Continuous Commissioning® of an Office/Laboratory Building

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Abstract

Initial implementation of Continuous Commissioning® (CC®) measures in Building 6585, the Technology Support Center at Sandia National Laboratory, was conducted during February and March, 2005. The major measures implemented were reduction of minimum flow settings of VAV boxes as appropriate, correction of an error in the control code that resulted in continuous operation of one AHU, and reduction of static pressure settings on the AHUs. In addition, AHU start times were generally delayed by one to two hours, chilled and hot water secondary loop performance was improved, and the preheat control strategy was changed. Data for heating and electricity consumption were analyzed for approximately four months following implementation of most of the measures, and savings of approximately 127,000 kWh of electricity and 250 MCF of gas were observed. If the savings continue at the same weather adjusted rate for one year, total cost savings will exceed $30,000, or more than 50% of the HVAC energy consumption of the building.

Background Information

Continuous Commissioning® (CC®)[1] has been shown to be a highly cost effective way of reducing energy cost while improving comfort in many different types of facilities in widely varying climates. (Liu et al. 2002) The Energy Management Team (EMT) at Sandia National Laboratory (SNL) was tasked to determine the effectiveness of CC in existing buildings at the Laboratory and determine if CC could become an important part of the overall energy management program at the SNL. The SNL staff chose Building 6585, a 99,579 ft² office and laboratory building as the test case. This building was built in 1995 as a design-build project, and control schemes had not been changed significantly since. Hence it was believed that there would be significant opportunities present in this building. Initial review of utility bills indicated that while chiller consumption was not excessive due to extensive use of economizers, evaporative cooling and cooling tower water for cooling, gas consumption seemed higher than necessary for a building with VAV air handling systems.

Given the level of ongoing team responsibilities, it was decided to contract with the Energy Systems Laboratory (ESL) to implement Continuous Commissioning® (CC®) in this trial building.

Facility Description and Energy Use

SNL Building 6585, the Technology Support Center is a 2-story building with a basement and an HVAC penthouse (see Figure 1). The total conditioned space is 99,579 ft² of which the mechanical rooms in the basement and penthouse account for approximately 20%. Heating and cooling

Figure 1. Technology Development Center at Sandia National Laboratory.

[1] Continuous Commissioning and CC are registered trademarks of the Texas Engineering Experiment Station. To improve readability, the symbol will sometimes be omitted.

for the building are provided by two 4 MMBtu/hr hot water boilers and three 225 ton electric screw chillers. Five single duct, Variable Air Volume (VAV) systems, with reheat at the terminal boxes serve the building. Air handler units 1 and 4 serve the exterior zones, which are primarily office space; air handler unit 5 provides conditioned air for a conference room; and the remaining air handlers, units 2 and 3 were originally designed to use 100% outside air and serve laboratory areas, which are interior zones. Some time near the end of the design phase or just prior to the construction phase, a decision was made to install returns with dampers for AHUs 2 and 3. This was done because it was anticipated that significant square footage would not be used as laboratories. Each of the AHUs contains both a chilled water coil and a cooling coil that is connected to the cooling tower sump through a heat exchanger. The cooling towers are used to provide building cooling for nearly six months per year since Albuquerque has over 5,000 hours per year when wet bulb temperature is below 50ºF (Air Force 1978). The EMCS (Energy Management Control System) is a Siemens Apogee system. The DDC (Direct Digital Control) hierarchical level is capable of monitoring and controlling down to the VAV terminal box.

Energy use in the building is measured using two electrical meters and a gas meter. The electrical meters provide hourly readings while the gas meter is normally read on the first day of each month. Since the CC project began, it has generally been read daily. One of the electric meters primarily monitors a number of computer servers so the nominal load of 100 kW on this meter shows very little variation throughout the day or the year. The other electric meter monitors all remaining electricity use in the building including the chillers and distribution systems.

Gas use from November 2003 – November 2004 is shown in Figure 2. Total use for the 12-month period beginning with December, 2003 which will be used as the baseline period for this project was 3464 MCF. An average gas cost of $7.00/MCF will be used. Electricity use was 3,070,189 kWh during the same December – November period, for an average use level of approximately 350 kW is shown in Figure 3. Figure 3 shows both total electricity consumption in the top series and process electricity consumption in the bottom series. The electricity price paid for September-November, 2004 averaged $0.0407/kWh, so this value will be used as the basis for this project. Using these prices, annual baseline energy costs for Building 6585 total $149,205 including $24,248 for gas and $124,957 for electricity as shown in Table 1.

Examination of the pattern of gas consumption shows that summer use is typically half of the winter consumption indicating that there is significant reheat in the building. Similar examination of the electricity consumption pattern shows that base process consumption increased by 15-20 kW during May and that chillers were used beginning in early May and continuing through late October with scattered use during November. Chiller operation appears to have been continuous from about mid-June through mid-August. Analysis of the consumption data, observations of AHUs and pumps during the site visit including selected pressure measurements and flow measurements, and use of EMCS schedule information lead to the estimates of HVAC consumption provided in Table 1.

Table 1. Electricity and gas consumption for Building 6585 from December 2003 – November 2004 including estimated HVAC use.

Use	Annual Consumption	Cost ($/year)
Electricity	3,070,189 kWh	$124,957
Gas	3464 MCF	$24,248
Baseline Energy Cost		$149,205
Estimated HVAC Use/Cost		
Heating	3464 MCF	$24,248
Chiller cooling	224,400 kWh	$9,135
Fans and pumps	475,000 kWh	$19,337
Total HVAC Cost		$52,720

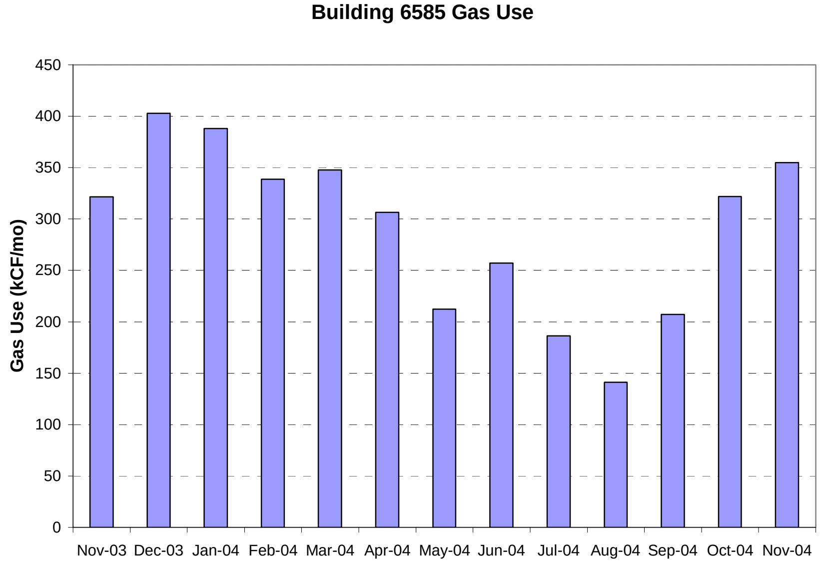

Figure 2. Gas use for Building 6585 from December, 2003 through November, 2004 in thousands of cubic feet per month.

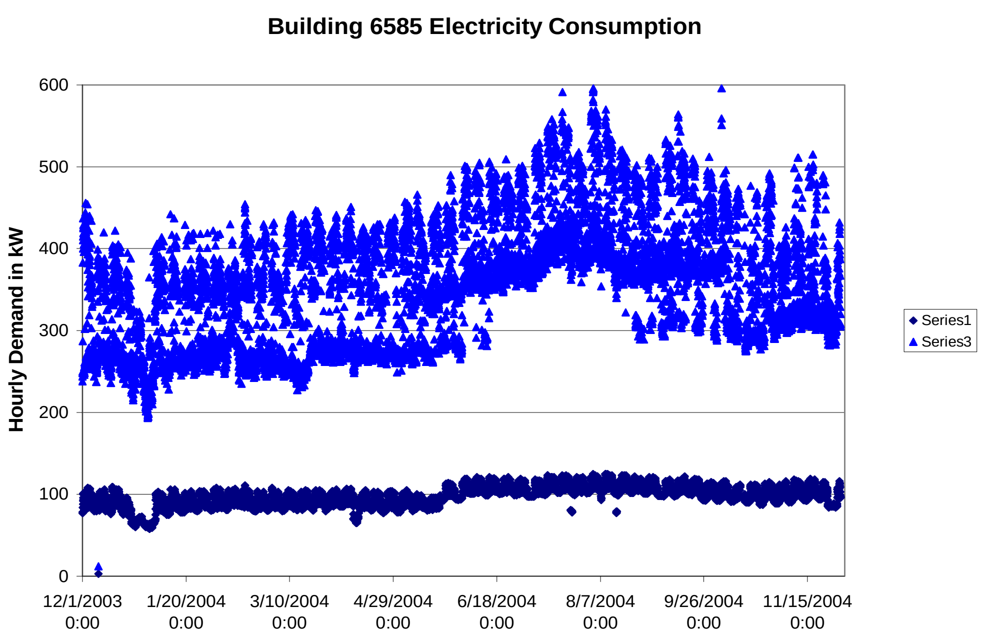

Figure 3. Total hourly electricity use for Building 6585 from December, 2003 through November, 2004 in kW (light blue). Bottom data is process consumption.

HVAC Systems and Operation

On each single duct VAV unit, the supply fan speed is controlled by the duct static pressure set point. The control algorithms indicate that constant value set points are used. The static pressure set points range from 1.0-1.8 in. H_2O. Air handler units 1, 4, and 5 are configured with return air fans as shown in Figure 4. The return fan speeds for units 1 and 4 are modulated and sequenced with the relief air dampers to control building pressurization. The return fan speed for unit 5 is controlled to maintain a constant ratio of 95% of the supply fan speed. Air handler units 2 and 3 are not configured with return air fans. They use face and bypass dampers.

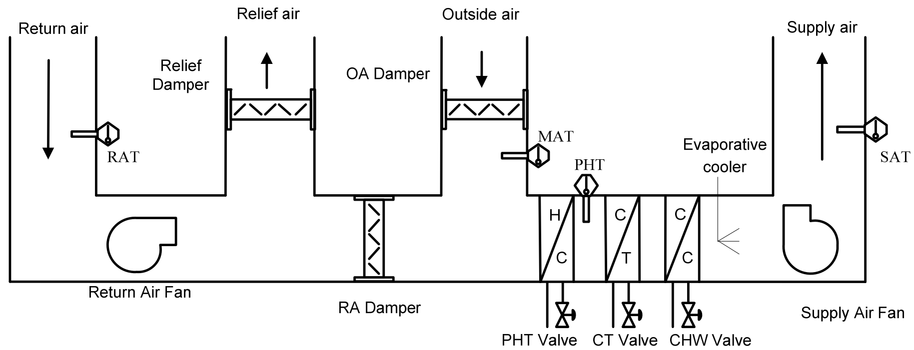

Figure 4. Air handler schematic for units 1, 4, and 5.

The supply air temperature set point for each unit uses a linear reset schedule based on outside air temperature (see Table 2), with the exception of unit 5. The supply air temperature set point for unit 5 is based on the VAV box cooling loop output values. According to the control program, the preheat valve, the cooling tower coil valve, the evaporative cooling (when ambient conditions meet the enthalpy and wet bulb temperature criteria for the outside and return air), and the chilled water valve are sequenced to maintain the supply air temperature.

Table 2. Supply air temperature reset schedules.

Supply Air Reset Schedule based on OAT				
AHU #	OAT LO (°F)	OAT HI (°F)	SA HI (°F)	SA LO (°F)
1	60	100	63	55
2	60	100	65	55
3*	60	100	65	55
4	60	100	63	55
Supply Air Reset Schedule based on VAV load				
AHU#	Load LO (%)	Load HI (%)	SA HI (°F)	SA LO (°F)
5	50	85	65	55

* No control programming available. Assumed reset schedule is the same as AHU #2.

A dedicated chilled water and hot water system is provided for the building cooling and heating loads. The cooling load for this building consists of the sensible and latent loads met by the AHUs in addition to process loads in the laboratory sections of the building met by fan coil units. The chilled water system is located in the basement of the building. Three chillers (with R-22, each at 225 tons) are operating in a parallel configuration supplying chilled water to a primary/secondary distribution system. The control strategy for the chiller staging is based on loop flow rate. If the loop flow rate is greater than 560 GPM, the chiller load is greater than 78%, and the loop supply water temperature is 2°F greater than its set point, then the lag chiller will be brought online. Typically, one chiller is online during the summer months (May-October). During extreme cooling load conditions a second chiller is called online. The logged runtime hours of the three chillers are 9,699, 8,495 and 8,016 for a total of 26,210 hours of chiller operating time, or an average of 2621 hours/year in the approximately 10 years since the building was built. This corresponds to 24 hour operation of a single chiller for 2 months with an average of 33 hours per week of chiller operation for an additional four The supply air temperature set point for each unit uses a linear reset schedule based on outside air temperature (see Table 2), with the exception of unit 5. The supply air temperature set point for unit 5 is based on the VAV box cooling loop output values.

An additional source of cooling for the building is provided by the cooling tower system. Three cooling towers are located on the south side of building 6585. Each tower has a nominal cooling capacity of 235 tons. Original cooling tower piping design allows the towers to operate with any chiller that is enabled. Two remote sumps for the cooling towers are located in the basement pump room. These remote sumps have a maximum storage capacity of 2,850 gallons. Under ambient conditions when the cooling tower sump temperature is sufficiently low, tower supply water can be used to provide cooling to the air handler units and the process chilled water system through a plate-frame heat exchanger. The cooling towers are enabled when a chiller condenser water pump is running, a process heat exchanger tower water pump is running, or the building supply fan tower water coil pump is running. Typically, two fans operate when the towers are enabled.

The building hot water system is located in the penthouse. Heating is provided by two natural gas water tube boilers (4 MMBTUH max. output/boiler). According to information provided, these boilers were converted from LPG and capacities corrected for 5500 ft elevation. The boilers and the secondary hot water pumps are controlled by unitary controllers. Apogee programming is used to interlock the two unitary controllers and stage the boilers based on outside air temperature set points. The hot water system is configured in a primary/secondary distribution system. The secondary hot water distribution system is driven by two variable speed hot water pumps (85 GPM each). In addition to the secondary distribution system, two variable speed pumps (41 GPM each) deliver hot water to the laboratory section.

CC Assessment

A Continuous Commissioning® (CC®) Assessment of Building 6585 was conducted in January 2005. The assessment began with a meeting between two engineers from the ESL, the Energy Manager, two other engineers on the Sandia EMT, and the building controls technician. At this meeting the HVAC system characteristics and control as currently implemented in the building were discussed and current gas and electricity consumption data was reviewed. It revealed that the building basically works well, but SNL staff indicated that they expected opportunities to improve operational characteristics of the building since the basic building operation was determined and set up as part of a turn-key project in the mid-1990s and has not been optimized since then. This was followed by examination and printing of EMCS screens providing current operating status for all major air handlers, chillers, boilers, and water side distribution systems in the building.

A walkthrough of Building 6585 was conducted the afternoon and the morning of the next day by the ESL personnel and the lab EMT. This walkthrough was primarily devoted to a detailed examination of the systems in the basement and penthouse mechanical rooms supplemented by visits to several offices on the first floor. Measurements of key temperatures, flows and pressures were made during the walkthrough. Information obtained during the walkthrough, supplemented by building drawings, energy consumption data, and additional information supplied by the EMT was subsequently analyzed to identify a preliminary list of CC® measures recommended for implementation in Building 6585.

Observations and Findings of the Walkthrough

During the walkthrough of the building, CO_2 measurements were taken in the office areas of the first floor. The average CO_2 reading was 385 ppm, or only 35 ppm above the ambient level of 350 ppm. This was due to the operation of the economizers in the air handlers at the time of the walk through.

Air Handler Operation

Air handler units 3, 4, and 5 were started at approximately 4:00 a.m. and stopped at 7:00 p.m., Monday through Friday. Air handler unit 2 was started at approximately 5:00 a.m. and stopped at 6:00 p.m. Air Handler unit 1 was operating on a continuous basis. During the periods when an air handler unit is scheduled off, occupants can use the override buttons located on the thermostats to activate the air handler unit for a two hour period. . Static pressure set points on all five AHUs were constant values.

Loop Balancing

In evaluating the chilled water and hot water systems, special attention was given to the positioning of all manual valves. The manual valves located on the discharge side of the secondary chilled water pumps were 50% closed. The manual valves located on the chilled water return lines for each air handler were also 50% closed. Rebalancing was recommended to reduce the pumping power needed to supply the loop.

The hot water system did not have any flow restriction. However, the bypass for the primary and secondary distribution system has a manual valve in place. The valve is 100% open. Only one pump was running at the time of the assessment and the VFD for the pump motor was operating at 60 Hz. No trend data was collected for the hot water supply and return temperatures.

VAV Box Operation

Based on information gathered through discussion with facility personnel, sensor calibration is not performed except when a problem is noted. VAV box calibration plays an important role in the reduction of fan power. Because of time constraints, verification of maximum and minimum air flows for individual terminal boxes was not possible. Because functions within the building change, minimum design flow settings may exceed the necessary airflow requirements. The combined minimum supply flow of 46,800 cfm currently set on the terminal boxes will lead to requirements for reheat during a significant portion of the year and is a contributor to the relatively high reheat observed in the building. It was recommended that minimum flow requirements for each box be evaluated and minimum flow settings be reduced where appropriate.

List of CC® Measures Recommended

1. Spot check calibration of existing sensors
2. Spot check VAV boxes, determine required minimum flows and reduce where appropriate.
3. Develop and implement optimum start-stop strategy for each AHU.
4. Develop and implement a static pressure reset schedule based on outside air temperature for each AHU.
5. Optimize chilled and hot water secondary loop performance. Installation of additional temperature sensors may be required to monitor the ΔT for each loop.
6. Measure minimum outside air flow settings and reduce when they exceed the amount needed to meet Standard 62, or increase if necessary.
7. Examine and optimize combined economizer/tower cooling control strategy and operation.
8. Optimize the preheat control strategy. Reheat the supply air at the terminal box only. Use preheat for coil freeze protection.
9. Evaluate the supply temperature reset strategy and optimize to minimize fan power and heating and cooling energy.

It was conservatively estimated that implementation of these CC® measures would provide annual HVAC operational savings of $23,086.

Implementation of CC® Measures

In order to begin implementation of the CC measures, each system (AHUs, hot water, and cooling system) was set up for trending on the EMCS. All analog input and output points, in addition to on/off and status points were trended. Time series plots were developed for each system and analyzed. System performance problems as well as physical component problems were identified.

Optimization of Air Handler Operation Schedule

Normal operating hours for Building 6585 are from 0600 hours to 1800 hours Monday- Friday. Normally, the air handler equipment is scheduled off for Saturday and Sunday.

It was learned that AHU 1 had been temporarily set to operate continuously in December, 2004. However, when the normal operating schedule was put in place, it still operated continuously due to a problem in the control program. Hence it had apparently been operating continuously for an unknown period, perhaps since the building was built. This problem was located and corrected, and operation then returned to the normal schedule.

The trend data showed that the building reached occupied conditions within 15 minutes of startup and that the optimum start/stop programs were not functioning properly. It was determined that the optimum start algorithms were complex and apparently contained one or more bugs. ESL recommended that the optimum start/stop programs be temporarily removed until the programming could be corrected. The start times for each AHU have been pushed back to 0600 hours. The stop time of 1800 hours was not altered. Building personnel that choose to work outside the normal operating time schedule can use the occupancy override button located at the thermostat to run the corresponding AHU for a two hour period. After the two hour period the AHU will shut off.

Preheat Control Strategy Optimization

Preheat control for AH01- AH04 was modified from its original discharge air temperature control strategy. It is based on mixed air temperature and outside air temperature. If the mixed air temperature falls below the discharge air temperature set point minus 3°F and the outside air temperature is below 45°F then the preheat valve will open. This is a preheat lockout control strategy. This strategy proved very useful for AH02 and AH03. The preheat valves for these AHUs were constantly opened any time the units were running since they are nominally 100% outside air units. Since preheat temperature sensors are not used on any of the AHUs, the alternative was to use the mixed air temperature. In order to optimize preheat control further it is recommended that preheat temperature sensors be installed. Using a preheat temperature set point will minimize preheat consumption further in addition to helping diagnose preheat valve leakage when it occurs.

Static Pressure Optimization

Static pressure sensors for each AHU were located and spot checked for accuracy by ESL Engineers. The static pressure transducer for AH02 was found to be faulty. The EMCS system showed that AH02 was supplying 1.5 in. H_2O to the system but field measurements indicated that 0.6 in. H_2O was actually being supplied. The building HVAC maintenance technician replaced the faulty transducer. Once sensor verification was complete static pressure measurements were taken at each box located at the end-of-line for each duct system. These measurements revealed an excessive amount of static pressure for all the AHU systems.

The terminal boxes used in these AHU systems require a minimum static pressure between 0.17-0.22 in. H_2O in order to operate properly. Field measurements taken by ESL Engineers indicated that 0.5 in. H_2O static pressure set point for each AHU system would satisfy the maximum airflow requirements for the most remote box in each system.

Table 3. Adjusted static pressure set points for each AHU system.

AHU	Static Pressure Set point (in. H2O)	
	Existing	Adjusted
AH01	1.8	0.5
AH02	1.5	0.5
AH03	1.5	0.5
AH04	1.8	0.5
AH05	1.0	0.5

The static pressure set points were reduced to the "Adjusted" values shown in Table 3. for each AHU. In each system the adjusted static pressure set point could have been reduced further. However, limitations of the variable frequency drives (VFDs) prohibit this from happening.

Assuming that building cooling and heating loads are linear functions of outside air temperature, static pressure reset schedules based on outside air temperature were implemented for each AHU system serving exterior zones (see Figure 5). This reset schedule includes three stages. When the outside air is below 40°F the static pressure set point will maintain a constant minimum value (0.5 in H_2O), when the outside air temperature is above 90°F the static pressure set point will not exceed its maximum value (0.8 in. H_2O). Between 40°F and 90°F the set point will vary linearly between the maximum and minimum settings. In addition to the outside air reset schedule, VAV box loading can also reset static pressure if a number of VAV boxes are calling for cooling. AH01, AH04, and AH05 were programmed with these control algorithms. Units such as AH02 and AH03 serve interior zones and typically are not influenced by ambient conditions. Therefore, static pressure reset schedules based on outside air temperature were not implemented for these units; only VAV box loading can reset static pressure.

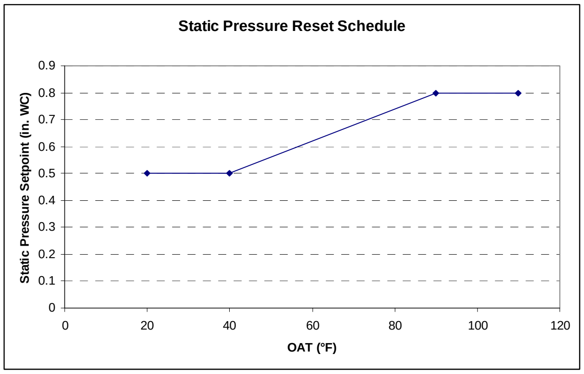

Figure 5. Static pressure set point reset schedule for exterior zone AHU systems.

Return Fan and Relief Damper Control Changes

The return fans and relief dampers for AH01 and AH04 were used to control building static pressure. Originally the return fan and relief dampers modulated simultaneously to maintain the building static pressure. This control strategy led to hunting. To correct this situation the return fan and relief damper were staged (see Figure 6). When the building static pressure is above set point, then the relief damper will open until it is at it maximum position. Once the relief damper is fully opened the return fan speed will increase. If the building pressure is below set point the return fan speed will reduce to minimum speed then modulate the relief damper.

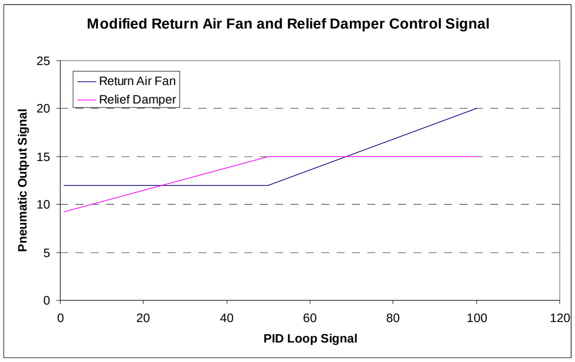

Figure 6. Modified return air and relief damper control strategy for AH01 and AH04.

Optimization of Hot Water Loop

All the manual valves on the preheat coils were opened (Office loop). The ESL Engineers attached gages at the end-of-line location, AH01 preheat coil, and then used the control system to place all the preheat valve positions on each AHU at 100%. Based on information provided from the AHU schedule, the pressure drop across the preheat coils is approximately 1.2 psi. This was the target differential pressure needed for the coil. To be conservative and adjusting for possible weather abnormalities that may develop the differential set point for the office loop was set at 5 psi.

The lab heating loop only serves the reheat coils for the interior sections. Typically, internal spaces don't require heat and outside weather conditions don't influence the system. The differential pressure for the lab loop was reduced to 5 psi. However, the heating demand was minimal for this loop and set point could not be achieved with the secondary pump running at minimum speed. The lowest obtainable differential pressure for this loop was 10 psi. Without the secondary pumps running, the differential pressure reduced to 8.0 psi which is still above the 5 psi set point. The boiler constant speed pump was capable of meeting the needs to the system.

The existing control strategy for each secondary loop systems was modified. Secondary pumps were turned off and allowed to cycle on as required to maintain the 5 psi set point. Dead bands were used to eliminate unnecessary cycling of the secondary pumps. The manual bypass between the primary and secondary loop could not be completely closed because each secondary loop does not contain a bypass or three-way valve to prevent pump dead heading. It was closed approximately 75% forcing supply hot water into the secondary loops instead of re-circulating the water back to the return side of the primary loop.

<u>Optimization of Minimum Outside Air</u>

Minimum outside air requirements for each AHU needed to be determined. However, it was found that the outside air damper for AH05 had mechanical problems prohibiting adjustment. It was found that as the pneumatic actuator applied force to the damper shaft it would bend the shaft instead of rotate it. Because this is a common problem with dampers in general, it was decided that all five AHUs be checked by the building HVAC technician prior to setting dampers. Attempting to set the outside air requirements with this type of damper problem is not recommended.

<u>Terminal Box Optimization</u>

Measurements of airflow were taken and compared to flow values reported by the DDC control system for several boxes. Typically these boxes were the ones used to determine the required static pressure for the system. Some boxes required that the flow coefficient be recalculated to correct the reading from the control system. Concluding that no major problems exist with the box flow stations, investigation into possible minimum airflow reduction was pursued.

The original minimum flow settings for most terminal boxes were found to be approximately 30% of their maximum settings. The design maximum cooling flow for this building was greater than 1.5 CFM per square foot, resulting in minimum flow settings of approximately 0.5 CFM per square foot. This is a fairly typical minimum flow setting, but was causing terminal boxes to use significant reheat in this building. To reduce the amount of reheat, minimum air flow settings were lowered. The airflow reductions were based on lighting density, plug loads, and observed space loads. The majority of minimum flow settings were reduced by 50% and in some cases were reduced even further. Design sizing of the terminal boxes prevents further reduction of airflow in many cases.

At the beginning of commissioning, each box's temperature set point was controlled separately by the occupants of the space. Space set points varied throughout the building to satisfy the comfort needs of the occupants. This means that adjacent zones could be in different modes (heating or cooling). A standard of 74°F for cooling and 70°F for heating has been established for the building. Occupants will have the capability to make minor adjustments to the thermostat as needed.

Energy Impact of CC Implementation

CC measures were implemented beginning on February 14 and continued through March. Figure 7 shows that electric consumption immediately dropped by about 50 kW. The figure shows (from top to bottom) a time series plot of the total electricity consumption in the building, the non-process consumption, and the process consumption. Figure 8 shows the daily electricity consumption for one two week period before any commissioning measures were implemented and two subsequent two week periods following initial implementation of commissioning measures. It is again clear that consumption has dropped by about 50 kW during both weekdays and on weekends.

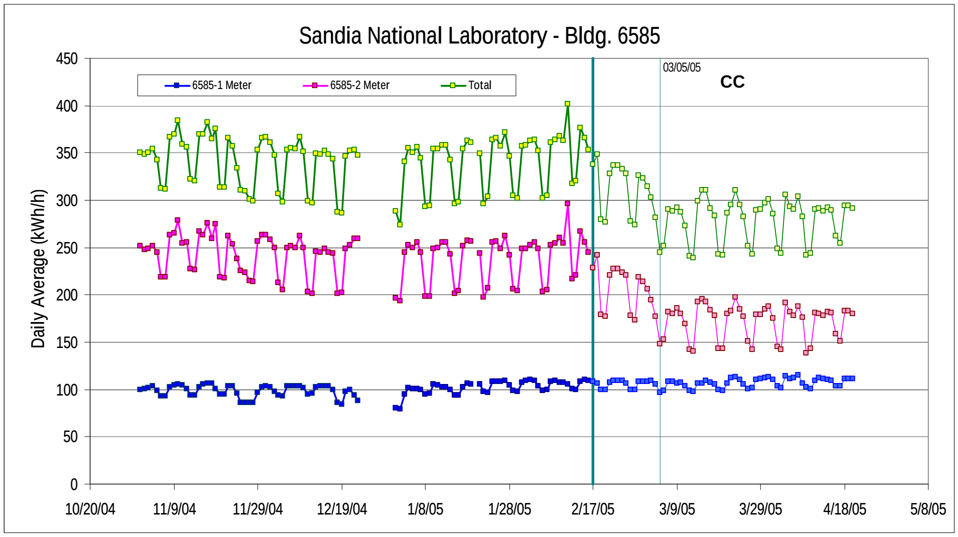

Figure 7. Time series of the electricity use for Building 6585 at Sandia National Laboratory for the previous period and after the CC measures were implemented.

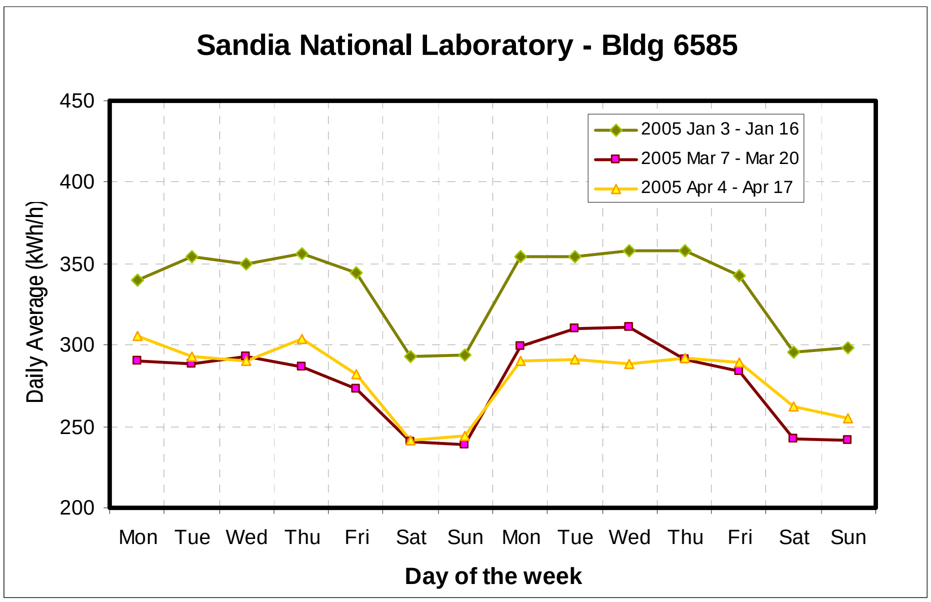

Figure 8. Comparison of the electricity use for the pre- and post –CC periods in Building 6585.

Figure 9 shows the baseline monthly gas consumption data with the appropriate 3-parameter model of the baseline use as a function of temperature (IPMVP 2001). Daily gas consumption data is shown for the two-week period while measures were being implemented and for two subsequent periods of about four weeks each. It is clear that consumption dropped by more than 50% of the baseline consumption. The large red circles show the average consumption for each of the three periods plotted.

The amount of post-CC data is still quite limited, but it is clear that savings will exceed the projected savings of $23,086 per year. Table 5 shows the actual savings for the February/March-July periods shown, with annual projections based on use of 3-parameter models of the gas and electricity use during the baseline period and models of the March – July data for the post-CC period. Weather data for August 2004 – February 2005 was used to estimate savings for the remainder of the year. It appears the savings will exceed 50% of the baseline HVAC consumption in this building.

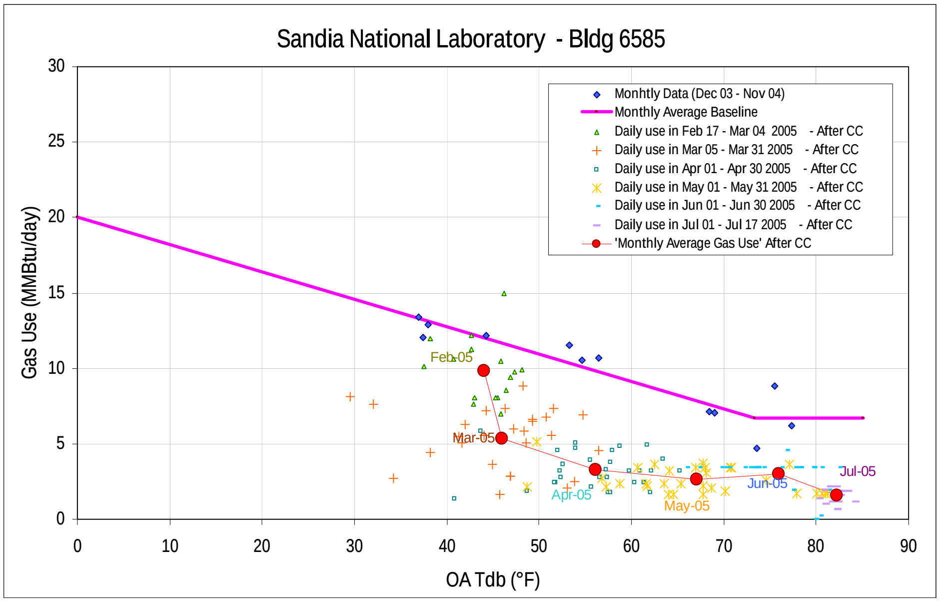

Figure 9. Baseline and daily gas use after CC measures implemented at Sandia National Laboratory Building 6585
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Table 5. Preliminary savings from implementation of CC measures in Building 6585.

Energy Type	Savings Period	Savings	Annual Projected
Electricity (kWh)	Mar 1 – July 17, 2005	$5,200 (127,756)	$16,018
Gas use (MCF)	Feb 17 – July 17, 2005	$5,295 (756)	$14,251 (2,036)
		TOTAL	$30,269

The chiller system was not optimized during the initial commissioning since the chiller was not operating. This will be optimized during summer operation as well as checking and correcting minimum outside air flows as necessary.

Lessons Learned

- Oversized VAV AHUs will tend to have minimum flow values that cause excess reheat.
- Static pressure set points should be determined by measurement in the hydraulically remote terminal boxes. Design values tend to waste fan power.
- Need to trend AHU operation periodically to be sure schedules haven't been changed.
- Need to track consumption to be sure efficiency is maintained.

Conclusions

Initial implementation of CC in Building 6585 has reduced energy cost by over $10,000 from March – mid-July. Projected annual savings based on measured consumption through mid-July are over $30,000 per year, for a 59% reduction in gas consumption and over a 50% reduction in the chiller, fan and pump consumption estimated from the metered data. Fine tuning through the rest of the summer is expected to produce modest additional savings.

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