputs making it possible to monitor multiple circuits on an individual monitor. The current transducers (CTs) were chosen based on the rated amp capacity of each circuit. The CTs used include the DranFlex 3003XL24 (30, 300, and 3,000 amp settings) at 1.1-2% accuracy, TR2510A (10 amp) at 1.2-2% accuracy, and TR2550A (100 amp) at 1% accuracy. Table 1 shows the instrumentation plan including circuits monitored, circuit rating, equipment selected, and full scale accuracy. The full scale accuracy is determined by the summation of the accuracy for the power meter and the CT. Since the CTs provide a range of accuracy, the largest percentage is assumed.

**TABLE 1. INSTRUMENTATION PLAN AND MONITORING EQUIPMENT SPECIFICATIONS**

| CIRCUIT DESCRIPTION | PANEL LOCATION | CIRCUIT RATING | MONITOR SELECTED (SERIAL #) | CT MODEL (AMP RATING) | FULL SCALE ACCURACY |
|---|---|---|---|---|---|
| Whole Building | MS | 277/480V 800A | PowerVisa (PVUSFA169) | DranFlex 3003XL24 (300A) | 2.15% |
| Lighting Panel | LP1 | 277/480V 150A | PowerVisa (PVUSFA170) | TR2550A (100A) | 1.15% |
| Atrium Highbay | LP1-3 | 277/480V 20A | PowerVisa (PVUSFA171) | TR2510A (10A) | 2.15% |
| Atrium Up Lights | LP1-7 | 277/480V 20A | | TR2510A (10A) | 2.15% |
| Kitchen Panel | DBKP | 120/208V 400A | PowerVisa (PVUSFA172) | DranFlex 3003XL24 (300A) | 2.15% |
| Private Rooms AHU 3 Return Fan | DBM 13/15/17 | 277/480V 15A | PowerVisa (PVUSFA173) | TR2510A (10A) | 2.15% |
| West Dining AHU 1 Return Fan | DBM 19/21/23 | 277/480V 20A | | TR2510A (10A) | 2.15% |
| Servery Kitchen AHU 4 Fan | DBM 31/33/35 | 277/480V 25A | PowerVisa (PVUSFA174) | TR2510A (10A) | 2.15% |
| Dining Atrium AHU 2 Supply Fan | DBM 37/39/41 | 277/480V 40A | | TR2550A (100A) | 1.15% |
| Exhaust Fans 1,2,3,5 Kitchen Hoods | DBM 2/4/6 | 277/480V 15A | PowerVisa (PVUSFA175) | TR2510A (10A) | 2.15% |

| | | | | | |
|---|---|---|---|---|---|
| Exhaust Fan 13 Kitchen Hood | DBM 8/10/12 | 277/480V 15A | | TR2510A (10A) | 2.15% |
| Exhaust Fan 9 Restrooms | DBM 14/16/18 | 277/480V 15A | PowerVisa (PVUSFA176) | TR2510A (10A) | 2.15% |
| Dining Atrium AHU 2 Return Fan | DBM 20/22/24 | 277/480V 20A | | TR2510A (10A) | 2.15% |
| Prep Kitchen AHU 5 Fan | DBM 26/28/30 | 277/480V 25A | PowerVisa (PVUSFA177) | TR2510A (10A) | 2.15% |
| Private Rooms AHU 3 Supply Fan | DBM 32/34/36 | 277/480V 30A | | TR2510A (10A) | 2.15% |
| West Dining AHU 1 Supply Fan | DBM 38/40/42 | 277/480V 60A | PowerVisa (PVUSFA178) | TR2550A (100A) | 2.15% |

Refer to the Dranetz PowerVisa Technical Specifications sheets in Appendix E for more information.

The monitors were setup to log amps, volts, power factor, and watts every 10 minutes with a sampling rate of 256 times per cycle.

The electrical contractor installed the power monitoring equipment using the appropriate personal protection equipment on December 8, 2010.

## Lighting Audit

In addition to power monitoring, the team performed a lighting audit of the facility to determine the existing lighting strategies employed by the facility. The lighting audit was performed by an SCE Technical Specialist with many years of experience conducting lighting audits.

In addition, the Clinic team collected illumination data using a heavy duty data logging light meter from Extech Instruments. It measures illumination in lux (lumens per square meter) from 0 to 4,000 with a resolution of 1 lux and an accuracy of 5%. In the fall semester, lighting analysis was performed based on the specified lighting schedule and illumination in the dining areas to get a better understanding of how the lighting system was functioning.

## Building Management System

The building management system control software was analyzed for sequence of operation and functionality. The HVAC and lighting systems are all controlled remotely through the HMC MasterFrame computer monitoring program. This program allows the user to make any necessary modifications to how the systems are being used, such as changing thermostats. The program records outdoor and indoor air temperature, indoor carbon dioxide levels, humidity, fan speed, and the operational temperatures of the cooling and heating coils. The lighting system is activated by an employee of the Hoch-Shanahan Dining Commons and is then controlled on a scheduled basis by a computer program. The control software has the ability to monitor and store several data points. This includes damper positions, outside air temperature, economizer setpoint, return air temperature, return air $CO_2$, fan speeds, mix air temperature, mix air setpoint, static pressure, filter pressure, room $CO_2$, room humidity, supply air temperature, hot/cold supply water temperature, hot/cold supply water setpoint, and hot/cold water valve position.

Data was collected from the software applet by interacting with managers of the software at the Claremont University Consortium. The data points selected to be logged were room $Co_2$ levels for the Atrium and West Dining areas, room temperatures for all air handler units (AHUs), and fan speeds of all AHUs. This data was used to analyze the control sequence of operations.

### AIR AND WATER BALANCE

A National Environmental Balanced Bureau (NEBB) certified contractor performed an air and water balance of the Hoch-Shanahan Dining Commons. The contractor was only to collect information on how the building was operating and was instructed by F&M staff not to make any adjustments. Additionally, the contractor provided recommendations for HMC to consider.

The contractor conducted the analysis following the protocol given in Section 8 "Air System TAB Procedures" and Section 9 "Hydronic System TAB Procedures" from *Procedural Standards for Testing Adjusting and Balancing of Environmental Systems 7$^{th}$ Edition* by NEBB. This document sets standards for instrumentation and calibration and provides a systematic procedure for testing, balancing, and adjusting air and water systems.

## RECOMMENDATIONS

The objective of this step was to determine the most cost-effective opportunities to recommend for implementation to the Hoch-Shanahan Dining Commons. Due to the many interactive effects in the dining hall, the economic analysis was kept to simplified savings percentages for each end-use.

## FINAL DOCUMENTATION

A recommissioning provider prepares a final report. In the case of this project, the students on the Harvey Mudd College Clinic team prepared a final report that detailed the project background, objectives, technical approach, results, and recommendations. The information from the student's report was used to write this report.

# RESULTS AND ANALYSIS

## DESIGN PHASE BUILDING SIMULATION ENERGY CONSUMPTION PREDICTIONS

During the design phase of the Hoch-Shanahan Dining Hall, the building energy modeling tool eQuest was used to predict the energy consumption of the building. Table 2 shows the predicted electrical energy consumption by end use as reported in the output file from the modeling tool.

TABLE 2. DESIGN PHASE BUILDING SIMULATION ENERGY CONSUMPTION PREDICTIONS USING EQUEST

| | SPACE COOLING | HEAT REJECTION | LIGHTS | PUMPS | VENT FANS | MISCELLANEOUS EQUIPMENT | **TOTAL** |
|---|---|---|---|---|---|---|---|
| **Electricity Consumption (MWh)** | 57.70 | 4.12 | 67.22 | 21.66 | 85.89 | 35.42 | **271.98** |
| **Electricity Consumption (%)** | 21% | 2% | 25% | 8% | 31% | 13% | **100%** |

## HISTORICAL WHOLE BUILDING ELECTRICAL CONSUMPTION

The historical energy consumption from 2005 to 2010 was obtained and displayed in Figure 2.

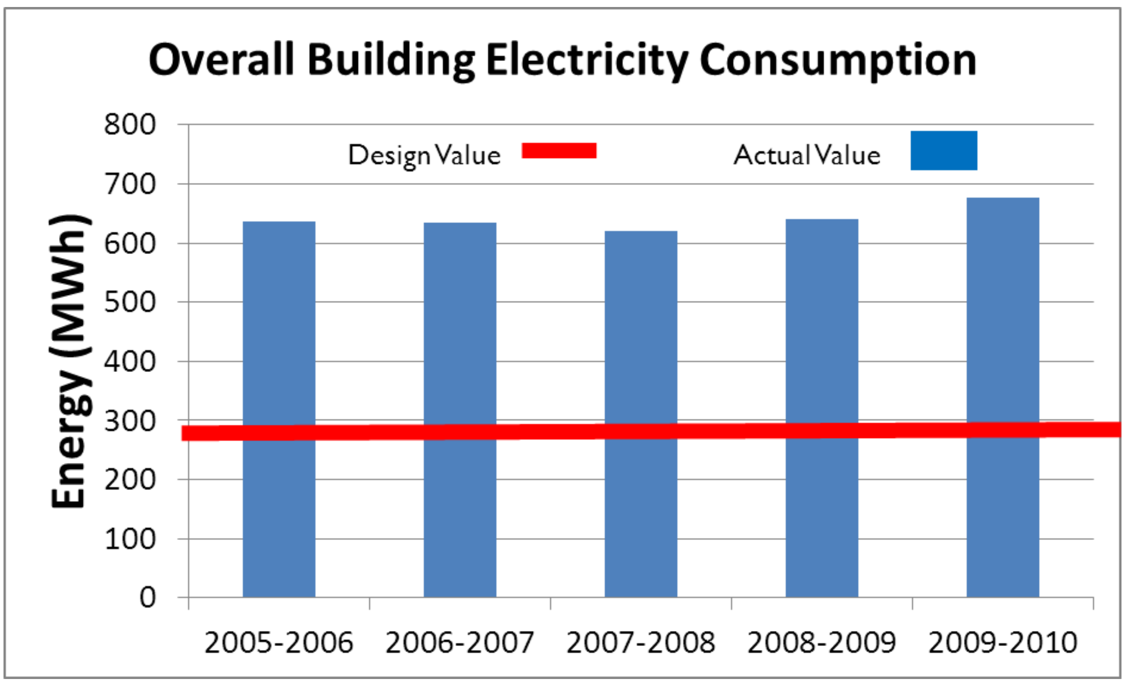



FIGURE 2. WHOLE BUILDING ENERGY CONSUMPTION FROM 2005 TO 2010

The chart indicates a slight decrease in energy consumption from 2005 to 2007, down as much as 2.2% from 2006 to 2007. However, the chart indicates a steady increase in energy consumption from 2008 to 2010, raising 3.0% in the 2008-2009 school year and 5.7% in the 2009-2010 school year. Additionally, these values are consistently more than double the design value, which was the estimated building's energy consumption from the building energy model. The students investigated the reason for the large difference between the design value and the historical data. It was determined the cause was primarily because the kitchen appliances were not included in the design model.

The team also ascertained the dining hall's historical customer occupancy from July 2008 through May 2010. Figure 3 shows the monthly energy usage per person. This graph indicates that there has been little change in monthly energy usage per person using the hall, so the increase in energy consumption from 2007 to 2009 is likely due to increased use of the building rather than efficiency degradation or deficiencies in operation. Additional whole building charts are available in Appendix A.

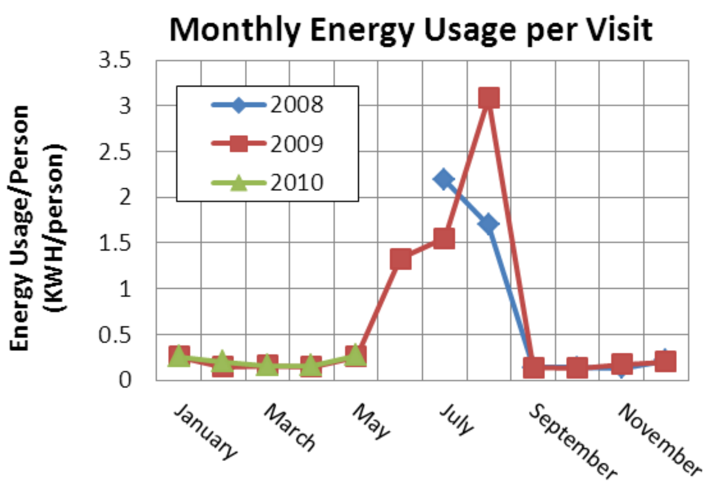



**FIGURE 3. MONTHLY ENERGY USAGE PER VISIT**

# POWER MONITORING – WHOLE BUILDING AND END-USE

Using the data obtained from the power monitors, the students broke down the building's energy consumption into its major components to obtain a general picture of how each end-use was contributing to the overall energy usage of the building. Figure 4 shows how the total building electricity power consumption was distributed between the various systems for the week of February 14-21.

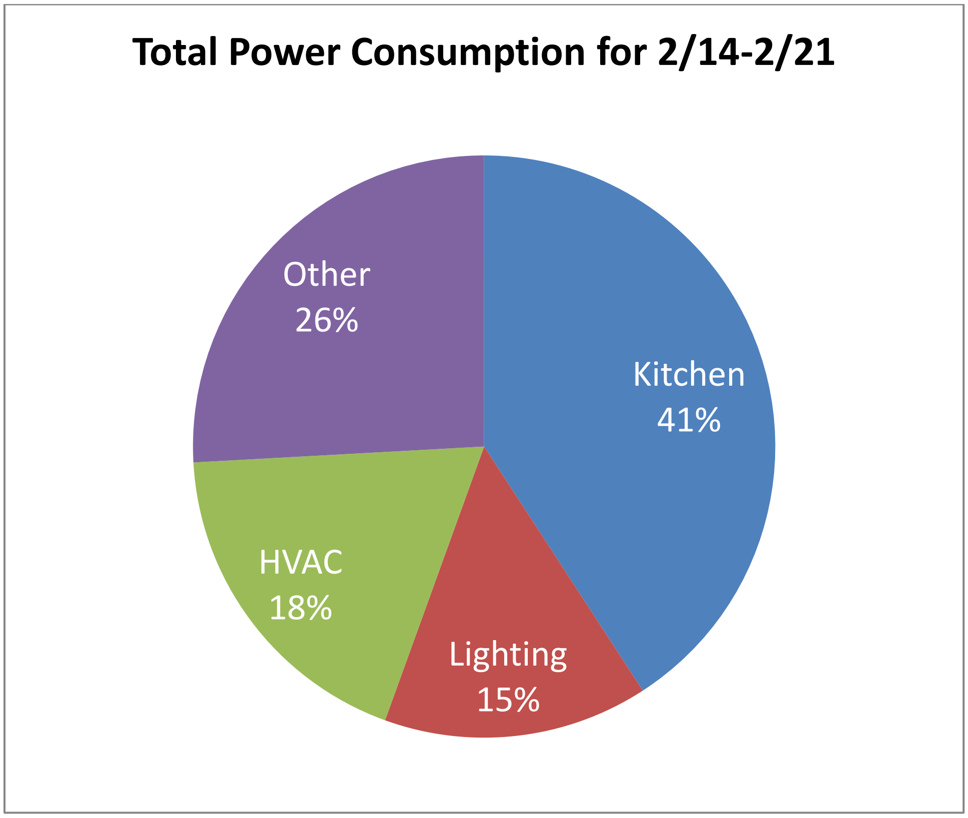



**FIGURE 4. BREAKDOWN OF TOTAL POWER CONSUMPTION AVERAGED OVER A WEEK**

The team gathered and analyzed data from a typical week to determine the relative usage of each of the main building components. The lighting fraction includes the entire lighting panel, and is within the expected range of a typical building. The HVAC fraction includes all of the AHU fans and exhaust fans monitored in Table 1. The kitchen fraction, composing the largest portion of the building's energy usage, includes all kitchen-related circuits, including kitchen appliances, dish washers and the refrigeration compressor rack. The 'Other' fraction was determined by subtracting the three other components by the data received from the 'Whole Building' monitor. This fraction includes three receptacle panels, various lighting circuits, fan coil units that serve the West Dining conference rooms, air curtains, trash compactors and hot water pumps.

It is important to note that this data was taken when the weather was relatively mild, and it is likely that the HVAC system consumes more power during the warmer summer months. However, peak cooling season in the dining hall may be offset by decreased heat loads from the kitchen due to minimal dining hall occupancy. Additional long-term monitoring would be necessary to determine the differences that occur based on weather conditions.

A comparison to the data in Figure 4 to the data in Table 2 shows significant differences in the breakdown of energy consumption by end use. It is clear that the kitchen load is significantly higher than predicted in the energy simulation. It is uncertain whether the simulation included kitchen appliances at all, since no clear definition of "miscellaneous equipment" could be obtained. The discrepancies between the simulation model and the measured results are likely due to inaccuracies in the assumptions in the simulation model, and less likely due to building degradation.

## KITCHEN

The usage trends for the kitchen were examined and allowed the team to gain insight into how the kitchen system responded to the varying demand levels throughout the day. The average weekday kitchen power consumption from February 5-20, 2011 was plotted and displayed in Figure 5.

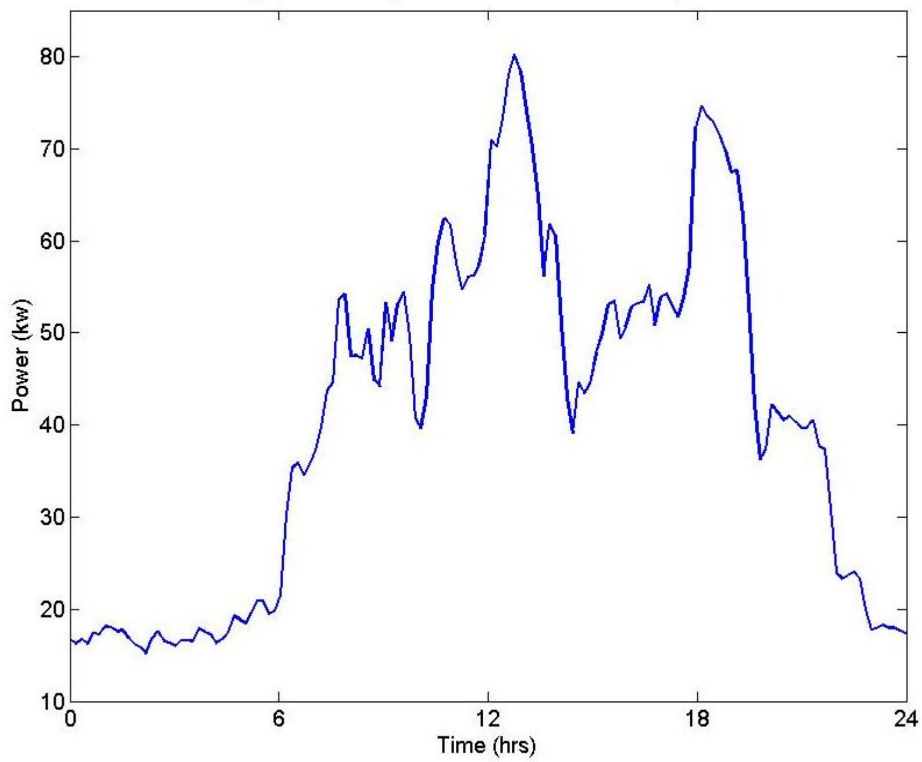



**FIGURE 5 AVERAGE WEEKDAY KITCHEN POWER CONSUMPTION, 2/15-2/24**

Figure 5 displays a general trend of what one would expect to see from the power consumption of a kitchen panel. A general upward trend throughout the day aligns with expectations as more and more appliances are needed for normal operation (cooking, displaying, serving food, as well as post-meal cleaning). Also, the peaks in power usages around 7:30 AM, 12:30 PM, and 6 PM occur slightly after the busiest times of each meal (breakfast, lunch and dinner, respectively), which is expected and possibly indicates that dishwashing and other cleaning duties associated with the end of each meal could account for a majority of the power on the kitchen panel.

Overall, the kitchen seemed to be operating as expected, with no immediately observable operational inefficiencies that could cause an increase in power consumption levels. There are potential energy savings that could be obtained by upgrading many of the appliances in the kitchen, but the team was not tasked with analyzing individual components within the kitchen. The team was able to compile a list of the main appliances within the kitchen and determine the power consumption for a select number. The HVAC and Kitchen Equipment List can be found in Appendix D.

## LIGHTING

The unique design of the Hoch-Shanahan's atrium and photosensor-controlled lighting system presented many interesting factors to consider in analyzing energy consumption and illumination data. Figure 6 shows the illumination levels during a sunny day in the dining areas. As expected, a large amount of daylighting in the atrium was observed.


**FIGURE 6. ILLUMINATION LEVELS IN THE DINING AREAS**

The power consumption data for the lighting panel was averaged over two weeks for weekdays and weekends. The weekend average power consumption values were normalized by the building's square footage to obtain a plot of Watts/square foot (W/sf) consumed by the Hoch-Shanahan's lighting system. Figure 7 shows the W/sf for the average weekday for January 18-February 4, 2011. The red line represents the designed watts/square foot value of 0.93 W/sf obtained from the original building energy model. As expected, the lighting system's power consumption drops during the day, although the levels still remain within a fairly narrow range throughout the day. The drop can be attributed to a photosensor placed in the southwest atrium window. The drop in consumption is limited due to the relatively few numbers of lights in the atrium area controlled by the photosensor.

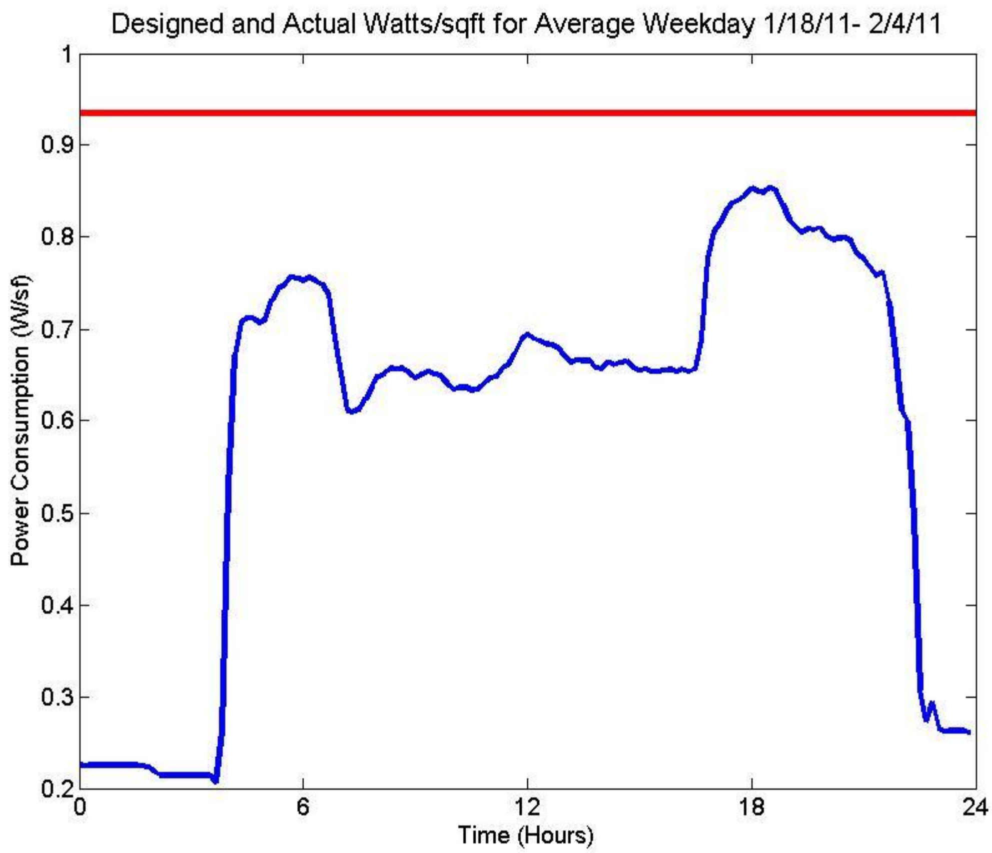



**FIGURE 7. DESIGNED AND ACTUAL LIGHTING WATTS/SF FOR AVERAGE WEEKDAY 1/18/11-2/4/11**

## HVAC SYSTEM

The Clinic team was instructed to focus much of their efforts on the HVAC system due to the unique design and complicated control system. The displacement ventilation system implemented in the Hoch-Shanahan is controlled through an Andover control system. It responds to changes in indoor air temperature and $CO_2$ levels, and works to maintain the building below the setpoint for each parameter through the use of chilled/heated water. The water is supplied from a central plant to heat or cool outside air as necessary before supplying the air to the dining hall.

The approach taken to analyze the HVAC system was to monitor the power consumption of the five AHUs as shown in Table 1 to gauge how the system was operating in response to peak meal times when the building occupancy and cooling demand were at their maximum. The Clinic team decided to draw the comparison between building occupancy, cooling demand, and HVAC system performance by comparing $CO_2$ levels, room temperature, and AHU fan power consumption.

The control system software was used to obtain $CO_2$ readings taken every ten minutes and overlaid with power consumption data for AHU 1 (West Dining area) and AHU 2 (Dining Atrium) over a given period of weekdays and weekends. The $CO_2$ level and power consumption data was then averaged over that time span to obtain both weekday and weekend $CO_2$ levels vs. power consumption plots. The plot for the West Dining area AHU 1 Return Fan is shown below Figure 8.

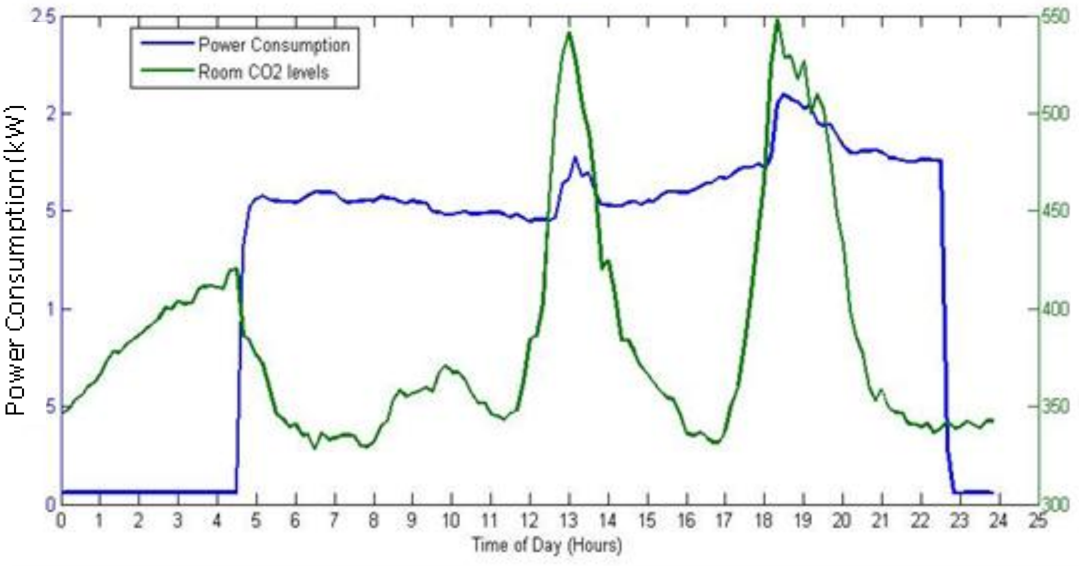



**FIGURE 8. POWER CONSUMPTION AND $CO_2$ LEVELS FOR WEST DINING AHU 1 RETURN FAN AVERAGED FROM 2/11/11 - 2/16/11**

For the most part, the plot matches what one would expect from the return fan. Its power consumption should ramp up significantly if the $CO_2$ levels exceed the setpoint of 530 parts per million (ppm), as it does briefly around 1:00 PM and 6:15PM Pacific Standard Time (PST). The peaks in room $CO_2$ levels seem to correspond with peaks in the power consumption of the supply fan, since the fan speed (and power consumption) must increase to remove the $CO_2$-rich indoor air from the building. This allows the supply fans to pump in fresh outside air (at a lower $CO_2$ concentration around 400 ppm) to reduce the indoor $CO_2$ level.

A similar plot of the weekday average $CO_2$ levels and power consumption vs. time, shown in Figure 9, was obtained for the West Dining AHU 1 Supply Fan, which further reinforces those findings. An interesting feature of both plots is the relationship between the $CO_2$ levels and fan power consumption between 2:00 PM and 5:00 PM. Even though the $CO_2$ levels are constantly decreasing over this interval (due to a sharp reduction in building occupancy during this time between meals), the supply fan power consumption continues to increase. Given the time of day, this is likely a result of larger heat loads from rising ambient temperatures. Both Figure 8 and Figure 9 indicate that the control system is responding appropriately to the indoor $CO_2$ levels.

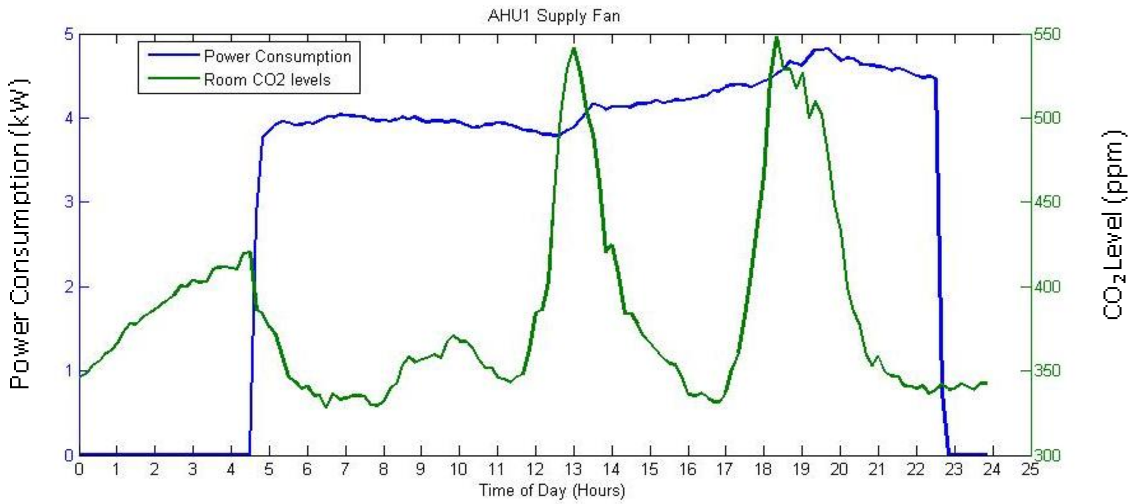



**FIGURE 9. POWER CONSUMPTION AND $CO_2$ LEVELS FOR WEST DINING AHU 1 SUPPLY FAN AVERAGED FROM 2/11/11 - 2/16/11**

To investigate further the performance of the control system, the team isolated and examined the HVAC system's response to room temperature changes throughout the day. Similar analysis techniques were carried out to obtain room temperature data. This included pulling the room temperature readings from the control system applet and the AHU return and supply fan power consumption data from the Dranetz power monitors, and average those values over a period of weekdays and weekends to obtain general trends for the response of the HVAC system to temperature changes. Figure 10 and Figure 11 depicts the relationship the team found between the indoor temperature and AHU power consumption for the supply and return fans for the West Dining area.

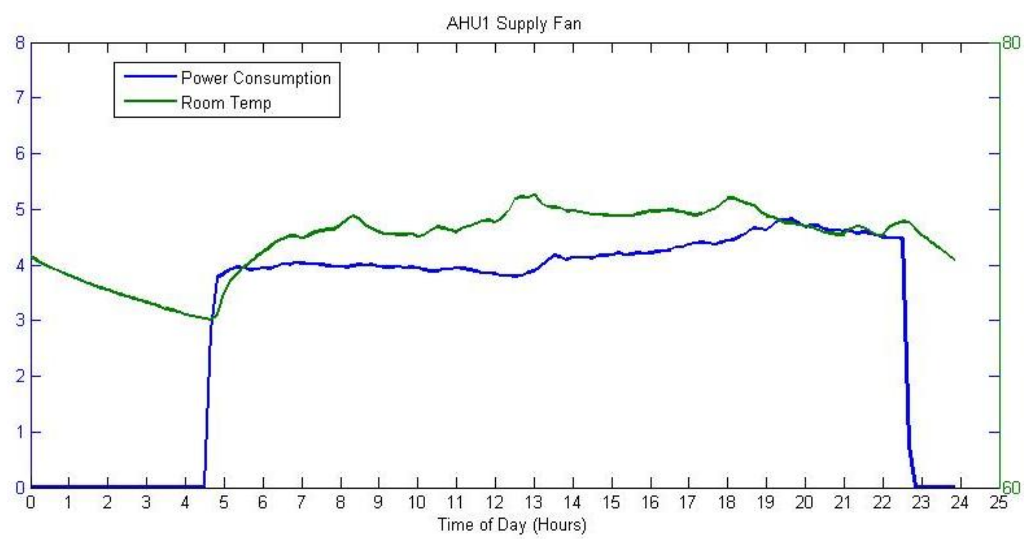



**FIGURE 10. ROOM TEMPERATURE AND POWER CONSUMPTION FOR WEST DINING AHU 1 SUPPLY FAN 2/11/11- 2/16/11**

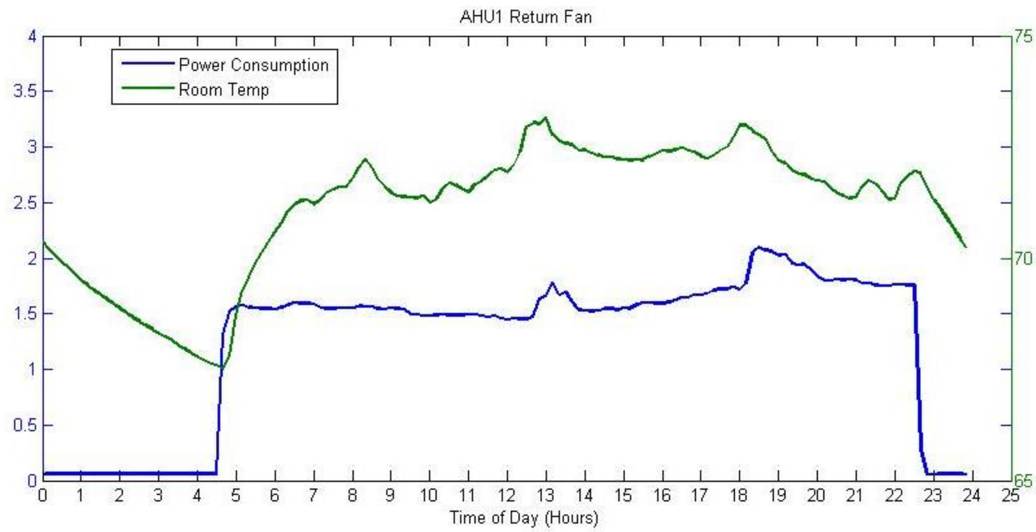



**FIGURE 11. ROOM TEMPERATURE AND POWER CONSUMPTION FOR WEST DINING AHU 1 RETURN FAN 2/11/11-2/16/11**

From Figure 10 and Figure 11, it is clearly shown that both the supply and return fan for West Dinging AHU 1 respond more to temperature than $CO_2$ levels. The power consumption characteristics observed here indicate that within the control system, the $CO_2$ levels affect the outside air dampers and the room temperature affects the fan speed. Examining the room temperature and fan power consumption data, we see that the system actually struggles to maintain the indoor temperature below the building's setpoint of 73°F during the day. Although the building is usually able to maintain the temperature within the specified three degree range of the temperature sensors, the building was slow to respond to changes in heating and cooling modes. This can be fixed by tuning the control system to cool the supply air more by opening the chilled water valve.

Next, the team examined the AHU systems individually to look for possible inefficiencies or anomalies within the power consumption data. AHU 1-3 (West Dining, Dining Atrium, Private Rooms) have supply and return fans, while AHU 4 and 5 each have only a dedicated supply fan – they serve the kitchen area and use the exhaust hoods in that section of the building as return fans. Shown in Figure 12 is a plot of the power consumption of the return fans for AHU 1-3 averaged over a period of ten weekdays.

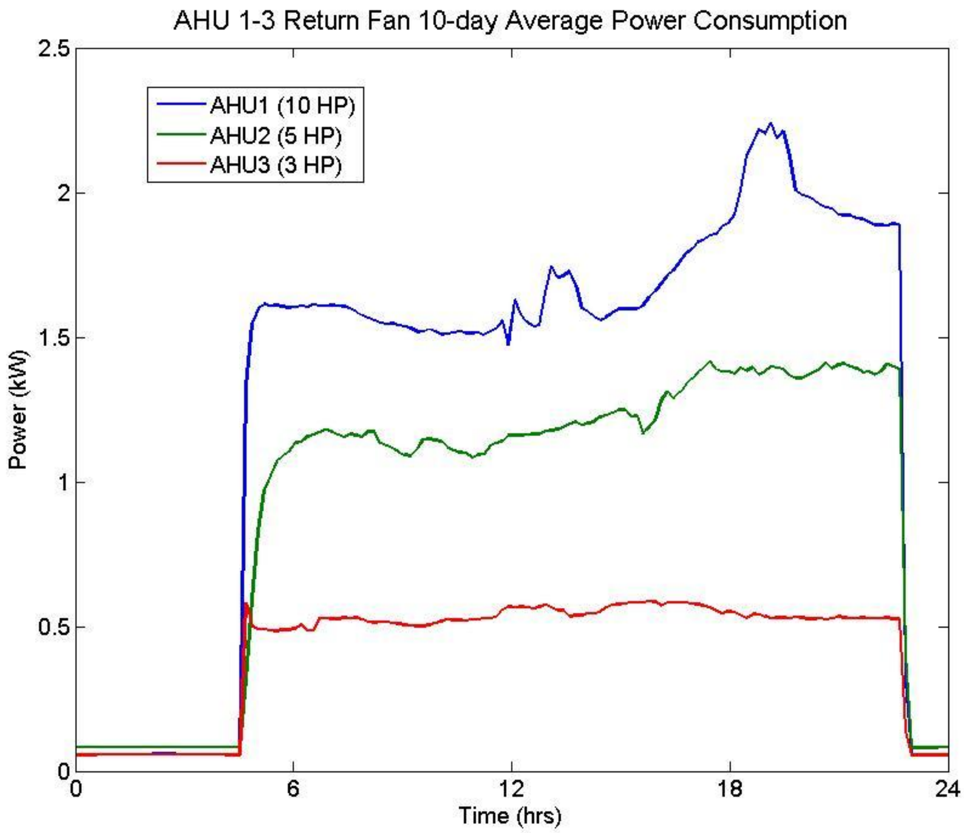



**FIGURE 12 . POWER CONSUMPTION FOR AHU 1-3 RETURN FANS AVERAGED OVER 10 WEEKDAYS**

The general shape of each dataset as well as the relative magnitudes of power usages for each return fan all align with the Clinic team's expectations. The general shape of each curve has an upward trend throughout the day, indicating heavier demand on the return fans in the later portions of the day as temperatures rise and building use increases from its minimum value during the night and early morning. The peaks in power consumption for West Dining AHU 1 return fan line up roughly with lunch and dinner, which is anticipated due to the West Dining area being the most heavily occupied during those times.

Additionally, the difference in power consumption between each return fan generally aligns with the indicated horsepower (HP) ratings for each fan motor, with AHU 1's 10 HP motor consuming the most power at any given time of day. To examine if the supply fans for the HVAC system were following similar trends, the team averaged power consumption data for AHU 1-5 supply fans over the same ten days as in Figure 12. The resulting plot is show in Figure 13.

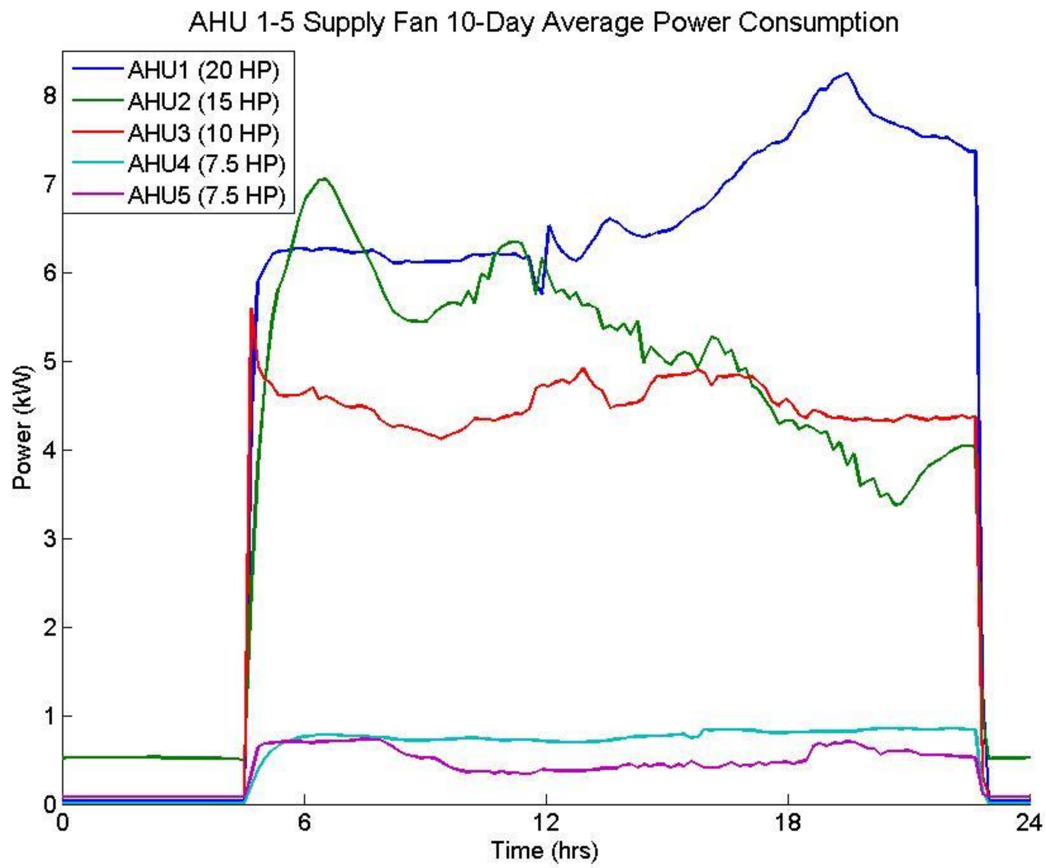



**FIGURE 13. POWER CONSUMPTION FOR AHU 1-5 SUPPLY FANS AVERAGED OVER 10 DAYS**

As shown, the Dining Atrium Supply Fan AHU 2 follows a different trend than the other supply fans. The fan did not match with the expected shape from the return fan in Figure 12 or the relative power usage amplitude anticipated from the fan motors power rating. The added anomaly of a downward trend throughout the day indicated that the team should further examine the data for each of the ten days from which the data was averaged. Figure 14 represents the power consumption from February 11-23 for the AHU 2 Supply Fan. The team found unexpected jumps in power consumption on certain days accompanied by an often erratic downward sloping curve profile. This showcases the characteristics of the AHU 2 Supply Fan data that contributed to both the increased magnitude and downward slope on the ten-day averaged plot in Figure 13. There was a sudden jump in maximum daily power consumption from approximately 3.75 kW to in excess of 10 kW around day 5, corresponding to February 16, 2011. The team initially suspected that some external factor, such as a short in the circuit somewhere or drastic change in weather from the previous days, was influencing the supply fan exclusively.

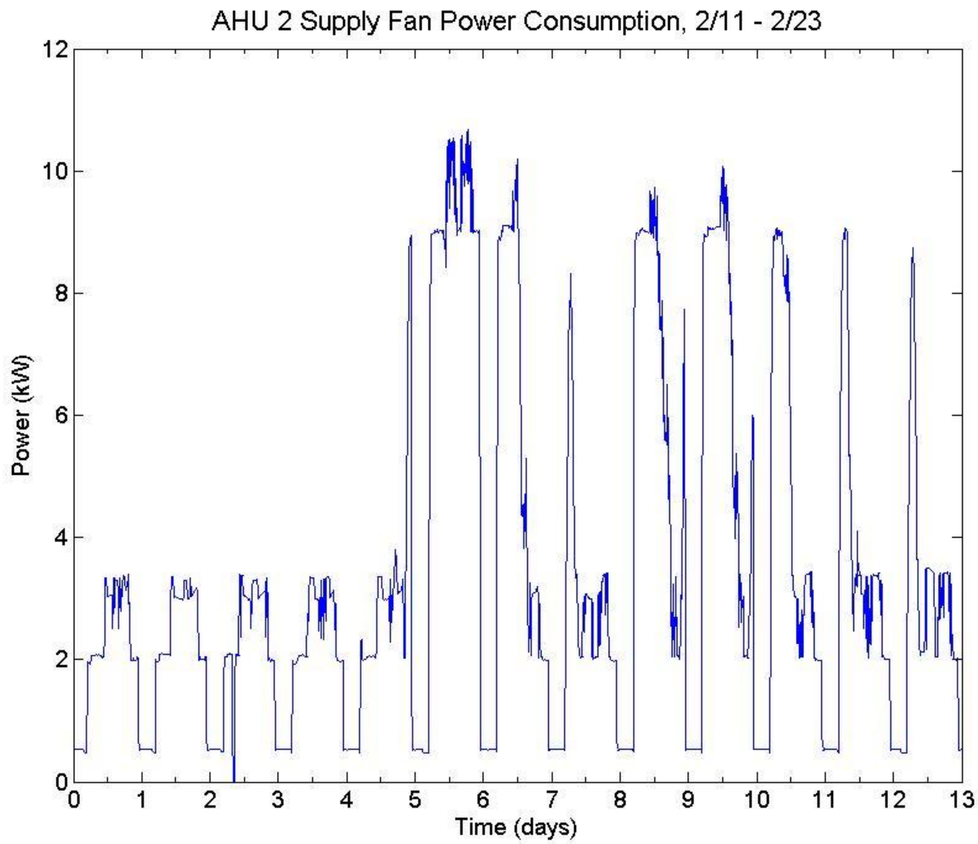



**FIGURE 14. DINING ATRIUM AHU 2 SUPPLY FAN POWER CONSUMPTION**

To attempt to discern the cause of the seemingly erroneous data values, staff from the F&M department at the college, went up to the unit and measured both voltage and current values directly with a clamp. Findings show that the current running through phases A and B of the circuit was within specifications, but the current on phase C was 14% higher than normal. This high current value was contributing to an incorrect calculation of the power factor of phase C, which was also affecting the calculation of phase B's power factor due to the way the data monitor was installed. The monitor was measuring current on only two phases, A and C, of the system, and simply calculating the current in phase B as an average of the two other measured phases. Thus, the skewed phase C current value contributed to two incorrect power factor calculations. This led to incorrect kW formulations.

A monitor was reinstalled to diagnose the cause for the discrepancy in loading between the three phases. The new monitor was installed for all three phases of the Dining Atrium AHU 2 Supply Fan. Additional meters were also installed monitoring all three phases for supply fans for AHU 1 and 3, and the DBM and MS panels in order to obtain more accurate power consumption data.

After monitoring all three phases of these circuits for several days it was found that the load on the AHU 2 supply fan was unbalanced. Because of this imbalance, the data collected earlier in the semester should not be used as calculating the B phase and is only appropriate for a balanced motor load. The new power data for AHU 2 is shown in Figure 15 and does not have the same unexplainable downward trend.

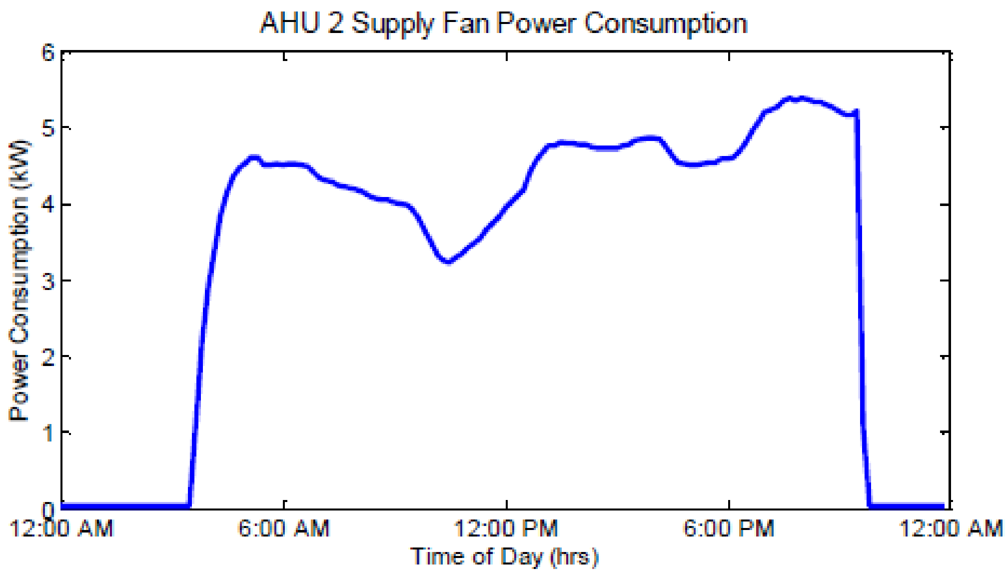



**FIGURE 15. REVISED POWER CONSUMPTION FOR DINING ATRIUM AHU 2 SUPPLY FAN AVERAGED FROM 4/23/11-4/26/11**

This plot shows the power consumption averaged between April 23 and April 26, 2011. The power is maximized at the end of dinner and dips in between meal times, which is what is expected for the dining area air handlers. Additionally, there was no power consumption observed when the air-handling unit was off during the night. There is still the problem of the unbalanced load as shown in Figure 16, however. The team determined that the current imbalance is not due to a problem with the variable frequency drive (VFD) as the data showed the same imbalance when the VFD was bypassed. Additional testing needs to be done to determine the reason for this anomaly. Figure 16 shows the current imbalance between the three phases.

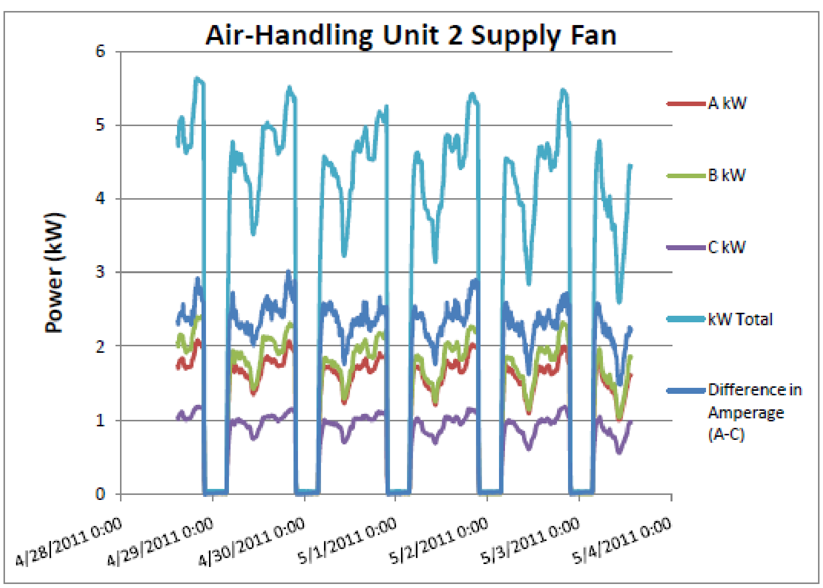



**FIGURE 16. 3-PHASE MEASUREMENTS OF DINING ATRIUM AHU 2 SUPPLY FAN FROM 4/28/11-5/4/11**

As shown in Figure 16, the C phase of the supply fan motor is lower than the A and B phases. The difference between the amperages is shown in dark blue. This difference tracks the shape of the power consumption itself, indicating that the C phase is off by a certain percentage of the power usage; in other words, the higher the power consumption, the greater the imbalance in the motor. Further investigation is needed to determine the cause of this imbalance.

# BUILDING MANAGEMENT SYSTEM

## CONTROL SOFTWARE MONITORING

The team had limited access to the software that controlled the HVAC system. Figure 17 shows an image of the software interface for the control system.

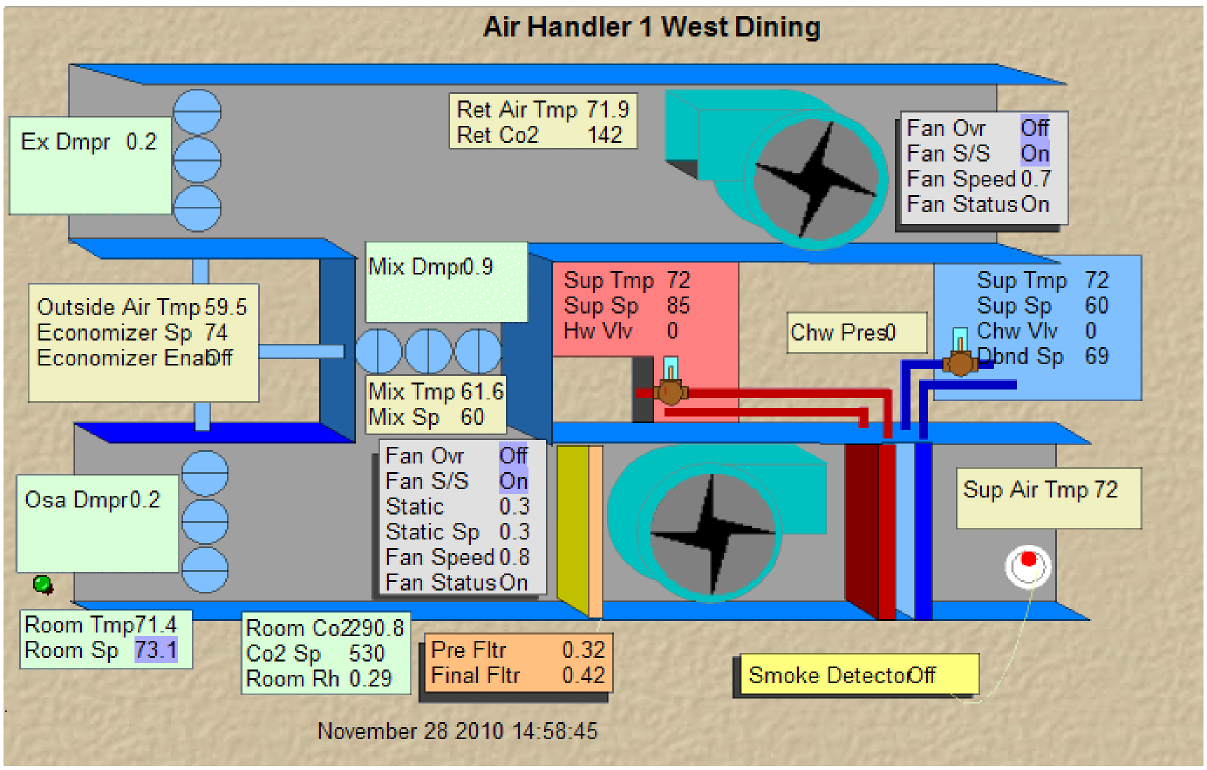



**FIGURE 17. CONTROL SOFTWARE INTERFACE**

This Figure 17 screenshot is for the West Dining AHU 1. The return air from the dining hall is collected up using the return fan where the return air temperature and $CO_2$ levels are being measured. The exhaust damper, Ex Dmpr, determines how much air is exhausted out of the building and how much is recycled. The recycled air then mixes with a certain amount of outside air, which is determined by the outside air damper, OSA Dmpr. The mixed air is then heated or cooled and pushed back into the building by the supply fan. The amount of outside air is determined by the room $CO_2$ sensor, while both the supply fan speed and the hot and cold water valves are modulated by the room air temperature. This setup is identical for AHU 2.

AHU 3 follows a similar setup, however, the fan speed is determined by the static pressure in the duct and heating is provided by the heating coils at each individual variable air volume (VAV) or constant air volume (CAV) unit only. AHUs 4 and 5 consist of a supply fan only and implement evaporative cooling. The fan speeds for these units are set to maintain a negative space pressure differential in the kitchen. The details of the sequence of operations was investigated using this software and will be discussed in the following sections.

The team collected a limited amount of data from the software applet by interacting with the managers of the software at Claremont University Consortium. These data points include the room $CO_2$ levels for the Atrium and West Dining Area, room temperatures for all AHUs, and fan speeds of all AHUs. This data is very useful in analyzing the control sequence of operations.

The team discovered several interesting discrepancies between the control sequence and the operation of the building. One of the first issues that the team ran into was with the $CO_2$ sensors. Not only are the sensors themselves not working (which will be discussed in detail later) but also the setpoint for the room $CO_2$ levels is much too low. The control sequence states that, "demand control ventilation shall be configured to maintain 530 ppm differential (adjustable) between indoor and ambient $CO_2$ concentration" (HVAC Control Submittal, Mazzetti). On the control software, the room $CO_2$ setpoint is 530 ppm. This, however, is the absolute $CO_2$ concentration rather than the differential. Based upon air quality research the team would recommend implementing an absolute $CO_2$ setpoint of up to 800 PPM. Raising this setpoint allows the building to recycle more air, which reduces the need for heating or cooling outside air. There must be special attention given to the change, however, as it could potentially affect the comfort of the diners, which is the first priority of the HVAC system.

The team also found some issues with both the heating and cooling modes of operation of the dining hall. The control submittal specifies that, "space air temperature (not supply air temperature) shall modulate chilled water and heating hot water valves to maintain room temperature at 74◦F (adjustable)". Additionally, "space air temperature shall modulate fan's variable speed drives to maintain space temperature setpoints (adjustable)" (HVAC Control Submittal, Mazzetti). First of all, it is interesting to notice that the one input variable (room temperature) is controlling two output variables (fan speed and heating/cooling valves). The specifics of this control relationship should be investigated further as it is not performing as it should. The following observations were made on Wednesday March 2, 2011 during dinner.

Here, in Figure 18, the $CO_2$ levels have just exceeded the setpoint. The Exhaust and Outside Air dampers opened from 0.2 to 0.6 to lower the $CO_2$ levels.

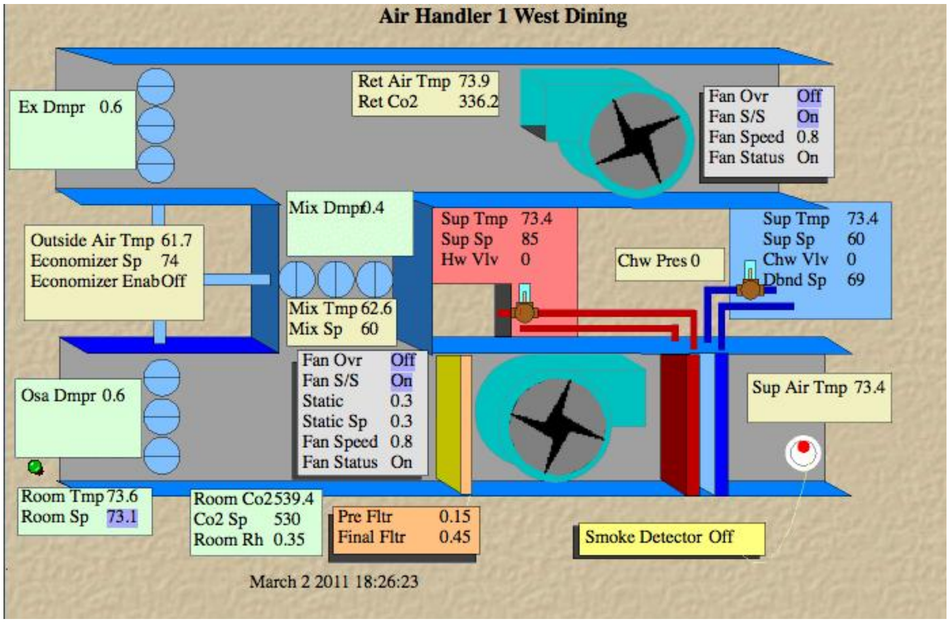



**FIGURE 18. WEST DINING AHU 1 CONTROL SYSTEM RESPONDING TO $CO_2$ LEVELS**

As the $CO_2$ stays above the setpoint in Figure 19, the Exhaust and Outside Air dampers open all the way to allow for maximum outside air. Additionally, the hot water valve begins to open to heat the outside air to the desired supply air temperature.

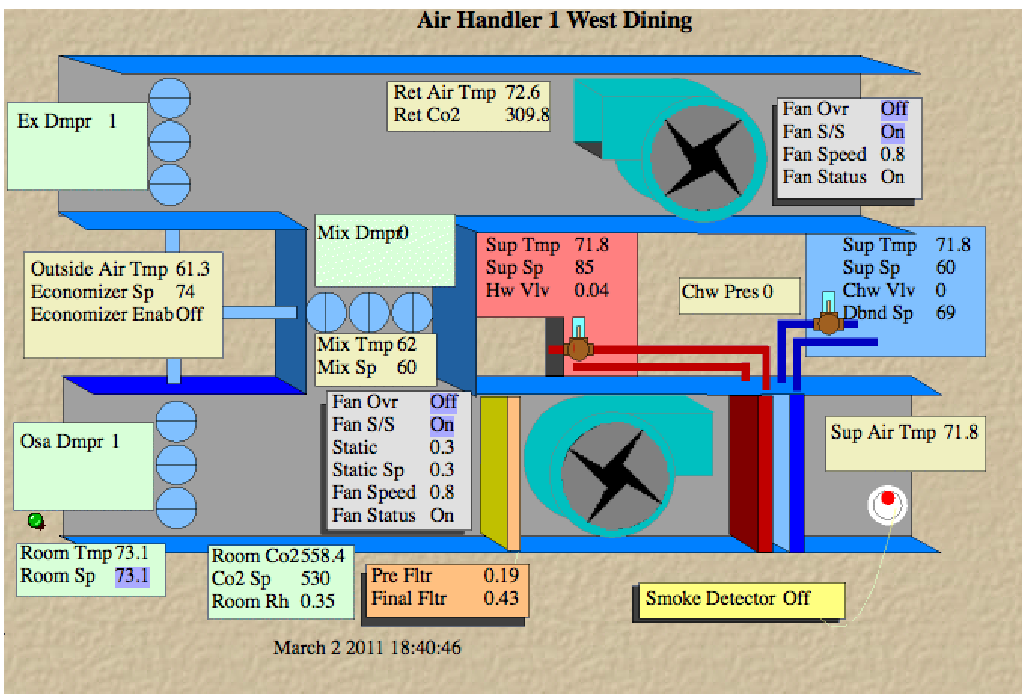



**FIGURE 19. WEST DINING AHU 1 CONTINUING TO RESPOND TO $CO_2$ LEVELS BY OPENING DAMPERS TO MAXIMUM POSITION**

The $CO_2$ levels return to below the setpoint and the Osa and Ex dampers go back to the default of 0.2, shown in Figure 20. The heat is still working to maintain a constant supply air temp. Note, however, that the fan speeds remain constant throughout the process. It is also interesting to note that the fan speeds to not drop when the room temperature and $CO_2$ both reach the setpoint.

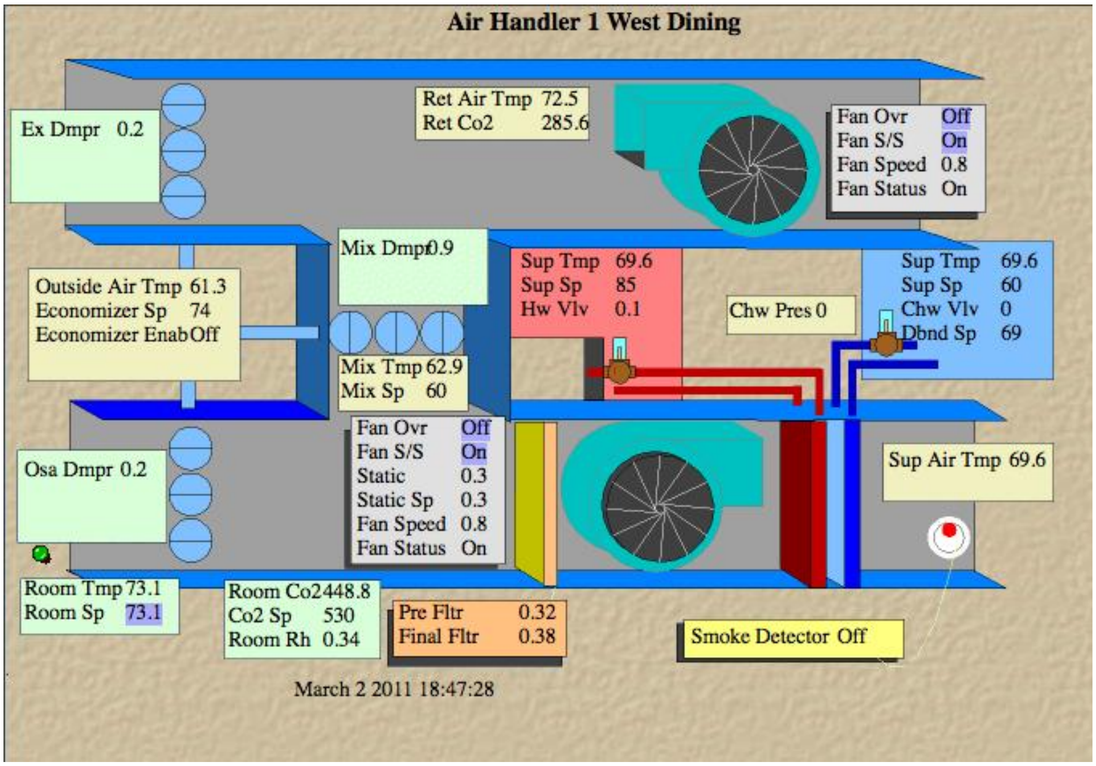



**FIGURE 20. WEST DINING AHU 1 RETURNING TO NORMAL OPERATION**

Switching focus to the Dining Atrium AHU 2 control system, the team noticed some issues with the heating mode of operation. In Figure 21, the $CO_2$ levels for AHU 2 consistently show a higher reading for both the room and return $CO_2$ than AHU 1. This discrepancy should be explored further. The outside air and exhaust dampers are fully open and the supply fan is operating at 90% capacity. The hot water valve is slightly open; however, the supply air temperature is below both the room temperature and setpoint.

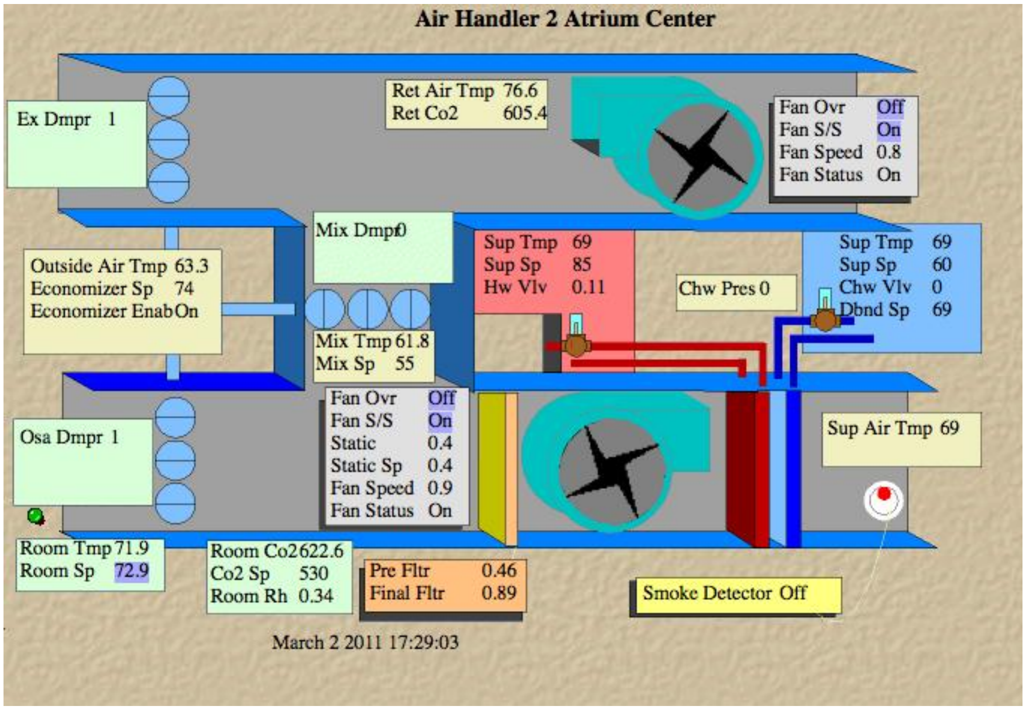



**FIGURE 21. DINING ATRIUM AHU 2 CONTROL SYSTEM IN HEATING MODE 5:29 PM**

As dinner continues, the $CO_2$ levels continue to rise above the setpoint despite the Osa and Ex dampers being completely open, shown in Figure 22. Additionally, the hot water valve opens a bit more, but the supply air temperature does not increase. This indicates that the control system for the hot water valve is too slow to react and the system is not capable of maintaining the $CO_2$ setpoint during peak hours.

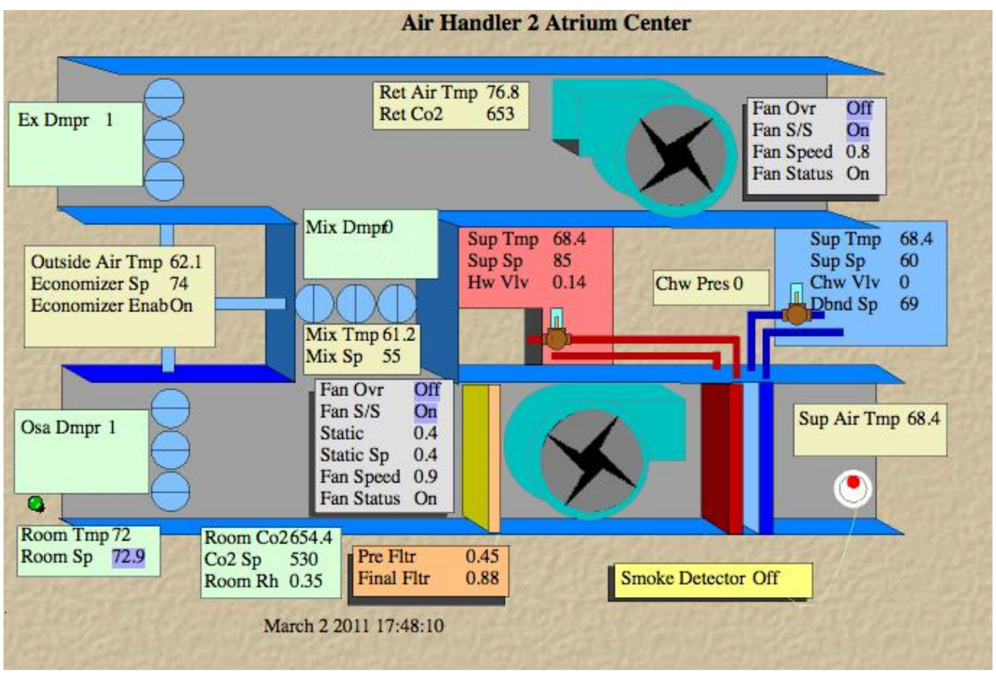



**FIGURE 22. DINING ATRIUM AHU 2 IN HEATING MODE 4:38 PM**

After another 15 minutes, we still see the same trend in Figure 23. $CO_2$ levels rise, the hot water valve opens slightly but the supply air temperature is still below the room and setpoint temperatures. Additionally, the team noticed that the supply temperature for both the hot water and chilled water are simply reading the supply air temperature of the room. This is likely an issue with the control software interface not displaying the proper data point at these locations.

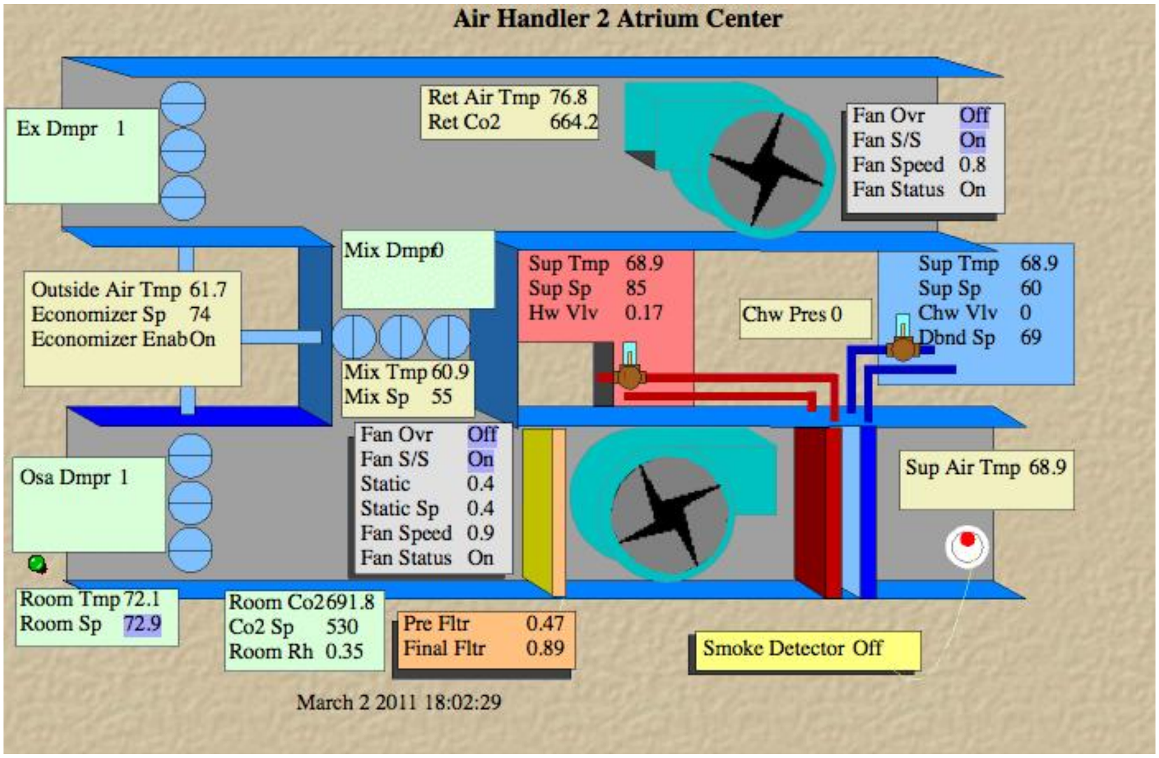



**FIGURE 23. DINING ATRIUM AHU 2 IN HEATING MODE 6:02 PM**

Using the data collected from Claremont University Consortium, as well as the power consumption data collected by SCE, the team was able to look at the issues in the control system a bit more closely.

Figure 24 shows the relationship between power consumption and fan speed for AHU 1 supply fan. The relationship is fairly linear until the fan speed reaches about 82.5% of its maximum capacity. This observation can also be seen in the following plot of fan speed overlaid with power consumption. It is important to note that this value is expressed as a fraction where 1 is the maximum fan speed. The team was not able to determine what value was used at the maximum fan speed in the control system and thus could not assign a numerical value to this fraction. The expected relationship between fan RPM and power consumption is cubic, according to the Second Fan Law. It is difficult to determine if this relationship is observed due to the small range of fan speeds measured and the fact that the revolutions per minute (RPM) values are not known.

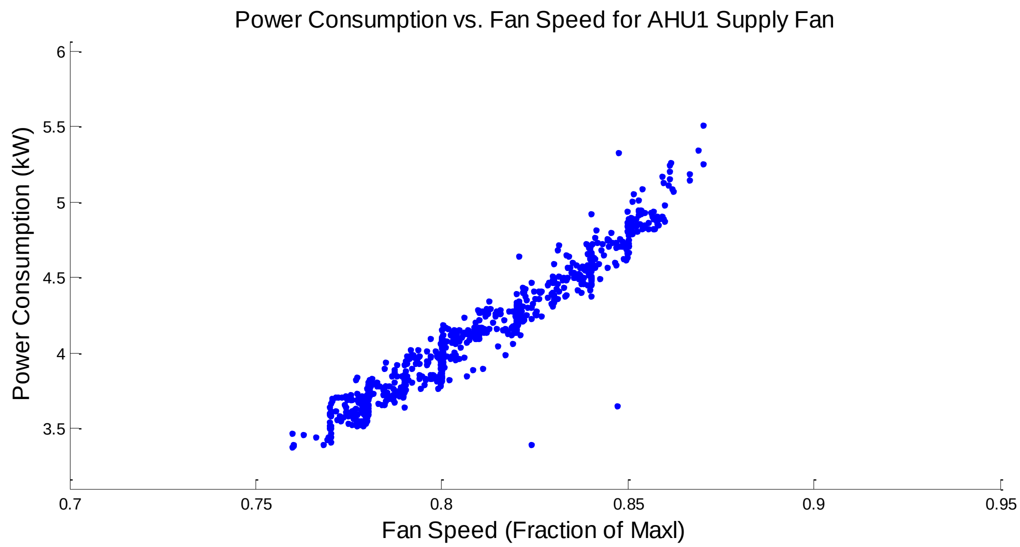



**FIGURE 24. FAN SPEED VS. POWER CONSUMPTION FOR WEST DINING AHU 1 SUPPLY FAN**

Figure 25 below shows the power consumption for AHU 1 supply fan as well as its fan speed as a percentage of maximum frequency. Around 1:00 PM there is a slight rise in the fan speed. This corresponds to a much larger rise in the power consumption of the fan, and this disparity continues to rise as fan speed increases throughout dinner. This suggests that the optimum fan speed would remain below this value of about 0.825 as a fraction of maximum capacity. Once the fan speed reaches this point, the control system should modulate the hot and chilled water dampers in order to maintain the room temperature setpoint. To get a bit more insight into this problem, the team examined the room temperature and $CO_2$ for this data.

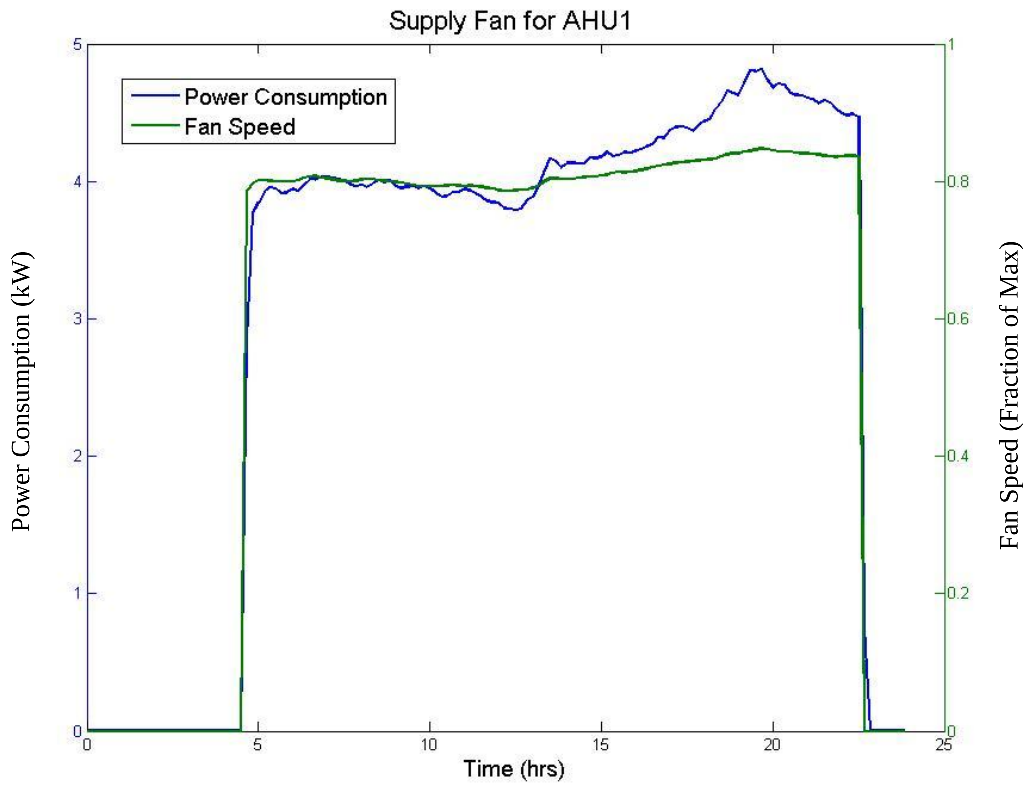



**FIGURE 25. POWER CONSUMPTION AND FAN SPEED FOR WEST DINING AHU 1 SUPPLY FAN**

Figure 26 shows the same power consumption data overlaid with the room temperature and $CO_2$ for AHU 1 that serves the west dining area. In this case, we see the room temperature jump up around 1:00 P.M. and the corresponding jump in power consumption. The $CO_2$ is also spiking during this time, however, the levels only reach above the setpoint at the very tip of the peak. The control system continues to ramp up the fan speed (causing the continued increase in power consumption) throughout the end of the day and is not able to bring the room temperature back down below the setpoint (73.1°F) until the very end of the day. This indicates that the control system is likely not modulating the chilled water valves correctly in order to sufficiently cool the supply air.

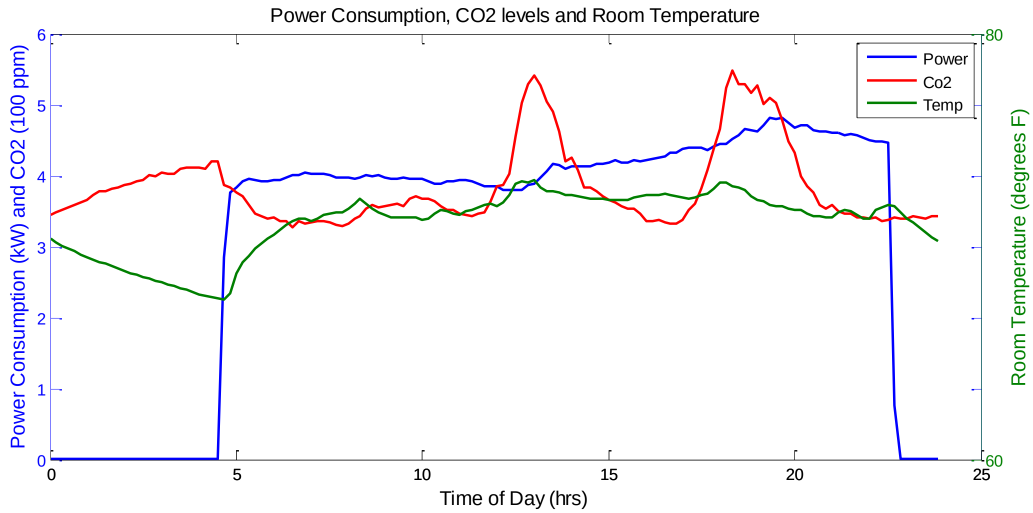



**FIGURE 26. POWER CONSUMPTION, $CO_2$ LEVELS, AND TEMPERATURE FOR AHU 1 SUPPLY FAN**

## $CO_2$ SENSOR TESTING

The Hoch-Shanahan Dining Commons features two wall-mounted $CO_2$ sensors: one in the West Dining area and one in the Atrium near the tray return entrance. The two sensors individually measure absolute $CO_2$ levels in their respective areas of the building in ppm. They then send the measured values to the HVAC control system, where they are compared with the system's setpoint of 530 ppm. If the measured $CO_2$ levels at either sensor are above the setpoint, the HVAC control system turns on the supply fan for the appropriate AHU to provide fresh outside air to the building to lower the indoor $CO_2$ level.

Even though the amount of carbon dioxide present in indoor air is not often noticed or thought of in relation to occupant comfort, it's important to monitor and control $CO_2$ levels because high levels of $CO_2$ indoors can cause an uncomfortable muggy and stuffy feeling in the building. To help keep $CO_2$ levels within a tolerable range, the HVAC system in the Hoch-Shanahan is controlled by both indoor air temperature and $CO_2$ levels. California's Title 24 Building Code requires that buildings with a demand-controlled ventilation system – one controlled at least in part by indoor $CO_2$ levels – maintain carbon dioxide levels below 800 ppm while the building is occupied and ventilation rate is less than 15 cubic feet per minute (cfm)/person. The Hoch-Shanahan's $CO_2$ setpoint is well below the required level, and it is possible to save appreciable amounts of energy by raising the building's $CO_2$ level setpoint while still staying within Title 24 requirements. Before we could determine if such a change would be possible and/or beneficial, though, it was first necessary to investigate the building's $CO_2$ sensors and check if they were measuring accurate levels.

To check the accuracy of the wall-mounted $CO_2$ monitors, the team used a handheld indoor air quality monitor, the Supco IAQ50. This monitor was chosen because it can measure and display absolute $CO_2$ levels in ppm (for easy direct comparison with the sensors in the Hoch-Shanahan), room temperature, and humidity. The $CO_2$ sensor is calibrated at the factory to 400 ppm and doesn't need to be re-calibrated before use. The portability of the IAQ50 allowed the team to take handheld readings at different locations within the Hoch-Shanahan to see the variation in $CO_2$ levels throughout the building.

The team used the handheld air quality monitor to determine the accuracy of the installed sensors by measuring $CO_2$ levels during lunchtime, when the building occupancy is near the highest point of the day. The team measured $CO_2$ levels on the handheld monitor near each wall-mounted sensor during lunch on March 28, 2011, and compared those values with the values obtained from the Hoch-Shanahan's sensors through the control software data applet in real time. The results of this test are given in Table 3.

**TABLE 3. HANDHELD MEASURED $CO_2$ LEVEL VS. WALL-MOUNTED MEASURED $CO_2$ LEVEL – 3/28/11 12:30 PM**

| AIR HANDLER UNIT | DINING AREA | SOFTWARE $CO_2$ READING (PPM) | HANDHELD $CO_2$ MONITOR READING (PPM) |
|---|---|---|---|
| AHU 1 | West Dining | 498 | 758 ± 5 |
| AHU 2 | Dining Atrium | 700 | 575 ± 5 |

Since both the handheld monitor and the Hoch-Shanahan's installed $CO_2$ sensors are measuring absolute $CO_2$ levels, we expect to see similar readings for each area of the dining hall. For the West Dining area, though, we found that the installed sensor measured about 260 ppm lower than the $CO_2$ level indicated on the handheld monitor. Conversely, in the atrium, the installed sensor read about 125 ppm higher than the IAQ50. Since the handheld monitor came pre-calibrated from the manufacturer, the team concluded the $CO_2$ sensors in the Hoch-Shanahan were reading incorrect $CO_2$ levels.

$CO_2$ sensors should generally be re-calibrated every 5 years, and at the time of the team's test, the installed sensors had not been re-calibrated since their installation in 2005. Without re-calibration, $CO_2$ sensors can drift up to 75 ppm per year, which could contribute to the inaccurate readings the team found for each sensor.

The team decided that it would be best if new sensors were bought to replace the existing ones. Through discussions with experts at CTG Energetics, the team discovered that $CO_2$ sensor technology has improved greatly since the Hoch-Shanahan opened in 2005. Two Honeywell non-dispersive infrared (NDIR) $CO_2$ sensors, which can be wall mounted, were purchased. The accuracy of the $CO_2$ sensor is ± (30 ppm +2% of reading) instead of ± (75 ppm +5% of reading). Both monitors use NDIR technology but the Honeywell sensors have an ABC algorithm from which it can self-calibrate itself, whereas a kit is needed for the current AirSense Model 310e $CO_2$ sensor. NDIR sensors use spectroscopic sensors to determine the $CO_2$ level. $CO_2$ molecules are absorbed and measured by an IR sensor of which larger concentrations of $CO_2$ absorb more light.[ii]

The Facilities and Maintenance Department of Harvey Mudd College has ordered calibration kits on their current $CO_2$ sensors. Another $CO_2$ monitoring test must be performed to see whether or not the calibration tests worked. If not, the team recommends that the college implement these new sensors to see if they give better accuracy of the $CO_2$ within the Hoch-Shanahan Dining Commons. Some work may be required to incorporate these new $CO_2$ sensors with the software if the college decides to take this route.

# AIR AND WATER BALANCE

The air and water balance report was executed on March 14, 2011 by the NEBB certified contractor. An air balance report checks on the performance of the HVAC system and determines how much the HVAC deviates from its designed specifications. After the Hoch-Shanahan Dining Commons was constructed, an air balance was performed. Therefore, the SCE team can compare numerical values and potentially determine the efficiency of the building then and now. The SCE clinic team has acquired an air balance report from 2006 that gives design and actual values of electricity and volumetric flow rates of the AHUs.

The air balance analysis conducted in 2011 was done with the HVAC system operating at a variety of speeds since the HVAC was not allowed to be shut down and ran at desired speeds because of the building being occupied. The amperage readings vary from the 2006 air balance report by at least 20% of which the HVAC was assumed to be running at maximum speed. By not running at maximum speed, the CFM readings also show a greater deviation to that of the desired CFM values. The static pressure readings for the HVAC units are deviated from the specified readings but are closer than that of the 2006 Air Balance report. The water balance details that there are two pumps that help operate the HVAC system. Both pumps have flow rates that are much greater than the designed flow rate. However, the friction head of the water pipes are somewhat close to the designed specifications. The contractor has suggested the following recommendations about their Air Balance Report in Appendix B.

- AHU 1 thru AHU 4 - set correct outside air quantity per plans, and balance AHU 1 to correct the quantity.
- AHU 2- balance supply to reduce fan to the required CFM
- AHU 3 - balance VAV's to the required CFM quantities. Return air on AHU-3 return grilles need to be uncovered and cleaned.
- AHU 4 – balance supply air to the required CFM quantities.
- EF 2 – increase CFM quantity to the required CFM. It was running at 64% when measured.
- EF 8 – decrease fan to required CFM. Fan is running 50% high.
- EF 9 – clean exhaust grilles to balance to the required CFM
- EF 11 – decrease fan to required CFM. Fan is running 80% to high.
- EF 14 – decrease fan to required CFM. Fan is running 60% to high.

# ANALYSIS OF BENEFITS

Many of the changes, such as replacing the $CO_2$ sensors, balancing the AHUs and tuning the control system, will have an effect on the building operation, but it is difficult to determine just how they will affect the building's efficiency. A typical recommissioning process uses a building model to estimate these effects and then compares the results to the results of re-monitoring the building after the changes are implemented. The building model is necessary to perform a typical economic cost-benefit analysis. Since these are outside the scope of this project, the team focused on the non-economic benefits and made estimates for the efficiency improvements that will result from making the recommended changes.

The team expects that implementing changes to the entire building could lead to a 10% reduction in energy usage.[iii] An overall reduction of 10% in the building's energy usage translates to savings of $6,000-$7,000 annually for the college.

Operational improvements are preferred over technological improvements, because the cost for operational improvements is usually negligible. Instead, operational improvements involve changing the habits of workers or changing settings in a building control system. The team believes that the kitchen is an area in which operational improvements could have a great effect on overall building efficiency, especially due to its unexpectedly high power consumption.

Table 4 shows the estimated improvement of the building subsystems if recommendations are implemented. As a rough estimate, the annual savings is based on a $65,000 annual electricity bill, consistent with past bills for the building. According to EnergyStar, tuning an HVAC system can lead to cost savings of 10% on cooling and heating needs. Additionally, if AHU 2 is fixed, the team estimates at least a 5% efficiency improvement. The team estimates that more efficient appliances in the kitchen coupled with operational changes by the staff could yield 15% less power consumption. The lighting system is functioning well and the team does not feel that any changes are necessary or would be economically beneficial. In the future, however, it may be useful to look into new lighting technologies, such as light-emitting diodes. The team feels that additional operational improvements may lead to more efficiency gains in the building systems covered in the "Other" category. Five percent was made as a conservative estimate for these improvements. In this scenario, the overall savings for the dining hall would be 6.2%.

**TABLE 4. ESTIMATED BENEFITS**

| System | Average Power Consumption | Estimated Improvement | Annual Saving |
|---|---|---|---|
| HVAC | 18 kW | 15% | $1,755.00 |
| Kitchen | 40 kW | 15% | $1,462.50 |
| Lighting | 15 kW | 0% | $0 |
| Other | 25 kW | 5% | $845.00 |
| **Total** | **98 kW** | **6.2%** | **$4,062.50** |

## COMPARISONS TO CURRENT LEED STANDARDS

While the primary goals of the recommissioning process often include investigating a building's operational condition, identifying inefficiencies, and determining possible sources of energy and/or cost savings, the results obtained from a recommissioning report can often aide in the process of applying for LEED certification. The Hoch-Shanahan dining commons was certified LEED-Silver before its construction, but that certification was awarded based on a theoretical energy model for how the building was intended to operate once constructed. LEED has developed a certification standard for existing buildings, known as LEED 2009 for Existing Buildings (or simply LEED E.B.).

A building does not need to be LEED certified before construction to be eligible for LEED certification at any point in the future – certain benchmarks simply must be met by the building and various energy consumption/building system data and information must be presentable to the U.S. Green Building Council (USGBC) to be considered for LEED E.B. certification. LEED E.B. standards focus on many of the same subjects as standard pre-construction LEED certification. However, there are certain LEED points that existing buildings are not eligible to receive, such as points for having an energy system designed to use a certain percentage of power consumption lower than building code standard energy usage, which, in the case of the Hoch-Shanahan, is Title 24 standards. The dining commons" energy system was designed to use 44.1% less energy than required by California Title 24, earning it nine LEED points before construction.

The findings of the recommissioning of a building can be used for submittal to the USGBC, since a full recommissioning provides a wealth of insight into the actual performance of the building, as opposed to the use of a theoretical building energy consumption model for comparison with LEED standards. For this project, however, the team was tasked with the investigation and diagnosis of the actual building's performance and malfunctions as opposed to the utilization of findings to prepare for LEED E.B. certification.

# RECOMMENDATIONS

In light of the findings of this project, the team has developed a list of recommendations for improving building comfort, operation and efficiency. Since the project focused on the HVAC system, most of the improvements regard this system. Below is the list of recommendations as well as details on how it will affect the building.

1. Perform air volume balance of all AHUs
   - Improve building comfort
   - Improve HVAC system function
2. Tune control sequence to better respond to building state by hiring contractor familiar with current Andover system, or replace existing control system
   - Improve building comfort
   - Improve HVAC system function
3. Raise $CO_2$ setpoint in software to 800 ppm
   - Increase efficiency of HVAC system by reducing outside air requirements
4. Replace $CO_2$ monitors
   - Provide more accurate input data to HVAC control system
5. Update kitchen hoods to demand controlled technology
   - Decrease power consumption of kitchen hoods
6. Clean or replace exhaust fans
   - Increase exhaust fan efficiency and indoor air quality
   - Decrease exhaust fan power consumption
7. Ensure AHU-2 supply fan turns off completely at night
   - Avoid unnecessary nighttime consumption
   - Estimated savings of $150-$200 annually
8. Purchase more energy efficient kitchen appliances
9. Continuous software/power monitoring
   - Provide real-time building data for operator
   - Provide long-term data to future building recommissioning projects

## LONG-TERM MONITORING

In order to keep the dining hall at its specified energy consumption and move towards future sustainability initiatives, part of the team's recommendations about the Hoch-Shanahan is the implementation of permanent, long-term power monitoring. This helps the building manager better assess building performance, and it would provide data for future recommissioning efforts. The team researched appropriate equipment for this purpose, and recommends the Dranetz Encore 61000 (pictured in Figure 27-Left). This equipment features four differential current inputs and four differential voltage inputs with up to 1 Mega Hertz (MHz) sampling. This equipment is similar to the PowerVisas used for temporary monitoring, but they are able to be permanently installed. They also feature a multi-user web interface that makes accessing the data simple. To monitor the entire building, the Dranetz Encore is the best solution. It is specified for the range of voltages and currents that are seen on this circuit and the data can be remotely accessed. However, for other building circuits with less current, much less expensive equipment is available. The Conzerv EM6436, pictured in Figure 27-Right, is a good solution for circuits up to 6A, and costs a fraction of the cost of the Dranetz product. The Conzerv product comes with software to log the data, but it is not network capable, so a computer is necessary to log data continuously. It measures and tracks voltage (line-to-line and line-to-neutral), current (phase wise and total), power factor, frequency, power (kW, phase wise and total), energy (kWh, total) and run hours. A comparison of the two types of equipment is summarized below in Table 5.

**TABLE 5. COMPARISON ON LONG-TERM MONITORING SOLUTIONS**

| | DRANETZ ENCORE ENC-TR-S | CONZERV EM6436 |
|---|---|---|
| Price | $8,000 | $350 |
| Input Voltage | 1 to 600 VAC | 80 to 600 VAC |
| Current Range | 0 to 6,000 A | 50 mA to 6 A |


**FIGURE 27. DRANETZ ENCORE ENC-TR-S (LEFT) AND CONZERV EM6436 (RIGHT)**

# CONCLUSION

The systematic process of recommissioning was used to assess the current operating conditions of the Hoch-Shanahan Dining Commons. Due to the lack of availability of historical building performance data, no concrete conclusions could be made about the degradation of the building's performance. It is clear that the building consumes more energy than predicted during the design phase and seems to be trending upward when analyzing the historical utility bills. This upward trend may be also due to the increase occupancy of the dining hall. Regardless, the Clinic team developed several recommendations to the building's current operations that will undoubtedly improve the overall performance of the building.

# APPENDIX A: CHARTS OF ENERGY COST AND USAGE

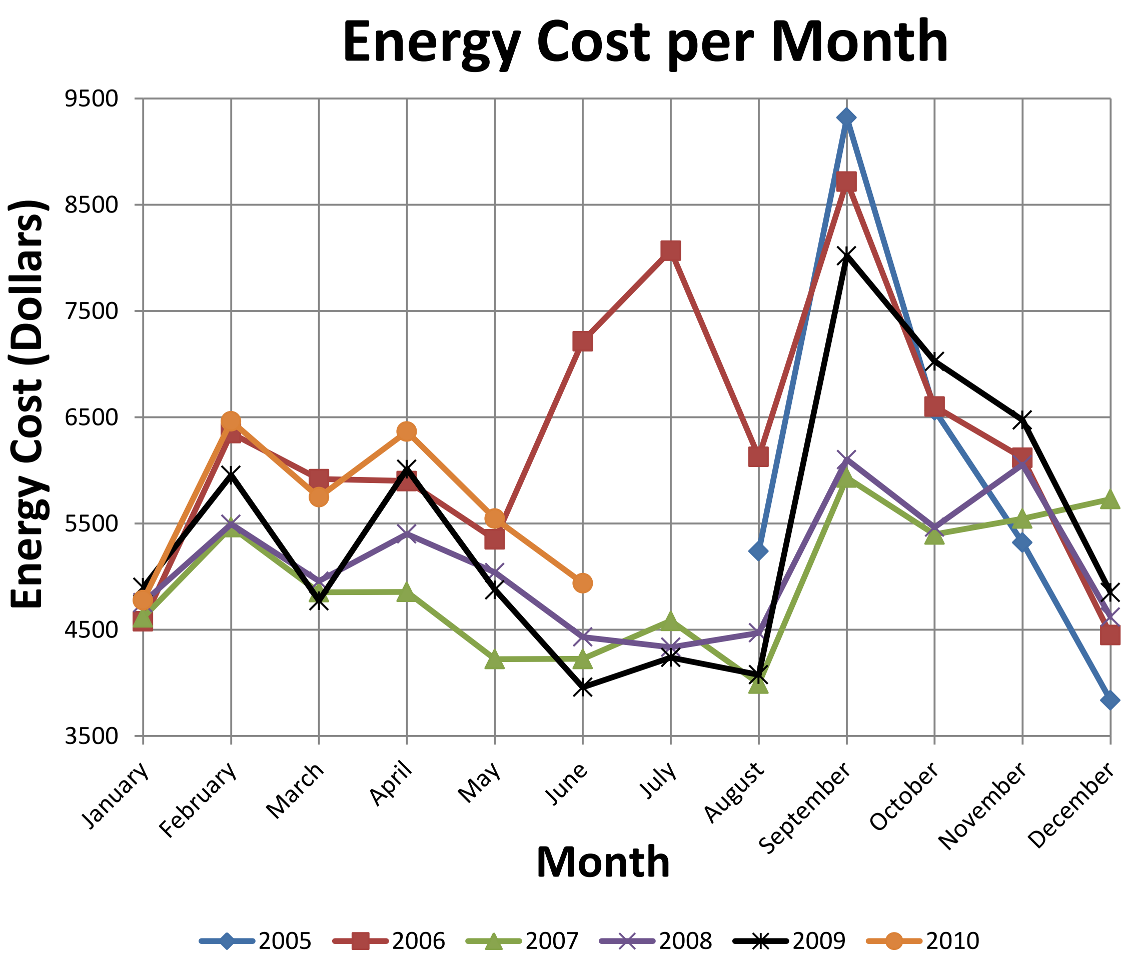



**FIGURE 28. ENERGY COST PER MONTH FOR AUGUST 2005 THROUGH JUNE 2010**

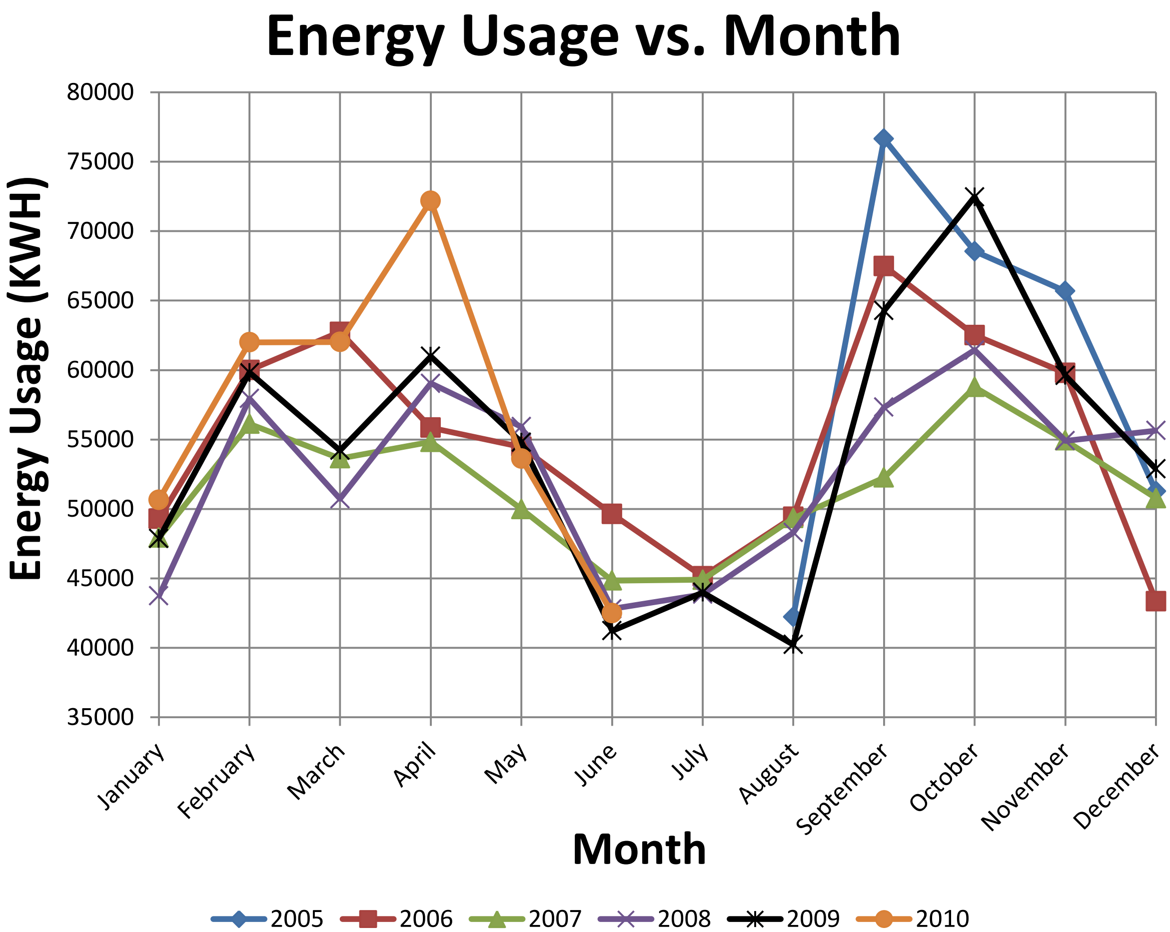



FIGURE 29. ENERGY USAGE PER MONTH FOR AUGUST 2005 THROUGH JUNE 2010

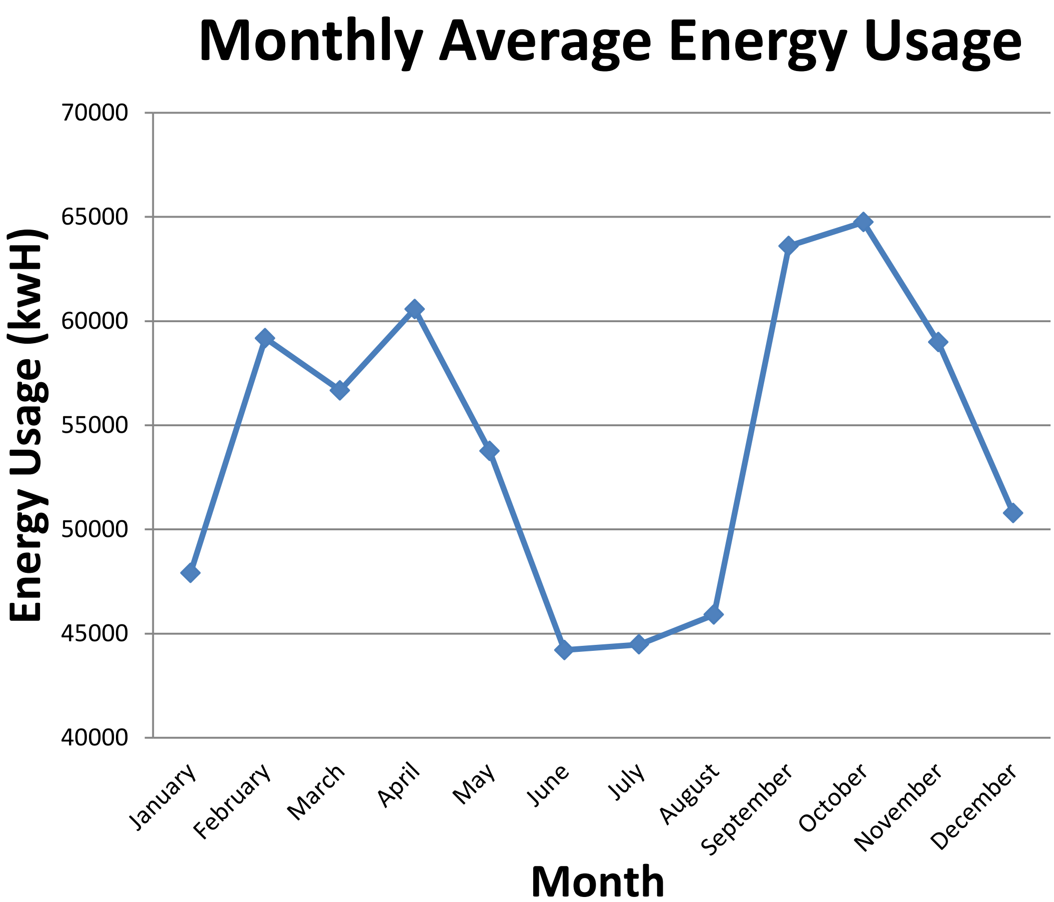



**FIGURE 30. MONTHLY AVERAGE ENERGY USAGE**

# APPENDIX B: AIR BALANCE REPORT RESULTS

The results of the 2006 and 2011 air balance tests and analyses are shown in Table 6 and Table 7. It is important to note that for the 2006 air balance, the contractors were able to take data while pushing the building to its maximum and minimum setpoints. The 2011 air balance report was performed during regular building operation.

**TABLE 6. SUMMARY OF 2006 AIR BALANCE RESULTS**

| | AHU 1 | AHU 2 | AHU 3 | AHU 4 | AHU 5 |
|---|---|---|---|---|---|
| **Voltage (V)** | | | | | |
| Design | 460 | 460 | 460 | 480 | 480 |
| Actual | 471 | 471 | 471 | 471 | 471 |
| **CFM-Total Fan** | | | | | |
| Design | 12430 | 9600 | 6500 | 7200 | 5520 |
| Actual | 12515 | 9705 | 6465 | 7365 | 5480 |
| **Static Pressure** | | | | | |
| Design | 4.7" | 4.7" | 4.7" | 1.5" | 1.5" |
| Actual | 1.82" | 1.4" | 1.24" | 1.47" | 1.33" |
| **Horsepower** | 20 | 15 | 10 | 7 | 7 |
| **Amperage** | | | | | |
| Designed | 24.5 | 18.5 | 11.9 | 10 | 10 |
| Actual | 19.8/19.7/19.4 | 14.8/15.1/14.7 | 8.6/8.7/8.9 | 8.3/8/7.9 | 6.6/6.8/6.9 |

**TABLE 7. SUMMARY OF 2011 AIR BALANCE RESULTS**

| | AHU 1 | AHU 2 | AHU 3 | AHU 4 | AHU 5 |
|---|---|---|---|---|---|
| **Voltage (V)** | | | | | |
| Design | 460 | 460 | 460 | 480 | 480 |
| Actual | 470/473/472 | 474/476/473 | 479/481/481 | 414/475/477 | 467/468/470 |
| **CFM-Total Fan** | | | | | |
| Design | 12,430 | 9,600 | 6,500 | 7,200 | 5,520 |
| Actual | 11,114 | 10,767 | 6,126 | 7,645 | 4,484 |
| **Static Pressure** | | | | | |
| Design | 4.7" | 4.7" | 4.7" | 1.5" | 1.5" |
| Actual | 2.68" | 2.73" | 3.78" | 3.54" | 1.85" |

| | | | | | |
|---|---|---|---|---|---|
| **Horsepower** | 20 | 15 | 10 | 7 | 7 |
| **Amperage** | | | | | |
| Designed | 24.5 | 18.5 | 11.9 | 10 | 10 |
| Actual | 11.1/11.0/11.0 | 10.5/10.4/10.4 | 7.6/7.4/7.4 | 3.6/3.6/3.7 | 4.2/4.0/4.0 |

Based on the 2011 report, the following nine statements are the Certified Air Balance Company's recommendations to Harvey Mudd College with regards to making their HVAC system in the Hoch-Shanahan Dining Commons more efficient.

1. AHU-1 thru AHU-4 - we recommend setting correct outside air quantity per plans. In doing this we also need to balance AHU-1 to correct the quantity.
2. AHU-2- we could balance supply to reduce fan to the required CFM
3. AHU-3 - we have multiple VAV's that require balancing to the required CFM quantities. Return air on AHU-3 return grilles need to be uncovered and cleaned.
4. AHU-4 supply air needs to be balanced to the required CFM quantities.
5. EF-2 CFM quantity needs to be increased to the required CFM. It is running at 64%
6. EF-8 is running 50% high, we recommend decreasing to its required CFM
7. EF-9 exhaust grilles need to be cleaned to balance to the required CFM
8. EF-11 is running 80% to high, we recommend decreasing down to its required CFM
9. EF-14 is running 60% to high, we recommend decreasing to its required CFM

# APPENDIX C: SUMMARY OF LEED POINTS

LEED currently offers four levels of building energy efficiency certification: Certified, Silver, Gold, and Platinum. Buildings receive their certification level based on the evaluation of their proposed energy usage and site plan models, which LEED compares to a code-standard model. It then allocates LEED certification points in six different categories: Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environmental Quality, and Innovation & Design Process.

Due to the unique nature of each building attempting to obtain LEED certification, buildings are not generally eligible to receive all the available certification points within a given category. Tables 1-6 below show the distribution of LEED certification points for each of the six categories that the Hoch-Shanahan obtained during its original commissioning. Entries with a 1 in the "Y" columns indicate LEED points that the Hoch-Shanahan received. The total points received for each category are given in the upper left corner of each table. The building's overall score of 36 LEED points yielded a Silver certification level.

**TABLE 8. LEED TABLE 1 – SUSTAINABLE SITES**

| 4 | | | Sustainable Sites | Possible Points | 14 |
|---|---|---|---|---|---|
| Y | ? | N | | | |
| Y | | | Prereq 1 | Erosion & Sedimentation Control | |
| 1 | | | Credit 1 | Site Selection | 1 |
| | | | Credit 2 | Urban Redevelopment | 1 |
| | | | Credit 3 | Brownfield Redevelopment | 1 |
| 1 | | | Credit 4.1 | Alternative Transportation, Public Transportation Access | 1 |
| | | | Credit 4.2 | Alternative Transportation, Bicycle Storage & Changing Rooms | 1 |
| | | | Credit 4.3 | Alternative Transportation, Alternative Fuel Refueling Stations | 1 |
| | | X | Credit 4.4 | Alternative Transportation, Parking Capacity | 1 |
| | | | Credit 5.1 | Reduced Site Disturbance, Protect or Restore Open Space | 1 |
| 1 | | | Credit 5.2 | Reduced Site Disturbance, Development Footprint | 1 |
| | | | Credit 6.1 | Stormwater Management, Rate and Quantity | 1 |
| | | | Credit 6.2 | Stormwater Management, Treatment | 1 |
| | | | Credit 7.1 | Landscape & Exterior Design to Reduce Heat Islands, Non-Roof | 1 |
| 1 | | | Credit 7.2 | Landscape & Exterior Design to Reduce Heat Islands, Roof | 1 |
| | | | Credit 8 | Light Pollution Reduction | 1 |

**TABLE 9. LEED TABLE 2 – WATER EFFICIENCY**

| 2 | | | Water Efficiency | Possible Points | 5 |
|---|---|---|---|---|---|
| Y | ? | N | | | |
| 1 | | | Credit 1.1 | Water Efficient Landscaping, Reduce by 50% | 1 |
| | | | Credit 1.2 | Water Efficient Landscaping, No Potable Use or No Irrigation | 1 |
| | | | Credit 2 | Innovative Wastewater Technologies | 1 |
| 1 | | | Credit 3.1 | Water Use Reduction, 20% Reduction | 1 |
| | | | Credit 3.2 | Water Use Reduction, 30% Reduction | 1 |

**TABLE 10. LEED TABLE 3 – ENERGY & ATMOSPHERE**

| 10 | | | Energy & Atmosphere | Possible Points | 17 |
|---|---|---|---|---|---|
| Y | ? | N | | | |
| Y | | | Prereq 1 | Fundamental Building Systems Commissioning | |
| Y | | | Prereq 2 | Minimum Energy Performance | |
| Y | | | Prereq 3 | CFC Reduction in HVAC&R Equipment | |
| 2 | | | Credit 1.1 | Optimize Energy Performance, 2.50 to 12.50% below T24 | 2 |
| 2 | | | Credit 1.2 | Optimize Energy Performance, 12.51 to 22.50% below T24 | 2 |
| 2 | | | Credit 1.3 | Optimize Energy Performance, 22.51 to 32.50% below T24 | 2 |
| 2 | | | Credit 1.4 | Optimize Energy Performance, 32.51 to 42.50% below T24 | 2 |
| 1 | | | Credit 1.5 | Optimize Energy Performance,42.51 to > 47.50% below T24 | 2 |
| | | | Credit 2.1 | Renewable Energy, 5% | 1 |
| | | | Credit 2.2 | Renewable Energy, 10% | 1 |
| | | | Credit 2.3 | Renewable Energy, 20% | 1 |
| 1 | | | Credit 3 | Additional Commissioning | 1 |
| | | | Credit 4 | Ozone Depletion | 1 |
| | | | Credit 5 | Measurement & Verification | 1 |
| | | | Credit 6 | Green Power | 1 |

TABLE 11. LEED TABLE 4 – MATERIALS & RESOURCES

| 5 | | | Materials & Resources | Possible Points | 13 |
|---|---|---|---|---|---|
| Y | ? | N | | | |
| Y | | | Prereq 1 | Storage & Collection of Recyclables | |
| | | | Credit 1.1 | Building Reuse, Maintain 75% of Existing Shell | 1 |
| | | | Credit 1.2 | Building Reuse, Maintain 100% of Existing Shell | 1 |
| | | | Credit 1.3 | Building Reuse, Maintain 100% Shell & 50% Non-Shell | 1 |
| 1 | | | Credit 2.1 | Construction Waste Management, Divert 50% | 1 |
| | | | Credit 2.2 | Construction Waste Management, Divert 75% | 1 |
| | | | Credit 3.1 | Resource Reuse, Specify 5% | 1 |
| | | | Credit 3.2 | Resource Reuse, Specify 10% | 1 |
| 1 | | | Credit 4.1 | Recycled Content, 5% (post-consumer + 1/2 post-industrial) | 1 |
| 1 | | | Credit 4.2 | Recycled Content, 10% (post-consumer + 1/2 post-industrial) | 1 |
| 1 | | | Credit 5.1 | Local/Regional Materials, 20% Manufactured Regionally | 1 |
| 1 | | | Credit 5.2 | Local/Regional Materials, 50% Extracted Regionally | 1 |
| | | | Credit 6 | Rapidly Renewable Materials | 1 |
| | | | Credit 7 | Certified Wood | 1 |

TABLE 12. LEED TABLE 5 – INDOOR ENVIRONMENTAL QUALITY

| 11 | | | Indoor Environmental Quality | Possible Points | 15 |
|---|---|---|---|---|---|
| Y | ? | N | | | |
| Y | | | Prereq 1 | Minimum IAQ Performance | |
| Y | | | Prereq 2 | Environmental Tobacco Smoke (ETS) Control | |
| 1 | | | Credit 1 | Carbon Dioxide (CO2) Monitoring | 1 |
| 1 | | | Credit 2 | Increase Ventilation Effectiveness | 1 |
| 1 | | | Credit 3.1 | Construction IAQ Management Plan, During Construction | 1 |
| 1 | | | Credit 3.2 | Construction IAQ Management Plan, Before Occupancy | 1 |
| 1 | | | Credit 4.1 | Low-Emitting Materials, Adhesives & Sealants | 1 |
| 1 | | | Credit 4.2 | Low-Emitting Materials, Paints | 1 |
| 1 | | | Credit 4.3 | Low-Emitting Materials, Carpet | 1 |
| | | | Credit 4.4 | Low-Emitting Materials, Composite Wood | 1 |
| 1 | | | Credit 5 | Indoor Chemical & Pollutant Source Control | 1 |
| | | | Credit 6.1 | Controllability of Systems, Perimeter | 1 |
| | | | Credit 6.2 | Controllability of Systems, Non-Perimeter | 1 |
| 1 | | | Credit 7.1 | Thermal Comfort, Comply with ASHRAE 55-1992 | 1 |
| 1 | | | Credit 7.2 | Thermal Comfort, Permanent Monitoring System | 1 |
| 1 | | | Credit 8.1 | Daylight & Views, Daylight 75% of Spaces | 1 |
| | | X | Credit 8.2 | Daylight & Views, Views for 90% of Spaces | 1 |

**TABLE 13. LEED TABLE 6 – INNOVATION & DESIGN PROCESS**

| Y | ? | N | | Innovation & Design Process | Possible Points |
|---|---|---|---|---|---|
| 4 | | | | | 5 |
| 1 | | | Credit 1.1 | ID: Exemplary Performance Recycled Content | 1 |
| 1 | | | Credit 1.2 | ID: Exemplary Performance Regional Materials | 1 |
| 1 | | | Credit 1.3 | ID: Reduced Kitchen Water Consumption | 1 |
| | | | Credit 1.4 | Innovation in Design: Specific Title | 1 |
| 1 | | | Credit 2 | LEED™ Accredited Professional | 1 |

# APPENDIX D: HVAC AND KITCHEN EQUIPMENT LIST

**TABLE 14. HVAC AND KITCHEN EQUIPMENT LIST**

| Asset Name | Manufacturer Name | Model | Rated Power |
|---|---|---|---|
| Chiller Unit | | | |
| Chiller Unit | | | |
| A/C Condenser | Carrier | 38TXA024340 | |
| Motor | GE | | |
| A/C Condenser | Carrier | 38TXA048330 | |
| Motor | GE | | |
| Fan Coil | Carrier | FX4BNF048 | |
| Motor | | | |
| Chiller Unit | Arctica | BC-48-D0-0-0-L1-I1C | |
| Chiller Unit | Arctica | BC-48-R2-0-0-L1-CC | |
| Chiller Unit | Delfield | N8156B | |
| Chiller/Burner Unit | Atlas Metal Industries | WCM-HP-2 | 1500W |
| Chiller/Burner Unit | Atlas Metal Industries | WCM-HP-2 | |
| Chiller Unit | Delfield | N8156B | 187 W (.25HP) |
| Chiller Unit | Delfield | N8156B | 187 W (.25HP) |
| Chiller Unit | Delfield | N8156B | 187 W (.25HP) |
| Chiller Unit | Delfield | N8156B | 187 W (.25HP) |
| Chiller Unit | Delfield | N8156B | 187 W (.25HP) |
| Chiller Unit | Delfield | N8156B | 187 W (.25HP) |
| Air Filter | Orenco Systems, Inc. | CF3 | |
| Air Handler AHU-1 | Energy Labs | C6872-FCH-L | |
| Air Handler AHU-2 | Energy Labs | C6265-FCH-L | |
| Air Handler AHU-3 | Energy Labs | C4866-FC-L | |
| Air Handler AHU-4 | Energy Labs | C5093-FH-L | |
| Air Handler AHU-5 | Energy Labs | C7355-FH-L | |
| Air Handler AHU-4A | Energy Labs | C6193-E | |
| Air Handler AHU-5A | Energy Labs | C7355-E | |
| Air Curtain | Berner International Corp. | | |
| Motor | | | |
| Air Curtain | Berner International Corp. | | |
| Motor | | | |
| Motor | | | |

| Asset Name | Manufacturer Name | Model | Rated Power |
|---|---|---|---|
| Air Curtain | Berner International Corp. | | |
| Motor | | | |
| Air Curtain | Berner International Corp. | | |
| Motor | | | |
| Water De-Ionizing System | Culligan | Hi-Flo 3E | 3W-100W |
| Water Filter | Ecolab | | |
| Water Filter | | AR-X | |
| Tank - Hot Water Storage | | | |
| Boiler | Raypak | WH3-0202 | |
| Pump | Armstrong | S-35 BF | 124 W |
| Motor | Baldor | | |
| Boiler | Raypak | WH3-0202 | |
| Pump | Armstrong | S-35 BF | |
| Motor | Baldor | | |
| Garbage Disposer | In Sink Erator | SS-500 | 3728 W (5HP) |
| Garbage Disposer | In Sink Erator | SS-200 | 2HP |
| Garbage Disposer | In Sink Erator | SS-200 | 2HP |
| Wheelchair Lift | | | |
| Light Control System LCP 1 | Lighting Control and Design | GR 2400 | |
| Light Control System LCP 2 | Lighting Control and Design | GR 2400 | |
| Electrical Operator | Chamberlain Group | Liftmaster | |
| Motor | AO Smith | | |
| Electrical Operator | Chamberlain Group | Liftmaster | |
| Motor | AO Smith | | |
| Hood UV Light Control Box | Halton | | |
| Exhaust Fan EF-1 | Greenheck | SWB-220-30-CCW-UB-G | |
| Exhaust Fan EF-2 | Greenheck | SFB-9-7-CCW-UB-X | |
| Exhaust Fan | Loren Cook Company | 150 CPS | |
| Motor | | | |
| Exhaust Fan EF-4 | Greenheck | SFB-210-5-CCW-UB-G | |
| Exhaust Fan EF-5 | Greenheck | SWB-210-7-CCW-UB-G | |
| Exhaust Fan EF-6 | Greenheck | SWB-210-5-CCW-UB-G | |
| Exhaust Fan EF-7 | Greenheck | SFB-210-5-CCW-UB-G | |
| Exhaust Fan EF-8 | Greenheck | SFB-210-F-CCW-UB-X | |
| Exhaust Fan RF-9 | Greenheck | GB-180HP-10-X | |
| Exhaust Fan EF-10 | Greenheck | GB-121-5-X | |
| Exhaust Fan | Greenheck | GB-091-4X-QD-R3 | |
| Exhaust Fan | Greenheck | FHI-14X14-G-IS | |

| Asset Name | Manufacturer Name | Model | Rated Power |
|---|---|---|---|
| Exhaust Fan EF-13 | Loren Cook Company | 150 CPS | |
| Motor | | | |
| Exhaust Fan | Greenheck | GB-101-4X-QD-R4 | |
| Exhaust Fan | Greenheck | FHI-16X16-G-IS | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Exhaust Hood | Halton | KVE | |
| Fire Alarm System - Control Panel | Silent Knight | 5820XL | |
| Fire Sprinkler Riser | | | |
| Fire Sprinkler Riser | | | |
| ANSUL Wet Fire Suppression System | ANSUL | R-102 | |
| ANSUL Wet Fire Suppression System | ANSUL | R-102 | |
| ANSUL Wet Fire Suppression System | ANSUL | R-102 | |
| ANSUL Wet Fire Suppression System | ANSUL | R-102 | |
| ANSUL Wet Fire Suppression System | ANSUL | R-102 | |
| ANSUL Wet Fire Suppression System | ANSUL | R-102 | |
| Door - Roll-up | Chamberlain Group | | |
| Door - Roll-up | Chamberlain Group | | |
| Boiler HHW #1 | Lochinvar | CHN0991 | |
| Boiler HHW #2 | Lochinvar | CHN0991 | |
| Pump HHW #1 | Taco | FI1509E2DAJ1L0B | |
| Motor | Baldor | | |
| Pump HHW #2 | Taco | FI1509E2DAJ1L0B | |
| Motor | Baldor | | |
| Air Separator | Taco | | |
| Chemical Feeder Tank | J.L. Wingert Co. | | |
| Expansion Tank | Taco | | |
| Appliance Outlet Center | Halton | KDS-I | |
| Electric Steam Kettle | Cleveland Range Ltd. | KET-12-T | 13,000W |
| Electric Steam Kettle | Cleveland Range Ltd. | KET-12-T | |
| Mixer | Hobart | H-600 | |
| Slicer - Meat/Cheese | Hobart | 1712 | |

| Asset Name | Manufacturer Name | Model | Rated Power |
|---|---|---|---|
| Food Cutter | Hobart | 84145 | |
| Tilt Skillet | Cleveland Range Ltd. | | |
| Stove - Gas Range | Garland | M44R | |
| Steamer | Electrolux | | |
| Mixer | Hobart | A-200 | |
| Oven - Convection | Vulcan | SG22 | |
| Stove - Gas Range | Garland | M44R | |
| BBQ Rotisserie Unit | Old Hickory | N/9GRH | |
| Heated Cabinet | Carter-Hoffman | PH1835 | 1,500W |
| Rotisserie Oven | Henny Penny | SCD-6 | |
| Deep Fryer | Pitco | | |
| Charbroiler | U.S. Range | | |
| Grill with burners | U.S. Range | | |
| Proofing Cabinet | Sammons Equipment | 9234-HP-IN-UA-17 | 2,075W |
| Pizza Oven | Lincoln | 1116-000-A | |
| Pizza Oven | Lincoln | 1116-000-A | |
| Panini Grill | Star | | |
| Griddle | Wells | | |
| Stove - Gas Range | U.S. Range | | |
| Soup Well | American Permanent Ware Co. (APW) | CH-11D | 1,650W |
| Steam Well | American Permanent Ware Co. (APW) | BM-30D | 1,200W |
| Food Warmer | Hatco | GRSBF-48-I | 1,000W |
| Food Warmer | Hatco | GRSBF-48-I | 1,000W |
| Food Warmer | Hatco | GRSBF-48-I | 1,000W |
| Food Warmer | Hatco | GRSBF-60-F | 950W |
| Charbroiler | U.S. Range | | |
| Banquet Cart | Carter-Hoffman | BB120XL | 1,500W |
| Stove - Gas Range | U.S. Range | | |
| Coffee Machine | Dagma | | |
| Slicer - Meat/Cheese | Berkel | 829A | 372W (0.5HP) |
| Soup Bar | | | |
| Soup Well | American Permanent Ware Co. (APW) | CH-11D | |
| Soup Well | American Permanent Ware Co. (APW) | CH-11D | |
| Salad Bar | | | |
| Dishwasher | Champion Industries | 6KPRB | |
| Condenser Unit - Icemaker | Manitowoc Ice, Inc. | JC0895 | |
| Condenser Unit | Scotsman | ERC301-32A | |
| Ice Machine | Manitowoc Ice, Inc. | Cme1006 | |
| Refrigerator | Traulsen | AHT 3-32NUT | |

| Asset Name | Manufacturer Name | Model | Rated Power |
|---|---|---|---|
| Refrigerator | Delfield | SD2R2-SH | |
| Refrigerator | Delfield | SD1R2-SH | |
| Chef Base | True Freezer | TRCB-110 | |
| Refrigerator | Delfield | SRRI1-S | |
| Sandwich/Salad Unit | True Freezer | TSSU-48-12 | |
| Refrigerator | Delfield | SRRI1-S | |
| Sandwich/Salad Unit | True Freezer | TSSU-48-12 | |
| Undercounter Refrigerator | True Freezer | TUC-93 | |
| Refrigerator | Delfield | SRRI1-S | |
| Ice Cream Cabinet | Kelvinator | 44HR | |
| Soft Serve Ice Cream Machine | Taylor | 794-33 | |
| Dessert Showcase | Arctica | | |
| Cold Pan Unit | Delfield | N8156B | |
| Hot/Cold Drop-In Unit | Atlas Metal Industries | WCM-HP-2 | |
| Hot/Cold Drop-In Unit | Atlas Metal Industries | WCM-HP-2 | |
| Cold Pan Unit | Delfield | N8156B | |
| Cold Pan Unit | Delfield | N8156B | |
| Chef Base | True Freezer | TRCB-52 | |
| Cold Pan Unit | Delfield | N8118B | |
| Refrigerator | Delfield | SD2R2-SH | |
| Walk-in Refrigerator no. 1 | Refrigerator Manufacturers, Inc. | | |
| Walk-in Refrigerator no. 2 | Refrigerator Manufacturers, Inc. | | |
| Condenser Unit | Keep Right | KUCB123A | |
| Motor | | | |
| Motor | | | |
| Motor | | | |
| Condenser Unit | Keep Right | KUCB123A | |
| Motor | | | |
| Motor | | | |
| Motor | | | |
| Walk-in Freezer | | | |
| Condenser Unit | Keep Right | KUCB204DED | |
| Motor | | | |
| Motor | | | |
| Motor | | | |
| Motor | | | |
| Cold Pan Unit | Delfield | N8118B | |
| Cold Pan Unit | Delfield | N8118B | |
| Cold Pan Unit | Delfield | N8118B | |
| Trash Compactor | Marathon | | |
| Cardboard Compactor | Marathon | | |

| Asset Name | Manufacturer Name | Model | Rated Power |
|---|---|---|---|
| Electrical Operator | Chamberlain Group | Liftmaster | |
| Motor | AO Smith | | |
| Electrical Operator | Chamberlain Group | Liftmaster | |
| Motor | AO Smith | | |
| Door - Roll-up | Chamberlain Group | | |
| Door - Roll-up | Chamberlain Group | | |

# APPENDIX E: DRANETZ POWERVISA® AND CURRENT TRANSDUCER TECHNICAL SPECIFICATIONS

## POWERVISA
### Power Quality Analyzer


*Equipped with 8 independent channels, the 3-phase PowerVisa® is the only advanced power monitoring instrument to incorporate a color touch screen into its lightweight design. Automated setups provide instant detection of circuits and configurations, ensuring that the instrument is ready to successfully collect data. Users can select the length and mode of data collection, including troubleshooting, data logging, power quality surveys, energy and load balancing. The PowerVisa collects data at 256 samples/cycle/channel, offers remote communications using RS-232, ethernet or USB options, and meets IEEE 1159 and the newest European standards.*

| |
|---|
| **Measured Parameters** |
| (4) differential inputs, 1-600 Vrms, AC / DC, 0.1% rdg + 0.05% FS, 256 samples/cycle, 16 bit ADC |
| (4) inputs with CTs 1-6000 Arms, CT -dependent, AC/DC, 256 samples/cycle, 0.1% rdg + CTs, 16 bit ADC |
| Frequency range, 10 mHz resolution, 45-65 Hz |
| Phase lock loop – standard PQ mode |
| **Monitoring/Compliance** |
| IEEE 1159 |
| IEC 61000-4-30 Class A |
| EN50160 Quality of Supply |
| **Power Quality Triggers** |
| Cycle-by-cycle analysis; 256 samples/cycle; ½ RMS stpes |
| L-L, L-N, N-G RMS variations: sags/swells/interruptions |
| RMS recordings and Waveshape recordings (30 pre-fault, 100 post -fault cycles) |
| Low and medium frequency transients – V&I |
| Harmonics summary parameters |
| Cross trigger V&I channels |
| RMS event characterization (IEEE or IEC) |
| **Distortion / Power / Energy** |
| W, VA, VAR, TPF, DPF, Demand, Energy, etc.; Harmonics & Interharmonics per IEC 61000-4-7 |
| THD/Harmonic Spectrum, TID/Interharmonic Spectrum (V, I, W) to 63rd |
| Crest factor, K factor, transformer derating factor, telephone interference factor |
| **General Specifications** |
| Size (HxWxD): 12" x 2.5" x 8"; Weight: 3.8 lbs |
| Operating temperature: 0 to 50 degrees C; Storage temperature: -20 to 55 degrees C |
| Humidity: 10 – 90% non-condensing |
| Memory options (must have one): Up to 128M removable compact flashcard |

## *AC Clamp-On Probes*

Clamp-on type probes are available in the following ranges as low as 0.1 A up to 3000 A RMS. All of the probes listed below plug directly into the PX5 family of products as well as the Series 61000 current module 61MAC.

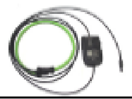
| Product Number | Range | | Amplitude Accuracy ± | Phase Accuracy ± | Frequency Range | Maximum Conductor Size |
|---|---|---|---|---|---|---|
| TR2500  | 10A to 500 Arms | 10A to 500 Arms | 1.5%of reading +0.6A | < 4° | 48Hz-1kHz | 30mm dia. |
| TR2500A  | 10A to 500Arms | 100A to 500A | 1% | 1.5° | 40Hz to 5KHz | 50mm dia. |
| | | 10A to 100A | 2% | 3° | | |
| TR2501  | 100mA to 1.2Arms | 1.2A | 1.5% | 1° | 40Hz to 5KHz | 15mm dia. |
| | | 100mA | 1.5% | 2° | | |
| TR2510  | 1A to 10 Arms | 1A to 10 A | 1% | 1.5° | 40Hz to 3 KHz | 20 mm dia. |
| TR2510A  | 1A to 10Arms | 5A to 10A | 1.2% | 1.5° | 40Hz to 5KHz | 15mm dia. |
| | | 1A to 5A | 2% | 1° | | |
| TR2520A  | 100A to 3000Arms | 1000A to 3000A | 0.5% | 0.5° | 40Hz to 5KHz | 72mm dia.* |
| | | 300A to 1000A | 0.75% | 0.75° | | |
| | | 100A to 300A | 1.5% | 1.5° | | |
| TR2530A  | 20A to 300Arms | 50A to 300A | 1% | 0.5° | 30Hz to 5KHz | 54mm dia. |
| | | 20A to 50A | 1.5% | 0.6° | | |
| TR2540A  | 10A to 1000A | 100A to 1000A | 1% | 0.4° | 30Hz to 5KHz | 54mm dia. |
| | | 10A to 100A | 1.5% | 0.5° | | |
| TR2550A  | 1A to 100Arms | 10A to 100A | 1% | 2.5° | 40Hz to 10KHz | 15mm dia. |
| | | 1A to 10A | 2% | 5° | | |

Transient Accuracy: ±10% of Reading, ±0.5% Full scale, ≥10 uSec

* or bus bar

## *Flexible Probes*

These types of probes are available in three lengths 24 inches, 36 inches, and 48 inch lengths and available in two maximum ranges of 3000 A RMS and 6000 A RMS. Each probe can be powered by battery or AC adapter and multiple probes can be powered by a single AC adapter.

| Product Number | Range | | Amplitude Accuracy ± | Phase Accuracy ± | Frequency Range | Maximum Conductor Size |
|---|---|---|---|---|---|---|
| DRANFLEX 3000XL  | 3A to 3000A (3 ranges) | 3A to 30A | ± 1 reading ±0.1 A | °1 | 10 Hz To 10 kHZ | 24 in. length up to 8 in. diameter<br>36 in. length up to 11 in. diameter<br>48 in. length up to 17 in. diameter |
| | | 30A to 300A | ± 1 reading ±0.1 A | °1 | | |
| | | 300 to 3000A | ± 1 reading ± 1 A | °1 | | |
| DRANFLEX 6000XL  | 6A to 6000A (3 ranges) | 6A to 60A | ± 1 reading ±0.1 A | °1 | 10 Hz To 10 kHZ | 24 in. length up to 8 in. diameter<br>36 in. length up to 11 in. diameter<br>48 in. length up to 17 in. diameter |
| | | 60A to 600A | ± 1 reading ±0.1 A | °1 | | |
| | | 600A to 6000A | ± 1 reading ± 1 A | °1 | | |
| RR3035A  | 3A to 3000A (3 ranges) | 3A to 30A | ± 0.3A | °1 | 10 Hz To 50 kHZ | 24 in. length up to 8 in. diameter<br>36 in. length up to 11 in. diameter<br>48 in. length up to 17 in. diameter |
| | | 30A to 300A | ± 3 A | °1 | | |
| | | 300 to 3000A | ± 30 A | °1 | | |
| RR6035A  | 6A to 6000A (3 ranges) | 6A to 60A | ± 0.6A | °1 | 10 Hz To 50 kHZ | 24 in. length up to 8 in. diameter<br>36 in. length up to 11 in. diameter<br>48 in. length up to 17 in. diameter |
| | | 60A to 600A | ± 6 A | °1 | | |
| | | 600A to 6000A | ± 60 A | °1 | | |
| CA4300BNC  | | | Required to allow connection of RR3035A or RR6035A flexible probes to PX5 family or Encore Series 61000 module 61MAC instruments. One adapter cable required for each probe to be connected to the PX5 or Encore Series instruments. | | | |

Transient Accuracy: ±10% of Reading, ±0.5% Full scale, ≥10 uSec

# REFERENCES

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