

**Advanced Automated HVAC Fault  
Detection and Diagnostics  
Commercialization Program**

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**Final Report on Field Demonstration of Air  
Handling Unit and Variable Air Volume Box  
Fault Detection Tools**

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**CONSULTANT REPORT**

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## **Executive Summary**

The purpose of the overall research effort, of which the work described here is one part, is to develop and commercialize FDD methods that can detect common mechanical faults and control errors in air-handling units (AHUs) and variable-air-volume (VAV) boxes. The tools are intended to be sufficiently simple that they can be embedded in commercial building control systems and rely only upon sensor data and control signals that are commonly available in commercial building automation and control systems. AHU Performance Assessment Rules (APAR) is a diagnostic tool that uses a set of expert rules derived from mass and energy balances to detect faults in air-handling units. VAV box Performance Assessment Control Charts (VPACC) is a diagnostic tool that uses statistical quality control measures to detect faults or control problems in VAV boxes.

This test report describes a demonstration study in which APAR and VPACC were embedded in commercial HVAC equipment controllers from several manufacturers and tested at a number of field sites. The goal of the study was to transfer the FDD methods from research to commercial use.

Key words: BACnet, building automation and control, cybernetic building systems, direct digital control, energy management systems, fault detection and diagnostics

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## 1 Introduction

Building HVAC equipment routinely fails to satisfy performance expectations envisioned at design. Such failures often go unnoticed for extended periods of time. Additionally, higher expectations are being placed on a combination of different and often conflicting performance measures, such as energy efficiency, indoor air quality, comfort, reliability, limiting peak demand on utilities, etc. To meet these expectations, the processes, systems, and equipment used in both commercial and residential buildings are becoming increasingly sophisticated. This development both necessitates the use of automated diagnostics to ensure fault-free operation and enables diagnostic capabilities for the various building systems by providing a distributed platform that is powerful and flexible enough to perform fault detection and diagnostics (FDD).

Most of today's emerging FDD tools are stand-alone software products that do not reside in a building control system. Thus, trend data files must be processed off-line, or an interface to the building control system must be developed to enable on-line analysis. This does not scale well because all of the data must be obtained at a single point. A better solution is to embed FDD in the local controller for each piece of equipment, so that the FDD algorithm is executed as a component of the control logic. NIST has developed FDD methods that can detect common mechanical faults and control errors in air-handling units (AHUs) and variable-air-volume (VAV) boxes. The tools are sufficiently simple that they can be embedded in commercial building control systems and only rely upon sensor data and control signals that are commonly available in commercial building automation and control systems.

Software tools have been developed to implement APAR and VPACC, then tested and refined using data generated by simulation, emulation, and laboratory testing [1] and data collected from real buildings [2]. APAR and VPACC were also embedded in commercial AHU and VAV box controllers from several manufacturers and tested in emulation and laboratory environments [3].

The current research project will build upon past work to resolve the remaining barriers to commercialization of FDD: the lack of confidence in automated diagnostics, the specialized knowledge required to embed FDD in HVAC controllers, and the trial and error method of determining fault thresholds. This test report describes a technology demonstration in which APAR and VPACC were embedded in commercial AHU and VAV box controllers and tested at a number of field sites. This demonstration is one component of a larger research project which also includes development of robust FDD parameters for both APAR and VPACC and technology transfer activities to move the FDD algorithms from the research environment to commercial HVAC control products.

## 2 Methodology

### 2.1 AHU Performance Assessment Rules (APAR)

The basis for the air handling unit fault detection methodology is a set of expert rules used to assess the performance of the AHU. The tool developed from these rules is APAR (AHU Performance Assessment Rules). A brief overview of APAR is presented here; a detailed description is available elsewhere [4].

APAR is applicable to single duct VAV and constant volume AHUs with airside economizers. The operation of this type of AHU during occupied periods can be classified into a number of modes, depending on the heating/cooling load and outdoor air conditions. Each mode of operation can be characterized by a different range of values for each of three control signals: the heating coil valve, cooling coil valve, and mixing box dampers. For convenience, the operating modes are summarized below:

- Mode 1: heating
- Mode 2: cooling with outdoor air
- Mode 3: mechanical cooling with 100 % outdoor air
- Mode 4: mechanical cooling with minimum outdoor air
- Mode 5: unknown

Once the mode of operation has been established, rules based on conservation of mass and energy can be evaluated using the sensor and control signal information that is typically available from AHUs. APAR has a total of 28 rules (see Table 2.1). Each rule is expressed as a logical statement that, if true, indicates the presence of a fault. Because the mass and energy balances are different for each mode of operation, a different subset of the rules applies to each mode. There are also some rules that are independent of the operating mode and are always evaluated. A list of possible causes is associated with each rule (see Table 2.2).

Several modifications to the basic APAR algorithm were made to enhance usability and reduce nuisance alarms. Each rule can be individually disabled by the user in order to eliminate nuisance alarms caused by fault conditions that are known to the maintenance staff, but will not be repaired immediately. Since the rules are based on steady state assumptions, there are several delays, during which the rules are not evaluated, to ensure that quasi-steady state conditions exist. There is a delay at the beginning of occupancy and another delay after each mode switch. A third delay establishes the length of time a rule must be satisfied before an alarm is reported. Furthermore, the rules are evaluated using exponentially weighted moving averages of the raw data rather than the current values [4].

The rules in Table 2.1 are generic, not tightly linked to a specific sequence of operations. The rule set was developed for AHUs with hydronic heating and cooling coils and relative enthalpy-based economizers, however, it can easily be adapted for different types of AHUs. For example, Rules 9 and 15 will change based on the type of economizer, whether it is temperature- or enthalpy-based, and whether it compares outdoor conditions to return or to a fixed changeover condition, or some combination thereof. If the cooling coil uses direct expansion instead of chilled water, Rules 13, 14, 19, and 20 do not apply. Also, the causes in Table 2.2 related to the

cooling coil valve (valve stuck or leaking) or the chilled water system (chilled water supply temperature too high, problem with chilled water circulating pump, chilled water not available) are interpreted as problems with the mechanical refrigeration system. If some form of staged heating (electric or combustion) is used instead of hydronic heating, Rules 3 and 4 do not apply. Also, the causes in Table 2.2 related to the heating coil valve (valve stuck or leaking) or the hot water system (hot water supply temperature too low, problem with hot water circulating pump) are interpreted as problems with the staged heating system. For single zone or other AHUs with no supply air temperature setpoint, Rules 5, 8, 13, 19, and 25 do not apply. If there is no mixed air temperature sensor, delete Rules 1, 2, 7, 10, 11, 16, 18, 26, and 27 cannot be evaluated and therefore do not apply.

**Table 2.1: APAR Rule Set**

Mode	Rule #	Rule Expression (true implies existence of a fault)
<b>Heating (Mode 1)</b>	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \varepsilon_t$
	2	For $ T_{ra} - T_{oa}  \geq \Delta T_{min}$ : $ Q_{od}/Q_{sa} - (Q_{od}/Q_{sa})_{min}  > \varepsilon_f$
	3	$ u_{hc} - I  \leq \varepsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \varepsilon_t$
	4	$ u_{hc} - I  \leq \varepsilon_{hc}$
<b>Cooling with Outdoor Air (Mode 2)</b>	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \varepsilon_t$
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	7	$ T_{sa} - \Delta T_{sf} - T_{ma}  > \varepsilon_t$
<b>Mechanical Cooling with 100% Outdoor Air (Mode 3)</b>	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \varepsilon_t$
	9	$T_{oa} > T_{co} + \varepsilon_t$
	10	$ T_{oa} - T_{ma}  > \varepsilon_t$
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	13	$ u_{cc} - I  \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	14	$ u_{cc} - I  \leq \varepsilon_{cc}$
<b>Mechanical Cooling with Minimum Outdoor Air (Mode 4)</b>	15	$T_{oa} < T_{co} - \varepsilon_t$
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	18	For $ T_{ra} - T_{oa}  \geq \Delta T_{min}$ : $ Q_{od}/Q_{sa} - (Q_{od}/Q_{sa})_{min}  > \varepsilon_f$
	19	$ u_{cc} - I  \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	20	$ u_{cc} - I  \leq \varepsilon_{cc}$
<b>Unknown Occupied Modes (Mode 5)</b>	21	$u_{cc} > \varepsilon_{cc}$ and $u_{hc} > \varepsilon_{hc}$ and $\varepsilon_d < u_d < I - \varepsilon_d$
	22	$u_{hc} > \varepsilon_{hc}$ and $u_{cc} > \varepsilon_{cc}$
	23	$u_{hc} > \varepsilon_{hc}$ and $u_d > \varepsilon_d$
	24	$\varepsilon_d < u_d < I - \varepsilon_d$ and $u_{cc} > \varepsilon_{cc}$
<b>All Occupied Modes (Mode 1, 2, 3, 4, or 5)</b>	25	$ T_{sa} - T_{sa,s}  > \varepsilon_t$
	26	$T_{ma} < \min(T_{ra}, T_{oa}) - \varepsilon_t$
	27	$T_{ma} > \max(T_{ra}, T_{oa}) + \varepsilon_t$
	28	Number of mode transitions per hour $> MT_{max}$

Where

$MT_{max}$	=	maximum number of mode changes per hour
$T_{sa}$	=	supply air temperature
$T_{ma}$	=	mixed air temperature
$T_{ra}$	=	return air temperature
$T_{oa}$	=	outdoor air temperature
$T_{co}$	=	changeover air temperature for switching between Modes 3 and 4
$T_{sa,s}$	=	supply air temperature set point
$\Delta T_{sf}$	=	temperature rise across the supply fan
$\Delta T_{rf}$	=	temperature rise across the return fan
$\Delta T_{min}$	=	threshold on the minimum temperature difference between the return and outdoor air
$Q_{od}/Q_{sa}$	=	outdoor air fraction = $(T_{ma} - T_{ra})/(T_{oa} - T_{ra})$
$(Q_{od}/Q_{sa})_{min}$	=	threshold on the minimum outdoor air fraction
$u_{hc}$	=	normalized heating coil valve control signal [0,1] where $u_{hc} = 0$ indicates the valve is closed and $u_{hc} = 1$ indicates it is 100 % open
$u_{cc}$	=	normalized cooling coil valve control signal [0,1] where $u_{cc} = 0$ indicates the valve is closed and $u_{cc} = 1$ indicates it is 100 % open
$u_d$	=	normalized mixing box damper control signal [0,1] where $u_d = 0$ indicates the outdoor air damper is closed and $u_d = 1$ indicates it is 100 % open
$\varepsilon_t$	=	threshold for errors in temperature measurements
$\varepsilon_f$	=	threshold parameter accounting for errors related to airflows (function of uncertainties in temperature measurements)
$\varepsilon_{hc}$	=	threshold parameter for the heating coil valve control signal
$\varepsilon_{cc}$	=	threshold parameter for the cooling coil valve control signal
$\varepsilon_d$	=	threshold parameter for the mixing box damper control signal

Table 2.2: APAR Diagnoses

Rule #	Alarm Description	Possible Diagnoses																		
		Supply Air Temperature Sensor Error	Return Air Temperature Sensor Error	Mixed Air Temperature Sensor Error	Outdoor Air Temperature Sensor Error	Leaking Cooling Coil Valve	Stuck Cooling Coil Valve	Undersized Cooling Coil	Fouled Cooling Coil	Chilled Water Supply Temperature Too High	Problem with Chilled Water Circulating Pump	Chilled Water not Available to Season	Leaking Heating Coil Valve	Stuck Heating Coil Valve	Undersized Heating Coil	Fouled Heating Coil	Hot Water Supply Temperature Too Low	Problem with Hot Water Circulating Pump	Leaking Mixing Box Damper	Stuck Mixing Box Damper
1	In heating mode, supply air temp should be greater than mixed air temp.	X		X		X	X													
2	Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X														X	X
3	Heating coil valve command is fully open and supply air temp error exists.	X				X	X						X	X	X	X	X			
4	Heating coil valve command is fully open. If heating load increases, supply air temp will drift from setpoint.	X				X	X					X	X	X	X	X	X			
5	Outdoor air temp is too warm for cooling with outdoor air.	X			X															
6	Supply air temp should be less than return air temp.	X	X									X	X							
7	Supply and mixed air temp should be nearly the same.	X		X		X	X					X	X							
8	Outdoor air temperature is too cool for mechanical cooling with 100% outdoor air.	X			X							X	X					X	X	
9	Outdoor air enthalpy is too great for mechanical cooling with 100% outdoor air.																			
10	Outdoor and mixed air temp should be nearly the same.			X	X														X	X
11	Supply air temp should be less than mixed air temp.	X		X			X	X	X	X	X	X	X	X						
12	Supply air temp should be less than return air temp.	X	X				X	X	X	X	X	X	X	X						
13	Cooling coil valve command is fully open and supply air temp error exists.	X					X	X	X	X	X	X	X	X						
14	Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X					X	X	X	X	X	X	X	X						
15	Outdoor air enthalpy is too low for mechanical cooling with minimum outdoor air.																			
16	Supply air temp should be less than mixed air temp.	X		X			X	X	X	X	X	X	X	X						
17	Supply air temp should be less than return air temp.	X	X				X	X	X	X	X	X	X	X						
18	Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X														X	X
19	Cooling coil valve command is fully open and supply air temp error exists.	X					X	X	X	X	X	X	X	X						
20	Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X					X	X	X	X	X	X	X	X						
21	Heating coil valve, cooling coil valve, and mixing box dampers are all modulating simultaneously.																			
22	Heating coil valve and cooling coil valve are both modulating simultaneously.																			
23	Heating coil valve and mixing box dampers are both modulating simultaneously.																			
24	Cooling coil valve and mixing box dampers are both modulating simultaneously.																			
25	Persistent supply air temp error exists.																			
26	Mixed air temp should be between return and outdoor air temp (mixed air temp too great).		X	X	X															
27	Mixed air temp should be between return and outdoor air temp (mixed air temp too low).		X	X	X															
28	Too many mode switches per hour.																			

## 2.2 VAV Box Performance Assessment Control Charts - VPACC

The challenges presented in detecting and diagnosing faults in VAV boxes are similar to those encountered with other pieces of HVAC equipment. Generally there are very few sensors, making it difficult to determine what is happening in the device. Limitations associated with controller memory and communication capabilities further complicate the task. The number of different types of VAV boxes and lack of standardized control sequences add a final level of complexity to the challenge. These needs and constraints led to the development of VAV Box Performance Assessment Control Charts (VPACC), a fault detection tool that uses a small number of control charts to assess the performance of VAV boxes. A brief overview of VPACC is presented here; a detailed description is available elsewhere [5].

VPACC implements an algorithm known as a CUSUM (cumulative sum) chart [6]. The basic concept behind CUSUM charts is to accumulate the error between a process output and the expected value of the output. Large values of the accumulated error indicate an out of control process. Mathematically, the technique can be expressed as:

$$z_i = (x_i - x_{exp}) / \sigma_{exp}$$

where  $z_i$  is the normalized error at time  $i$ ,  $x_i$  is the error at time  $i$ ,  $x_{exp}$  is the expected value of the error, and  $\sigma_{exp}$  is the expected variation of the error. Separate positive ( $S$ ) and negative ( $T$ ) sums are then accumulated. The slack parameter,  $k$ , is defined as the amount of variation that is considered normal, and therefore ignored. The cumulative positive and negative sums are calculated by:

$$S_i = \max[0, z_i - k + S_{i-1}]$$

$$T_i = \max[0, -z_i - k + T_{i-1}]$$

The final step is to compare  $S$  and  $T$  to the alarm limit,  $h$ , to determine whether the process is out of control.

In order to make VPACC independent of the control strategy used in a particular controller/VAV box application, four generic errors were identified: the airflow rate error, the absolute value of the airflow rate error, the temperature error, and the discharge air temperature error. As long as the VAV box controller has an airflow setpoint, as well as heating and cooling temperature setpoints, VPACC will function independently of the specific control strategy used. Common mechanical and control faults will result in a positive or negative deviation of one or more of these errors from its value during normal operation, which can be detected by a CUSUM chart. A list of possible causes is associated with each alarm (see Table 2.3).

The airflow rate error,  $Q_{error}$ , is defined as the difference between the measured airflow rate and the airflow rate set point. The absolute value of the airflow rate error,  $|Q_{error}|$ , is defined simply as the absolute value of the difference between the measured airflow rate and the airflow rate set point. Only one CUSUM value is defined for this error since it is never negative.

The zone temperature error,  $T_{error}$ , is defined as

$$\begin{aligned} T_{error} &= T_{zone} - CSP && : \text{ If } T_{zone} > CSP \\ T_{error} &= 0 && : \text{ If } HSP \leq T_{zone} \leq CSP \\ T_{error} &= T_{zone} - HSP && : \text{ If } T_{zone} < HSP \end{aligned}$$

where

$$\begin{aligned} T_{zone} &= \text{zone temperature} \\ CSP &= \text{cooling set point} \\ HSP &= \text{heating set point.} \end{aligned}$$

The discharge air temperature error,  $DAT_{error}$ , is only applied to VAV boxes with hydronic reheat. The  $DAT_{error}$  is calculated only when the reheat coil valve is fully closed, otherwise it is set equal to zero. It is defined as the difference between the VAV box discharge air temperature and the entering air temperature. The supply air temperature from the AHU serving the VAV box can be used as a surrogate for the entering air temperature. This value is generally obtained via the building control network.

The errors and CUSUMs are only calculated during occupied periods. During unoccupied periods, the errors are not computed and the CUSUMs are reset to zero. There is a delay at the onset of the occupied period to allow quasi-steady state conditions to develop. Also, the CUSUMs are periodically reset to zero to prevent alarms from being reported due to small steady state errors. Each alarm can be individually disabled by the user in order to eliminate nuisance alarms caused by fault conditions that are known to the maintenance staff, but will not be repaired immediately.

VPACC was developed for pressure independent VAV boxes with hydronic reheat coils, however, it can easily be adapted for different types of VAV boxes. For cooling only VAV boxes or boxes that do not have discharge air temperature sensors, the discharge air temperature error ( $\Delta T_{error}$ ) does not apply. For dual duct boxes, two airflow errors ( $Q_{error,hot}$  and  $Q_{error,cold}$ ) and two absolute value airflow errors ( $|Q_{error,hot}|$  and  $|Q_{error,cold}|$ ) are needed, and the discharge air temperature error ( $\Delta T_{error}$ ) does not apply. Although VPACC was originally tested using VAV boxes without fans [1, 2, 3, 5], the algorithm is independent of fan configuration and can be applied to boxes with series or parallel fans without modification.

**Table 2.3. VPACC Diagnoses.**

Alarm Description	Possible Diagnoses																				
	Zone temperature sensor drift/failure	Airflow (DP) sensor drift/failure	Discharge temperature sensor drift/failure	Damper stuck or failed	Damper actuator stuck or failed	Reheat coil valve stuck or failed	Reheat coil valve actuator stuck or failed	AHU Supply air too warm	AHU Supply air too cool	Supply air static pressure too low	Scheduling conflict with AHU	Undersized VAV box	Tuning problem with airflow feedback control loop	Tuning problem with zone temperature feedback control loop	Inappropriate zone temperature setpoint	Minimum airflow setpoint too low	Minimum airflow setpoint too high	Maximum airflow setpoint too low	Maximum airflow setpoint too high	Sequencing logic error	
High zone temperature alarm	X	X				X	X				X	X	X	X	X						X
Low zone temperature alarm	X	X				X	X		X		X	X	X	X	X						X
High airflow alarm		X		X	X						X	X	X	X							X
Low airflow alarm		X		X	X					X	X	X	X							X	X
Unstable airflow alarm		X		X	X					X	X	X	X			X					X
High discharge temperature alarm			X			X	X														
Low discharge temperature alarm			X			X	X														

### **3 Data Sources**

Previous research has established the performance of APAR and VPACC [1, 2, 3, 4, 5]. A primary goal of this study was to evaluate the practicality and usability of embedding these FDD algorithms in commercial AHU and VAV box controllers. By involving controls manufacturers and dealers as well as building engineers in the study, the tools were evaluated under conditions as close as possible to those in which they will be used. This approach was selected to ensure that any obstacles to commercialization would be revealed during the course of the test. Another goal was to evaluate modifications to APAR and VPACC for different system types. The field sites are described below.

#### **3.1 SITE-1**

SITE-1 is a private office building. APAR was embedded in the controllers of two VAV rooftop AHUs with hydronic heating coils and staged direct-expansion (DX) cooling coils. VPACC was embedded in 53 VAV box controllers, including 20 pressure independent, single-duct, parallel fan powered VAV boxes with hydronic reheat and 33 pressure independent, single-duct, throttling (no fan), cooling-only VAV boxes. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed monthly. Personnel at the site responded to investigate and verify any reported faults.

#### **3.2 SITE-2**

SITE-2 is a large federal government office building in California. APAR was embedded in the controllers of two constant-volume AHUs with hydronic heating and cooling coils. VPACC was embedded in 1000 pressure independent, dual-duct VAV box controllers. Rather than configuring trendlogs, a computerized maintenance management system (MMS) was configured to automatically generate a work order whenever a fault was detected. The building engineers responded to investigate, verify, and repair any faults reported through the MMS.

#### **3.3 SITE-3**

SITE-3 is a private office building with some light industrial spaces. APAR was embedded in one VAV AHU with staged (combustion) heating and DX cooling coils. VPACC was embedded in the controllers of 46 pressure independent, single-duct, throttling (no fan), cooling-only VAV boxes. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed periodically. Also, the building automation system's alarm/event handling function was configured to alert the operator whenever an APAR rule violations or VPACC alarm occurred. Each FDD event was also recorded in an alarm history database. Personnel at the site responded to investigate and verify any reported faults.

#### **3.4 SITE-4**

SITE-4 is a federal government building with a combination of office and laboratory spaces. APAR was embedded in the controller of one constant-volume AHUs with hydronic heating and cooling coils. Since the AHU controller operated in standalone mode (not connected to a

network), selected raw data and APAR rule violations were logged by a standalone datalogging software tool running on a computer physically connected to the AHU controller. The trendlogs were archived and reviewed weekly. Personnel at the site responded to investigate and verify any faults that were detected.

### **3.5 SITE-5**

SITE-5 is a large federal government office building. APAR was embedded in the controllers of two VAV AHUs with hydronic heating and cooling coils. VPACC was embedded in two pressure independent, single-duct, throttling (no fan) VAV boxes with hydronic reheat and two pressure independent, single-duct, throttling (no fan), cooling-only VAV boxes. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed periodically. Also, the building automation system's alarm/event handling function was configured to record each FDD event in an alarm history database. Personnel at the site responded to investigate and verify any reported faults.

### **3.6 SITE-6**

SITE-6 is a classroom building on a community college campus. APAR was embedded in the controllers of two VAV AHUs with hydronic heating and cooling coils. VPACC was embedded in 101 pressure independent, single-duct, series fan-powered VAV boxes with hydronic reheat. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed periodically. Personnel at the site responded to investigate and verify any reported faults.

### **3.7 SITE-7**

SITE-7 is a museum building on a university campus. A specialized HVAC system maintains precise temperature and humidity conditions for the museum's artifacts; however, there is also a general purpose HVAC system for office and visitor spaces. APAR was embedded in the controllers of two VAV rooftop AHUs with hydronic heating coils and DX cooling coils. VPACC was embedded in nine pressure independent, single-duct, throttling (no fan) VAV boxes with hydronic reheat. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed weekly. Personnel at the site responded to investigate and verify any reported faults.

### **3.8 SITE-8**

SITE-8 is a small office building on a university campus. Control of each of the AHUs was divided between the building automation system (supply and relief fan, mixing box dampers, and heating coil) and a non-programmable proprietary controller packaged with each AHU (DX cooling). Since each device contained some of the data needed for APAR, and the devices were not interoperable, it was not possible to implement APAR at this site. However, VPACC was embedded in 28 pressure independent, single-duct, throttling (no fan) VAV boxes with hydronic reheat. The building automation system's alarm/event handling function was configured to alert the operator whenever an APAR rule violation or VPACC alarm occurred. Each FDD event was also recorded in an alarm history database. Personnel at the site responded to investigate and verify any reported faults.

### **3.9 SITE-9**

SITE-9 is a classroom and office building on a community college campus. APAR was embedded in the controllers of one VAV AHU with hydronic heating and cooling coils. VPACC was embedded in 11 VAV box controllers, including 10 pressure independent, single-duct, parallel fan powered VAV boxes with electric reheat and one pressure independent, single-duct, throttling (no fan), cooling-only VAV box. The building automation system's alarm/event handling function was configured to alert the operator whenever an APAR rule violations or VPACC alarm occurred. Each FDD event was also recorded in an alarm history database. Personnel at the site responded to investigate and verify any reported faults.

### 3.10 System Coverage

Tables 3.1 and 3.2 show the extent of AHU and VAV box system types that will be studied, as well as the coverage of those system types by the four field sites already identified.

**Table 3.1. AHU System Types.**

Site	Cooling Medium		Heating Medium		Volume Control	
	Chilled Water	DX	Hot water / Steam	Staged (Electric Resistance or Combustion)	Variable Volume	Constant Volume
SITE-1		X	X		X	
SITE-2	X		X			X
SITE-3		X		X	X	
SITE-4	X		X			X
SITE-5	X		X		X	
SITE-6	X		X		X	
SITE-7		X	X		X	
SITE-8		X	X		X	
SITE-9	X		X		X	

**Table 3.2. VAV Box System Types.**

Site	System Type		Fan Configuration			Reheat Medium		
	Single Duct	Dual Duct	Throttling (No Fan)	Parallel Fan-Powered	Series Fan-Powered	No Reheat	Electric Reheat	Hydronic Reheat
SITE-1 (Type 1)	X			X				X
SITE-1 (Type 2)	X		X			X		
SITE-2 (Type 1)	X		X			X		
SITE-2 (Type 2)		X	X			X		
SITE-3	X		X			X		
SITE-4								
SITE-5 (Type 1)	X		X					X
SITE-5 (Type 2)	X		X			X		
SITE-6	X				X			X
SITE-7	X							
SITE-8	X		X					X
SITE-9 (Type 1)	X			X			X	
SITE-9 (Type 2)	X		X			X		

## 4 Procedure

The following procedure was applied to each field site, except as noted in 3.1 – 3.9:

1. Collect the HVAC control system points list and the relevant control application programs from the site.
2. Modify the control application programs to incorporate the FDD algorithms.
3. Download the modified control application programs to the appropriate controllers at the site.
4. Establish trend logs of selected raw data along with the results of the FDD algorithms.

For each AHU, trend the following data points:

- AHU run status (on - off)
- Supply air temperature setpoint
- Supply air temperature
- Return air temperature
- Outdoor air temperature
- Mixed air temperature
- Return air enthalpy or humidity, if used in economizer control sequence
- Outdoor air enthalpy or humidity, if used in economizer control sequence
- Cooling coil valve control signal, if chilled water is used for cooling; or mechanical cooling status, if DX cooling is used
- Heating coil valve control signal, if hot water or steam is used for cooling; or heating status, if electric resistance or combustion heating is used
- Mixing box dampers control signal
- Status of each APAR rule (on - off)

For each VAV box, trend the following data points:

- Occupancy status (on - off)
- Zone temperature
- Heating setpoint
- Cooling setpoint
- Airflow rate (if box is dual duct, then trend both hot and cold airflow rates)
- Airflow rate setpoint (if box is dual duct, then trend both hot and cold airflow rate setpoints)
- Damper control signal
- Reheat coil valve control signal, if reheat coil is present
- Discharge air temperature, if sensor is present
- Supply air temperature from the AHU serving the VAV box, only if a discharge air temperature sensor is present
- Status of each VPACC alarm (on - off)

5. Once per week, collect and analyze the trend data to evaluate the performance of the FDD algorithms. The data can be made available by either enabling online access to the

building control system's trend log database, or by exporting the trend logs to text files and submitting them via email or CD.

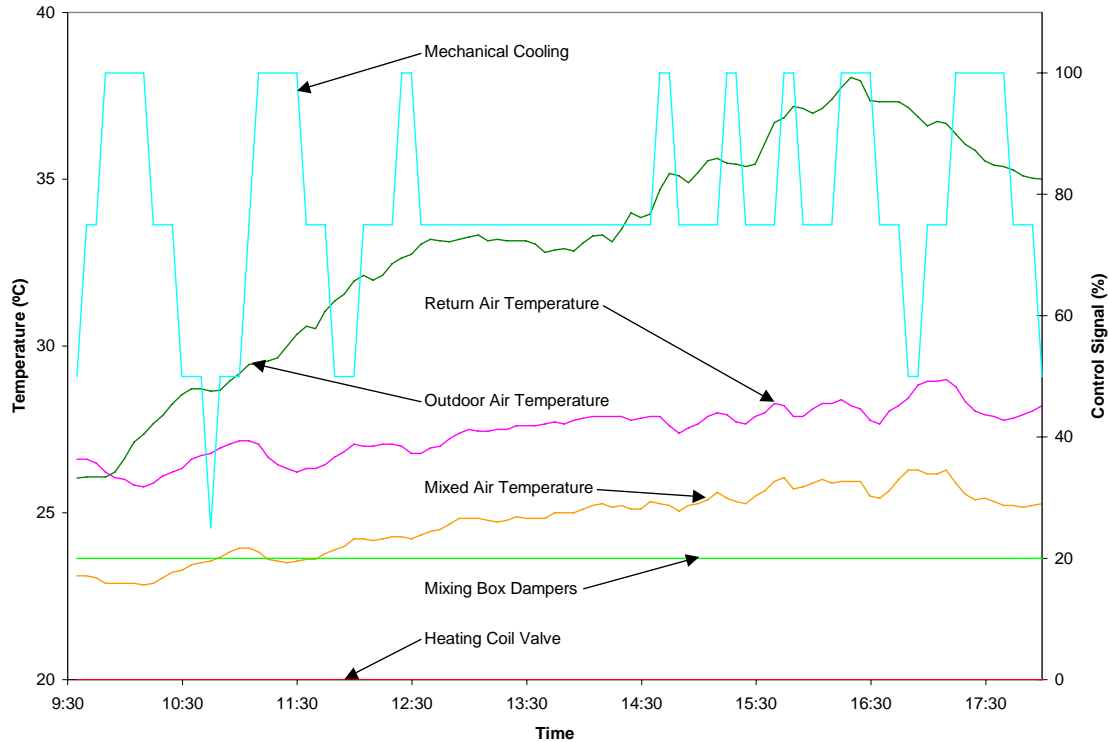
6. Follow up with the facility maintenance staff to verify the presence of any faults detected by either of the FDD algorithms. Verify whether the actual cause of the fault is one of the causes listed by the FDD algorithm.
7. Record the presence and cause of any faults reported through any other means that were not detected by the FDD algorithms.

## **5 Results**

Selected examples of faults that were detected during the study are presented.

## 5.1 SITE-1

### 5.1.1 Mixed Air Temperature Sensor Error



**Figure 5.1. SITE-1 Mixed Air Temperature Sensor Error.**

Figure 5.1 shows a plot of temperature and control signal data from one of the rooftop AHUs at SITE-1. The heating coil valve is fully closed and the mixing box dampers are positioned for the minimum outdoor air fraction needed to meet ventilation requirements (20 %). Stages of mechanical cooling are energized based on cooling requests from the terminal units served by the AHU. This combination of control signals corresponds to Mode 4: mechanical cooling with minimum outdoor air. In addition to the set of rules specific to Mode 4, there is a set of rules that applies to all occupied modes of operation (see Table 2.1). One rule which applies to all occupied modes is Rule 26, which states that the mixed air temperature should be greater than the minimum of the return and outdoor air temperatures. For nearly the entire time period shown in Figure 5.1, the return air temperature is less than the outdoor air temperature, so according to Rule 26, the mixed air temperature should be greater than the return air temperature. However, Figure 5.1 shows that the mixed air temperature is less than the return air temperature by approximately 3 °C. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 26. As shown in Table 2.2, the possible causes of this fault are a return, mixed, or outdoor air temperature sensor error. Onsite personnel investigated, determined that the mixed air temperature sensor had drifted out of calibration, and recalibrated it.

### 5.1.2 Leaking Heating Coil Valve

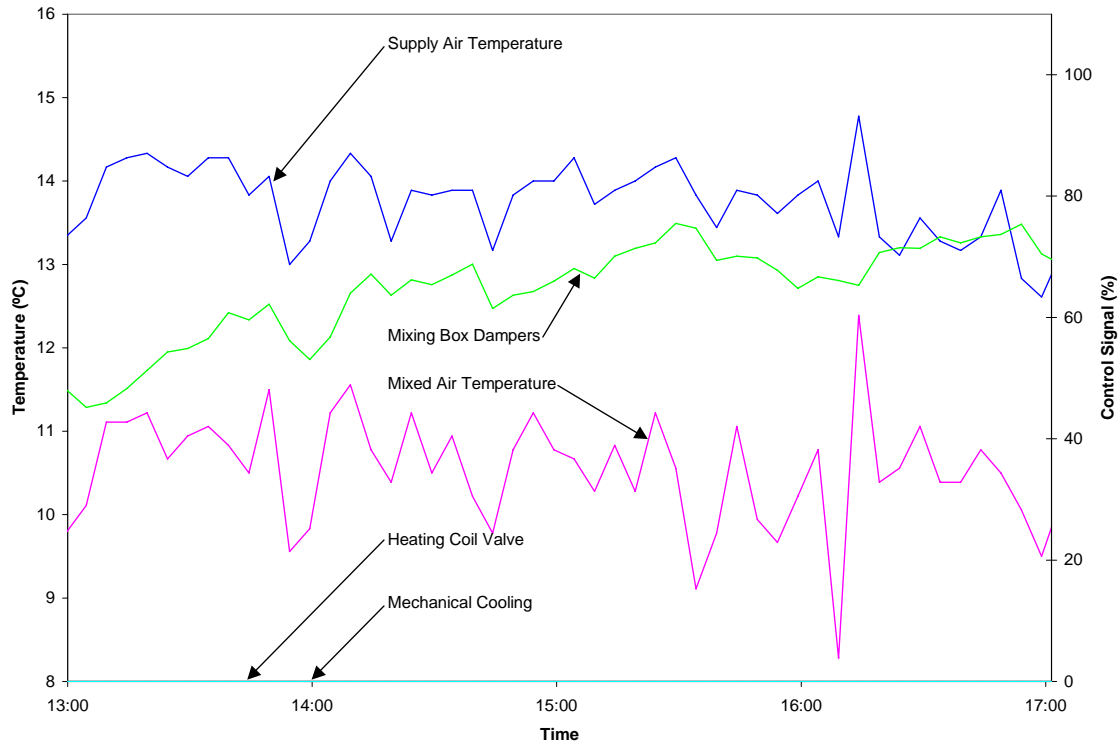


Figure 5.2. Leaking Heating Coil Valve.

Figure 5.2 shows a plot of temperature and control signal data from one of the rooftop AHUs at SITE-1. The heating coil valve is fully closed and all stages of mechanical cooling are de-energized. The mixing box dampers modulate to maintain the supply air temperature at its setpoint (not shown). This combination of control signals corresponds to Mode 2: cooling with outdoor air. One of the rules for Mode 2 is Rule 7, which states that the supply air and mixed air temperatures should be nearly the same. Figure 5.2 shows that the supply air temperature is greater than the mixed air temperature by approximately 3 °C. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 7. As shown in Table 2.2, the possible causes of this fault are a supply or mixed air temperature sensor error, a problem with the mechanical cooling system (since chilled water is not used), or a stuck or leaking heating coil valve. Onsite personnel investigated and determined that there was a leak in the heating coil valve.

### 5.1.3 Outdoor Air Temperature Sensor Error

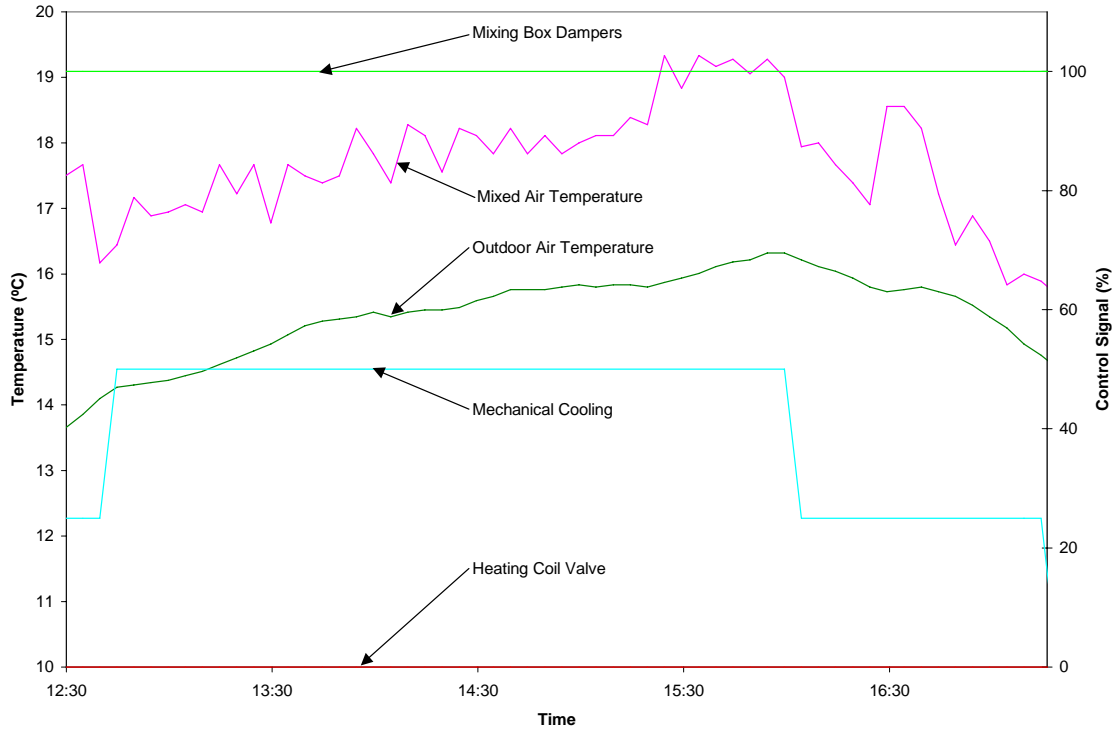


Figure 5.3. Outdoor Air Temperature Sensor Error.

Figure 5.3 shows a plot of temperature and control signal data from one of the rooftop AHUs at SITE-1. The heating coil valve is fully closed and the mixing box dampers are positioned for 100 % outdoor air. Stages of mechanical cooling are energized based on cooling requests from the terminal units served by the AHU. This combination of control signals corresponds to Mode 3: mechanical cooling with 100 % outdoor air. One of the rules for Mode 3 is Rule 10, which states that the outdoor air and mixed air temperatures should be nearly the same. Figure 5.3 shows that the mixed air temperature is greater than the outdoor air temperature by 2 to 3 °C. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 10. As shown in Table 2.2, the possible causes of this fault are an outdoor or mixed air temperature sensor error or a stuck or leaking mixing box damper. Onsite personnel investigated and determined that the fault was due to an outdoor air temperature sensor error caused by a difference in temperature between the location of the outdoor air temperature sensor and the AHU's outdoor air intake.

### 5.1.4 Mechanical Cooling Fault

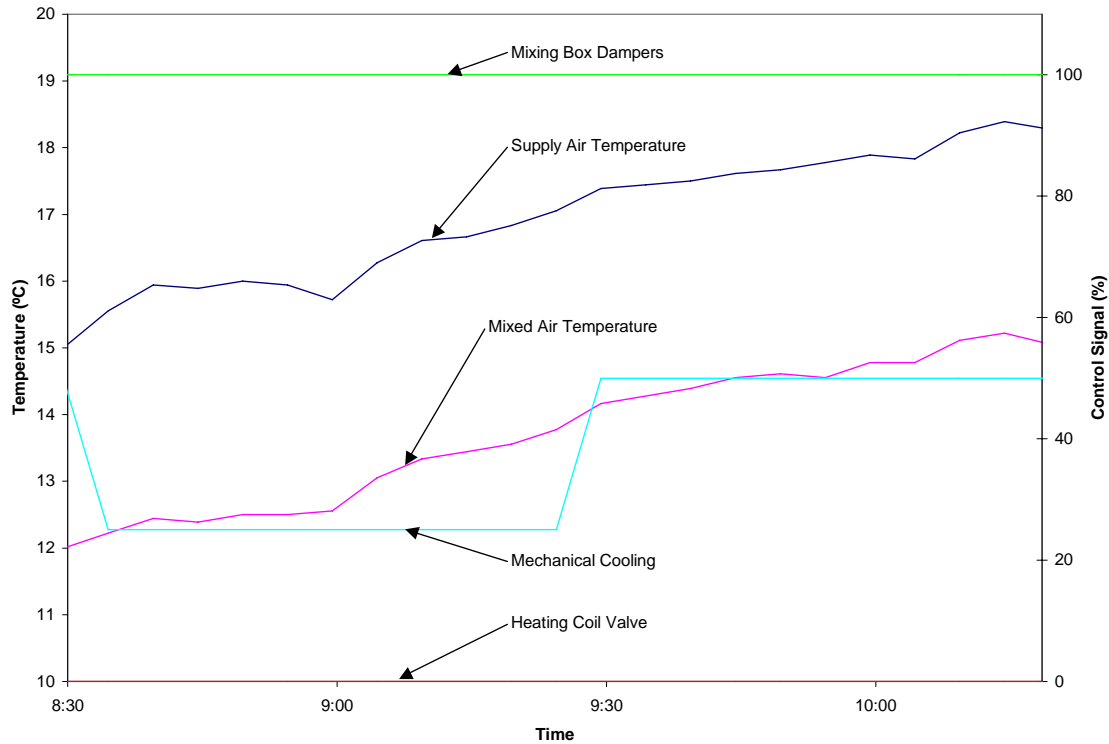
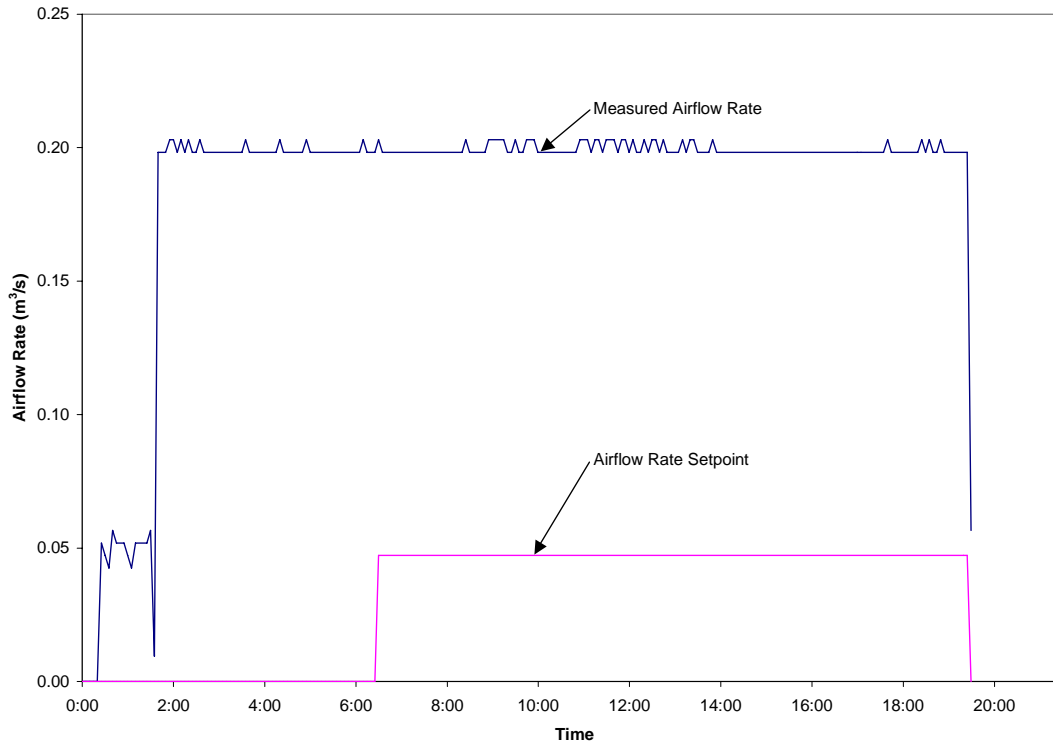


Figure 5.4. Mechanical Cooling Fault.

Figure 5.4 shows a plot of temperature and control signal data from one of the rooftop AHUs at SITE-1. The heating coil valve is fully closed and the mixing box dampers are positioned for 100 % outdoor air. Stages of mechanical cooling are energized based on cooling requests from the terminal units served by the AHU. This combination of control signals corresponds to Mode 3: mechanical cooling with 100 % outdoor air. One of the rules for Mode 3 is Rule 11, which states that the supply air temperature should be less than the mixed air temperature. Figure 5.4 shows that the supply air temperature is 3 to 4 °C greater than the mixed air temperature. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 11. Table 2.2 lists the possible causes of this fault including a supply or mixed air temperature sensor error, a fouled or undersized heating or cooling coil, and problems associated with mechanical cooling system. Onsite personnel investigated, determined that the fault was due to a problem with the mechanical cooling system, and added it to a list of tasks that was prepared for a maintenance contractor.

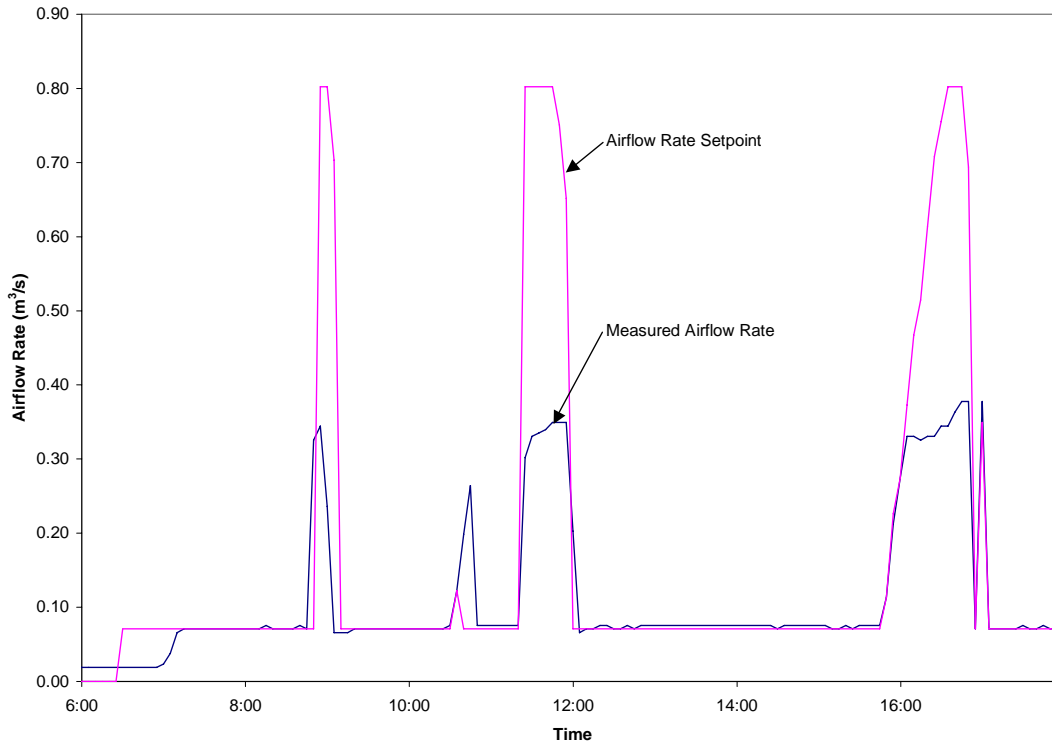
### 5.1.5 Stuck VAV Box Damper Actuator



**Figure 5.5. Stuck VAV Box Damper Actuator.**

Figure 5.5 shows a plot of airflow data from one of the fan powered VAV boxes at SITE-1. The plot shows that there was a large positive airflow error, since the measured airflow rate was substantially greater than the airflow rate setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a high airflow alarm. Table 2.3 lists the possible causes of this fault including an airflow (DP) sensor error, a stuck or failed damper or damper actuator, a scheduling conflict with the AHU, a tuning problem with the airflow control PID loop, and a sequencing logic error. Onsite personnel investigated and determined that the fault was due to a stuck damper actuator.

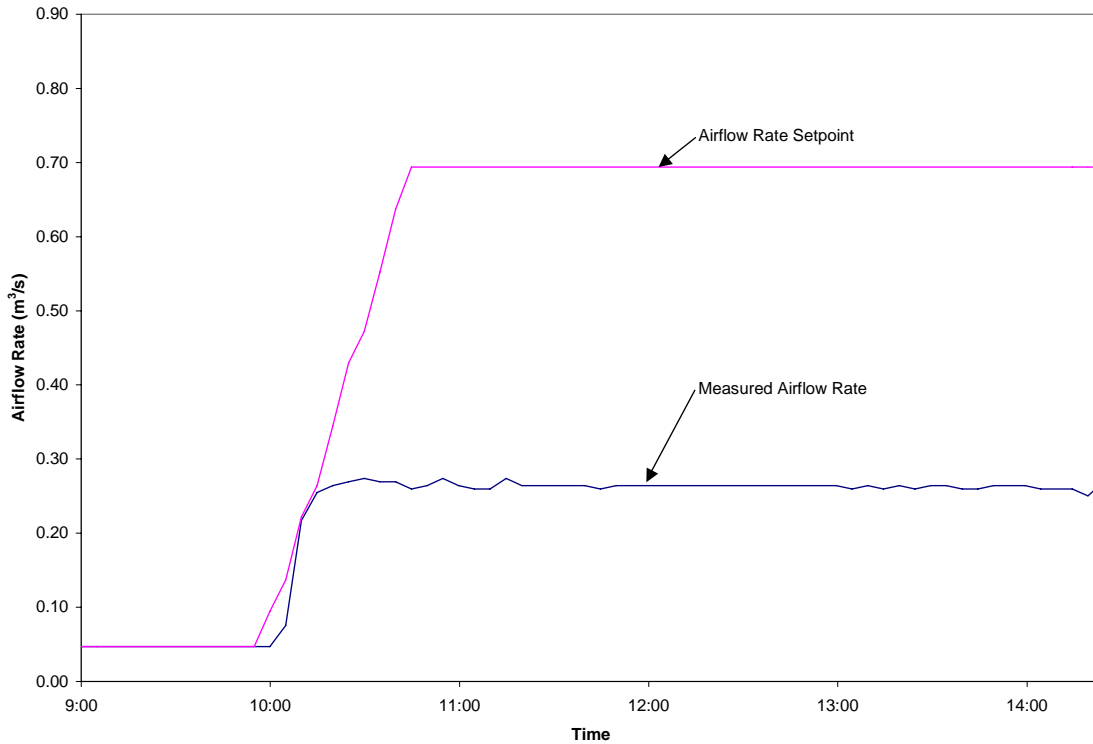
### 5.1.6 VAV Box Airflow Parameter Error



**Figure 5.6. VAV Box Airflow Parameter Error.**

Figure 5.6 shows a plot of airflow data from one of the fan powered VAV boxes at SITE-1. The plot that whenever the airflow setpoint increased above the minimum, there was a large negative airflow error, since the measured airflow rate was substantially less than the airflow rate setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low airflow alarm. Table 2.3 lists the possible causes of this fault, including an airflow (DP) sensor error, a stuck or failed damper or damper actuator, low static pressure in the supply air duct, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control PID loop, a maximum airflow setpoint that is too high, and a sequencing logic error. Onsite personnel investigated and determined that the fault was due to a maximum airflow setpoint that was too high. The VAV box controller was originally installed on a larger VAV box. During a building renovation, the controller was moved to a smaller VAV box, but the maximum airflow parameter was not changed. As a result, even when the damper was fully open, the airflow rate never reached the nominal maximum value.

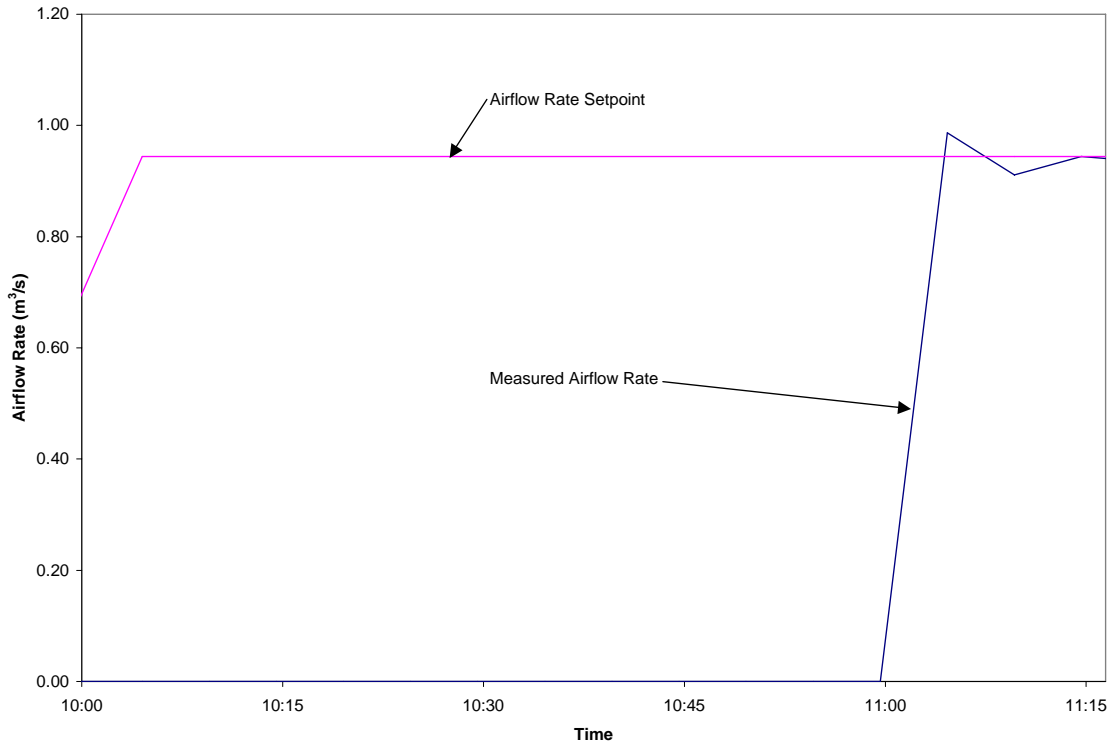
### 5.1.7 Slipping Supply Fan Drive Belt



**Figure 5.7. Slipping Supply Fan Drive Belt.**

Figure 5.7 shows a plot of airflow data from one of the fan powered VAV boxes at SITE-1. The occupied period was from 0630 until 1930. During occupancy, the VAV box had a minimum airflow rate setpoint of  $0.047 \text{ m}^3/\text{s}$  to meet ventilation requirements. The plot shows that whenever the airflow setpoint increased above the minimum, there was a large negative airflow error, since the measured airflow rate was substantially less than the airflow rate setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low airflow alarm. Table 2.3 lists the possible causes of this fault, including an airflow (DP) sensor error, a stuck or failed damper or damper actuator, low static pressure in the supply air duct, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control PID loop, a maximum airflow setpoint that is too high, and a sequencing logic error. Onsite personnel investigated and determined that the fault was due to low static pressure caused by a slipping supply fan drive belt in the AHU that serves this VAV box. Figure 5.7 illustrates that early in the day, the airflow rate setpoint was at the minimum and the supply fan was able to maintain sufficient static pressure. When the airflow setpoint increased later in the day, the actual airflow fell below the setpoint as the supply fan was not able to maintain the static pressure at the setpoint due to the slipping belt.

### 5.1.8 Communication Failure



**Figure 5.8. Communication Failure.**

Figure 5.8 shows a plot of airflow data from one of the throttling (no fan) VAV boxes at SITE-1. It shows a large negative airflow error, since the measured airflow rate was substantially less than the airflow rate setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low airflow alarm. Table 2.3 lists the possible causes of this fault, including an airflow (DP) sensor error, a stuck or failed damper or damper actuator, low static pressure in the supply air duct, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control PID loop, a maximum airflow setpoint that is too high, and a sequencing logic error. Onsite personnel investigated and determined that the fault was due to low static pressure caused by a temporary communication failure of the building control network. The AHUs at SITE-1 are scheduled based on the number of run requests received from the VAV boxes they serve. Since the AHU serving this VAV box did not receive any run requests, the supply fan was not energized and the static pressure in the supply air duct was too low. Figure 5.8 also shows that the fault disappeared when network communications were restored at approximately 11:00.

### 5.1.9 Undersized Supply Duct

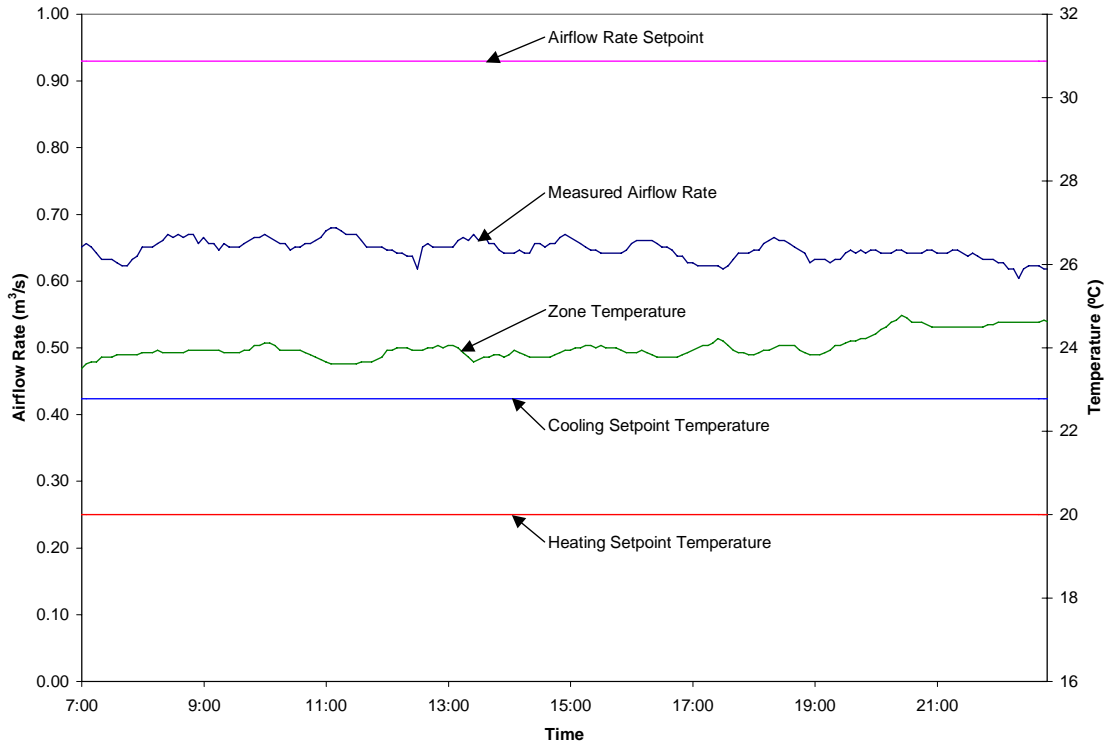
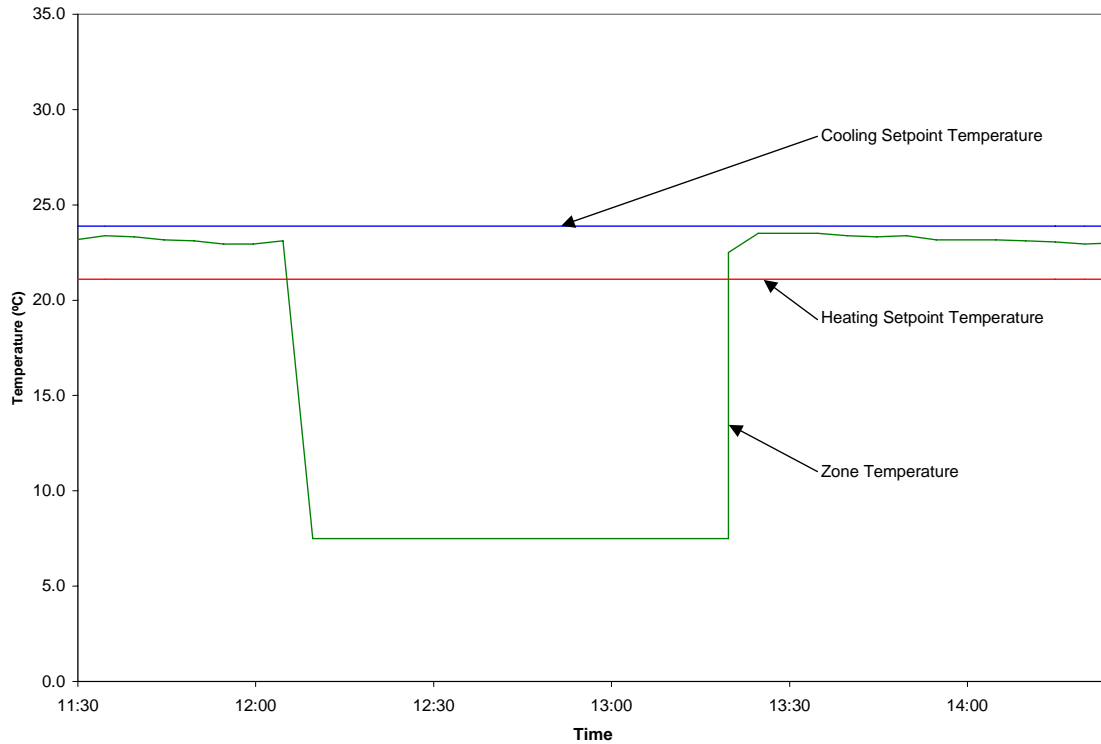


Figure 5.9. Undersized Supply Duct.

Figure 5.9 shows a plot of airflow and temperature data from one of the throttling (no fan) VAV boxes at SITE-1. It shows a large negative airflow error, since the measured airflow rate was substantially less than the airflow rate setpoint. There is also a large positive zone temperature error, since the zone temperature is greater than the cooling setpoint temperature. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low airflow alarm and a high zone temperature alarm. Table 2.3 lists the possible causes of this fault, including a zone temperature sensor error, an airflow (DP) sensor error, a stuck or failed damper or damper actuator, supply air too warm, low static pressure in the supply air duct, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, a maximum airflow setpoint that is too low or too high, an inappropriate zone temperature setpoint, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Table 2.3 do not apply. Onsite personnel investigated and determined that the fault was due to low static pressure in the supply duct. This is a large VAV box at the distant end of the supply duct from the serving AHU. The duct is undersized so under high load conditions this VAV box is starved of supply air. When this happens, the airflow rate drops below the airflow rate setpoint, and the zone temperature rises above the cooling setpoint temperature, since there is not enough airflow to meet the cooling load.

### 5.1.10 Disconnected Zone Temperature Sensor



**Figure 5.10. Disconnected Zone Temperature Sensor.**

Figure 5.10 shows a plot of temperature data from one of the throttling (no fan) VAV boxes at SITE-1. It shows a large negative zone temperature error, since the zone temperature is less than the heating setpoint temperature. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low zone temperature alarm. Table 2.3 lists the possible causes of this fault, including a zone temperature sensor error, airflow (DP) sensor error, supply air too cool, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a minimum airflow setpoint that is too high, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Table 2.3 do not apply. Onsite personnel investigated and determined that the fault was due to a zone temperature sensor error which occurred when the zone temperature sensor was inadvertently disconnected during maintenance. The sensor was configured for 0-10 V with a value of 7.5 °C at 0 V. When the sensor was disconnected, 0 V was read at the input on the VAV box controller, so a value of 7.5 °C was recorded, as shown in Figure 5.10. The figure also shows that the fault disappeared when the sensor was reconnected.

## **5.2 SITE-2**

At SITE-2, the maintenance management system (MMS) was configured to automatically generate a work order whenever a fault was detected. The building engineer responded to investigate and verify any faults reported through the MMS. Since no trendlogs of the raw data were established for the AHUs, there are no plots to illustrate the AHU faults described in this section. Supplemental trendlogs were configured for some of the VAV boxes, so plots are shown where data were available.

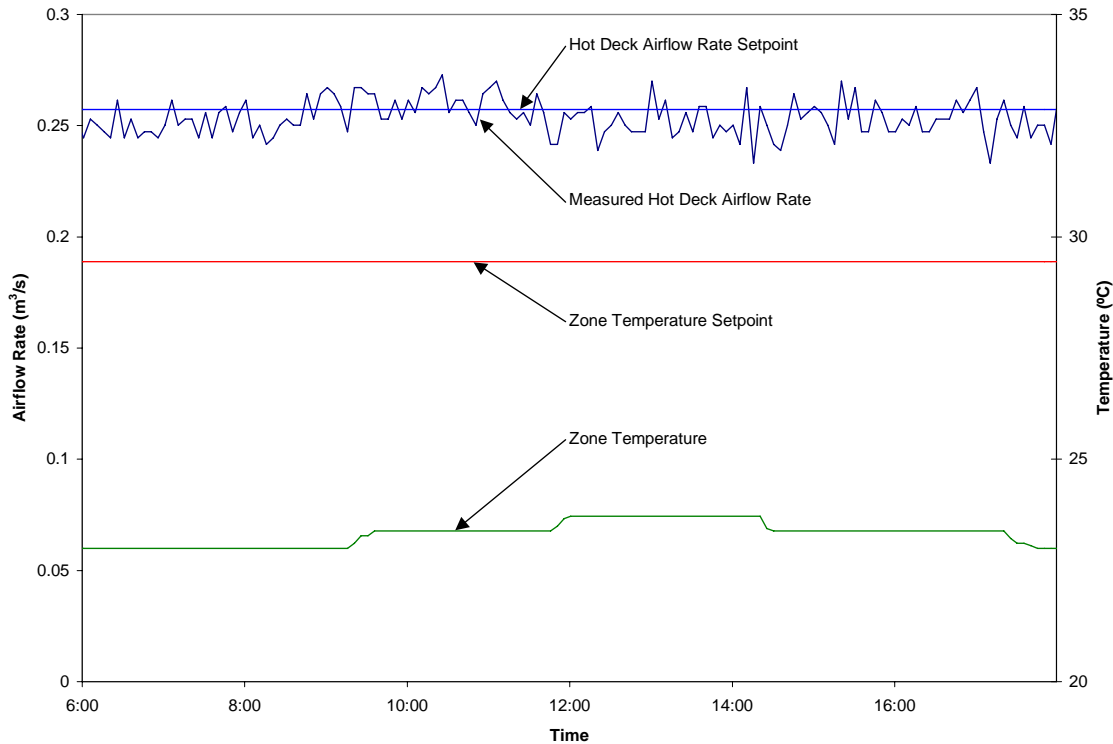
### **5.2.1 Outdoor Air Temperature Sensor Error**

The APAR algorithm embedded in one of the AHU controllers at SITE-3 reported faults due to Rules 8 and 10. Rule 8 states that, in mechanical cooling with 100 % outdoor air mode, the outdoor air temperature should be greater than the supply air temperature setpoint (otherwise, the AHU should be operating in cooling with outdoor mode). As shown in Table 2.2, the possible causes associated with Rule 8 are a supply or outdoor air temperature sensor error, a stuck or leaking heating coil valve, a stuck or leaking mixing box damper, or a controller logic error. Rule 10 states that, in mechanical cooling with 100 % outdoor air mode, the outdoor and mixed air temperatures should be nearly the same. Table 2.2 shows that the possible causes associated with Rule 10 are a mixed or outdoor air temperature sensor error and a stuck or leaking mixing box damper. Onsite personnel investigated and determined that the fault was due to an outdoor air temperature sensor error caused by the AHUs taking outdoor air from a plenum which was consistently 5 to 10 °C warmer than the actual outdoor air temperature. A project was undertaken to retrofit the outdoor air plenum with ventilation fans to bring the plenum temperature closer to the actual outdoor air temperature, thus reducing the chilled water load and the number of hours of chiller operation.

### **5.2.2 Chilled Water Not Available**

The APAR algorithm embedded in one of the AHU controllers at SITE-3 reported faults due to Rule 12, while another AHU controller reported faults due to Rule 13. Rule 12 states that, in mechanical cooling with 100 % outdoor air mode, the supply air temperature should be less than the return air temperature. As shown in Table 2.2, the possible causes associated with Rule 12 are a supply or return air temperature sensor error, a stuck cooling coil valve, an undersized cooling coil, a fouled cooling coil, chilled water too warm, a problem with one of the chilled water pumps, chilled water not available, a stuck or leaking heating coil valve, and a controller tuning error. Rule 13 observes that the cooling coil valve is saturated fully open and a persistent supply air temperature error exists. Table 2.2 shows that the possible causes associated with Rule 13 are a supply air temperature sensor error, a stuck cooling coil valve, an undersized cooling coil, a fouled cooling coil, chilled water too warm, a problem with one of the chilled water pumps, chilled water not available, a stuck or leaking heating coil valve, and a controller tuning error. Onsite personnel investigated and determined that the fault was due to chilled water not being available. The current sequence of operations for the chiller specifies that the chiller is only operated if several AHUs require chilled water. A project is being developed at the site to modify the chiller plant sequence of operations to ensure that chilled water is available when needed.

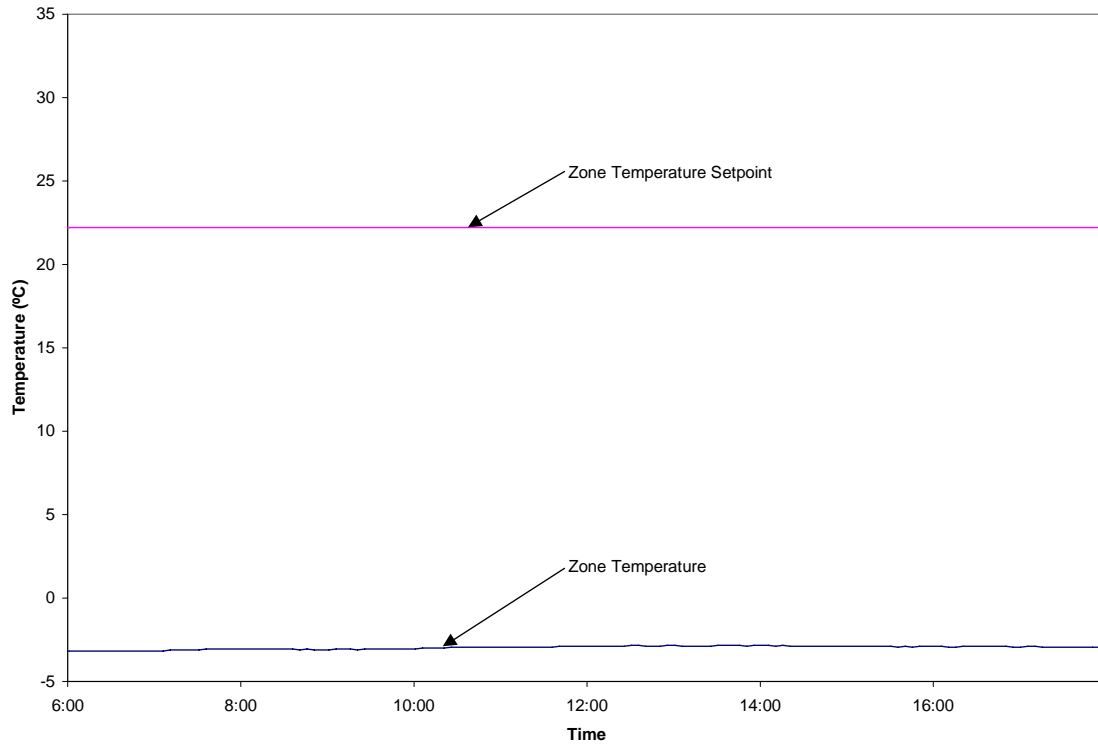
### 5.2.3 Airflow (DP) Sensor Drift



**Figure 5.11. Airflow (DP) Sensor Drift.**

Figure 5.11 shows a plot of airflow and temperature data from one of the dual-duct VAV boxes at SITE-2. It shows a large negative zone temperature error, since the zone temperature is less than the zone temperature setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low zone temperature alarm. Table 2.3 lists the possible causes of this fault, including a zone temperature sensor error, airflow (DP) sensor drift or failure, supply air too cool, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a minimum airflow setpoint that is too high, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Table 2.3 do not apply. Onsite personnel investigated and determined that the fault was due to an airflow sensor error which occurred due to debris buildup in the tubing connecting the pressure probes in the hot deck inlet to the differential pressure sensor onboard the VAV box controller. Figure 5.11 shows that the measured hot deck airflow rate was at the setpoint, which was also the maximum hot deck airflow rate for the VAV box. However, the actual hot deck airflow rate was less than the measured value due to the sensor drift. Insufficient warm airflow was provided to the zone, causing the zone temperature to drift well below the setpoint. The fault was repaired by removing the debris from the tubing.

## 5.2.4 Zone Temperature Sensor Failure



**Figure 5.12. Zone Temperature Sensor Failure.**

Figure 5.12 shows a plot of temperature data from one of the dual-duct VAV boxes at SITE-2. It shows a large negative zone temperature error, since the zone temperature is less than the zone temperature setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low zone temperature alarm. Table 2.3 lists the possible causes of this fault, including a zone temperature sensor error, airflow (DP) sensor drift or failure, supply air too cool, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a minimum airflow setpoint that is too high, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Table 2.3 do not apply. Onsite personnel investigated and determined that the fault was due to a zone temperature sensor failure. The zone temperature shown in Figure 5.12 is close to the minimum of the range for the sensor, so this fault is not a complete failure, but an extreme sensor drift. The fault was repaired by replacing the sensor.

## 5.2.5 Damper Actuator Failure

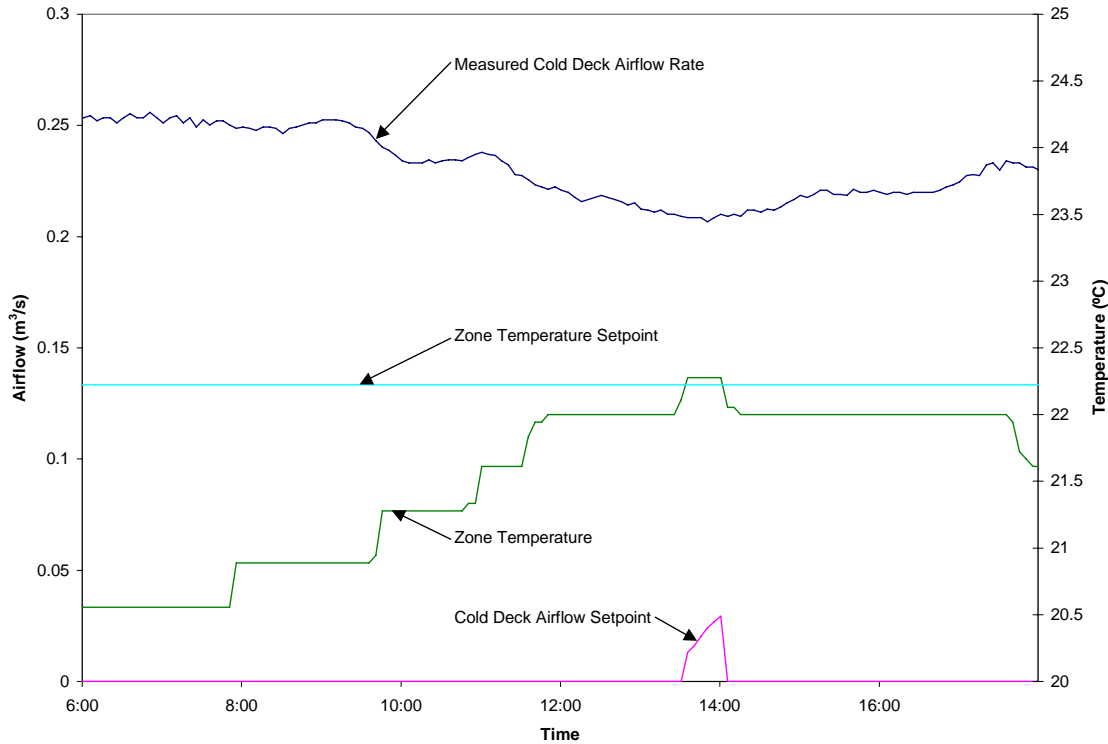
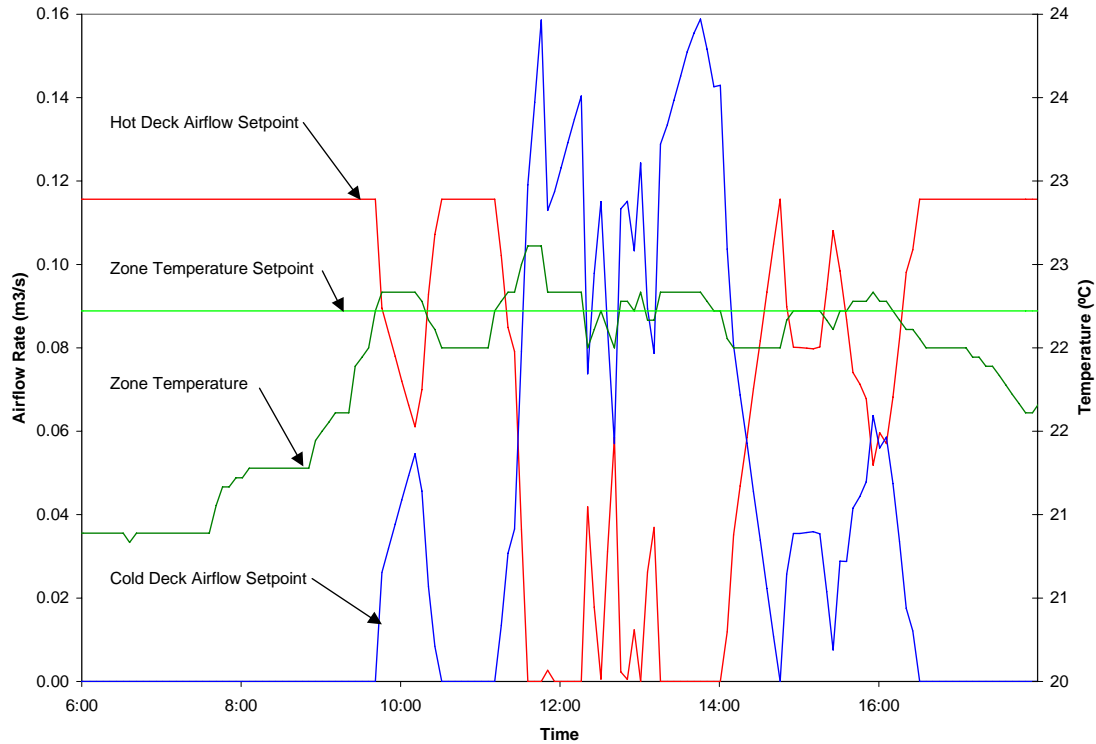


Figure 5.13. Damper Actuator Failure.

Figure 5.13 shows a plot of airflow and temperature data from one of the dual-duct VAV boxes at SITE-2. It shows a positive cold deck airflow rate error and a negative zone temperature error. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a high cold deck airflow alarm and a low zone temperature alarm. Table 2.3 lists the possible causes of these faults, including a zone temperature sensor error, airflow (DP) sensor drift or failure, cold deck damper or actuator stuck or failed, supply air too cool, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a minimum airflow setpoint that is too high, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Table 2.3 do not apply. Onsite personnel investigated and determined that the fault was due to a failed cold deck damper actuator. The damper failure allowed uncontrolled cold deck airflow to the zone, causing the zone temperature to fall well below the setpoint. The fault was repaired by replacing the broken actuator.

## 5.2.6 Zone Temperature Control Loop Tuning Problem

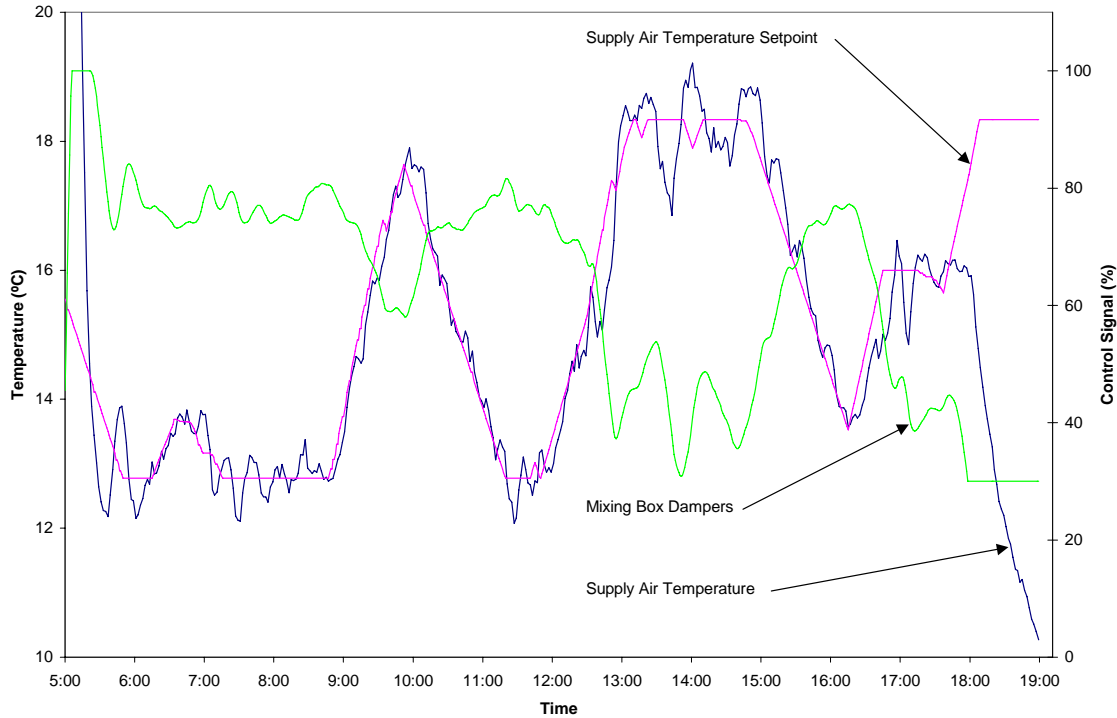


**Figure 5.14. Zone Temperature Control Loop Tuning Problem.**

Figure 5.14 shows a plot of airflow and temperature data from one of the dual-duct VAV boxes at SITE-2. It shows a negative zone temperature error, since the zone temperature is less than the zone temperature setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low zone temperature alarm. Table 2.3 lists the possible causes of this faults, including a zone temperature sensor error, airflow (DP) sensor drift or failure, supply air too cool, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a minimum airflow setpoint that is too high, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Table 2.3 do not apply. Onsite personnel investigated and determined that the fault was due to an underdamped temperature control PID loop. The outputs of the zone temperature control loop are the hot and cold deck airflow setpoints. The hot and cold deck airflow control loops successfully maintained the hot and cold airflow rates (not shown) at their respective setpoints. Figure 5.14 shows that as the zone temperature approached the setpoint, the temperature control loop oscillated, as seen in the varying hot and cold deck airflow setpoints.

## 5.3 SITE-3

### 5.3.1 Supply Air Temperature Error

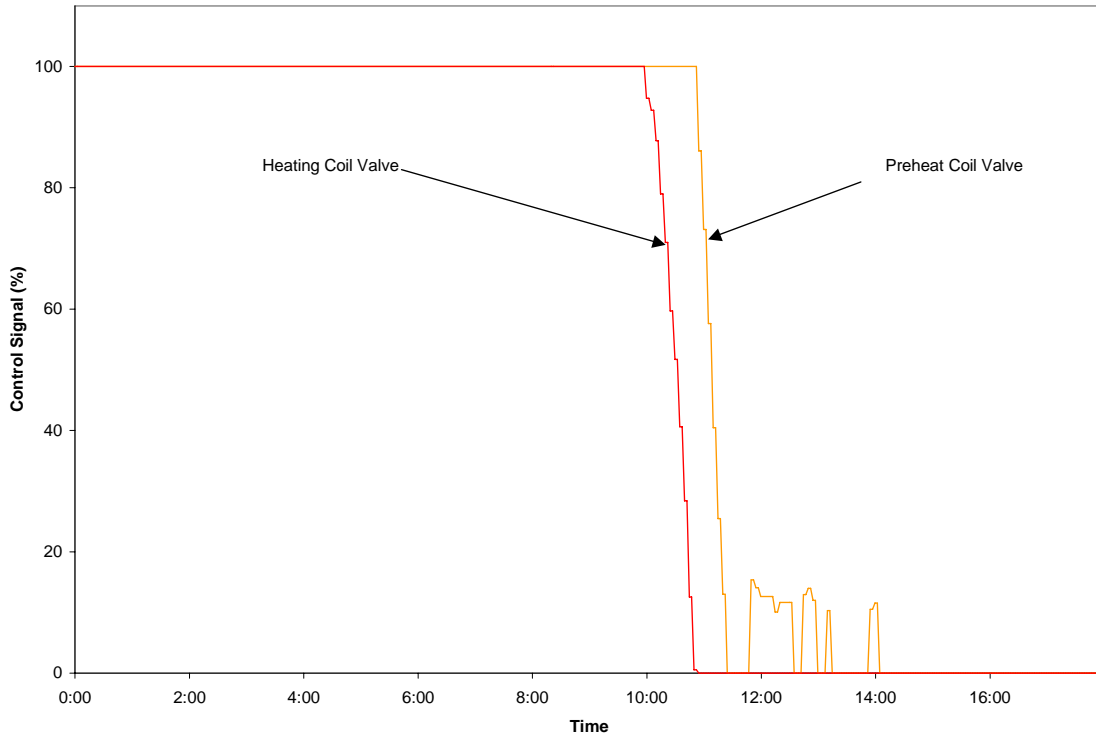


**Figure 5.15. SITE-3 Supply Air Temperature Error.**

Figure 5.15 shows a plot of temperature and control signal data from the AHU at SITE-3 for the occupied portion of one day. Both stages of heating (not shown) and all four stages of cooling (not shown) remain off while the mixing box dampers modulate to maintain the supply air temperature at its setpoint. This combination of control signals corresponds to Mode 2: cooling with outdoor air. In addition to the set of rules specific to Mode 4, there is a set of rules that apply to all occupied modes of operation (see Table 2.1). One rule which applies to all occupied modes is Rule 25, which states that the supply air temperature should be nearly equal to the supply air temperature setpoint. For most of the day shown, the supply air temperature is nearly equal to the setpoint, but from 17:45 until 19:00, the supply air temperature drifts well below the setpoint. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 25 late in the day. As shown in Table 2.2, the only possible causes of this fault are either a controller tuning or logic error. Onsite personnel investigated and determined that the fault was not due to either of the possible causes listed by APAR. Instead it was the result of a low supply airflow rate due to a low cooling load. The constant toilet exhaust airflow rate caused the AHU outdoor air fraction to rise despite the mixing box dampers closing to the minimum position. It is unknown whether the AHU controller would have energized the first stage of heating had the condition persisted.

## 5.4 SITE-4

### 5.4.1 Hot Water Converter Offline



**Figure 5.16. SITE-4 Hot Water Converter Offline.**

Figure 5.16 shows a plot of control signal data from the AHU at SITE-4. This AHU has a preheat coil and a heating coil, which are sequenced in series to meet the heating load. Relatively small heating loads are met by opening the preheat coil valve only, while the heating coil valve remains closed. As the heating load increases, the preheat coil valve saturates open and the heating coil valve opens to meet the load. Figure 5.16 shows the AHU operating in Mode 1: heating. One of the rules for Mode 1 is Rule 4, which warns that the heating coil valve is saturated fully open. For the first 10 hours of the day shown, both the preheat and heating coil valves are saturated at 100 % open. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 4. As shown in Table 2.2, the possible causes of this fault are either a supply air temperature sensor error, a stuck or leaking cooling coil valve, a stuck heating coil valve, an undersized heating coil, a fouled heating coil, hot water supply temperature too low, a problem with the hot water circulating pump, or a controller tuning error. Onsite personnel investigated and determined that the fault was due to a steam to hot water converter going offline. The converter supplies hot water to the preheat and heating coils of the AHU. When the converter was offline, the hot water supply temperature was too low. Figure 5.16 shows that the fault disappeared when the converter was brought back online at approximately 10:00.

## 5.4.2 Manual Override of Outdoor Air Damper

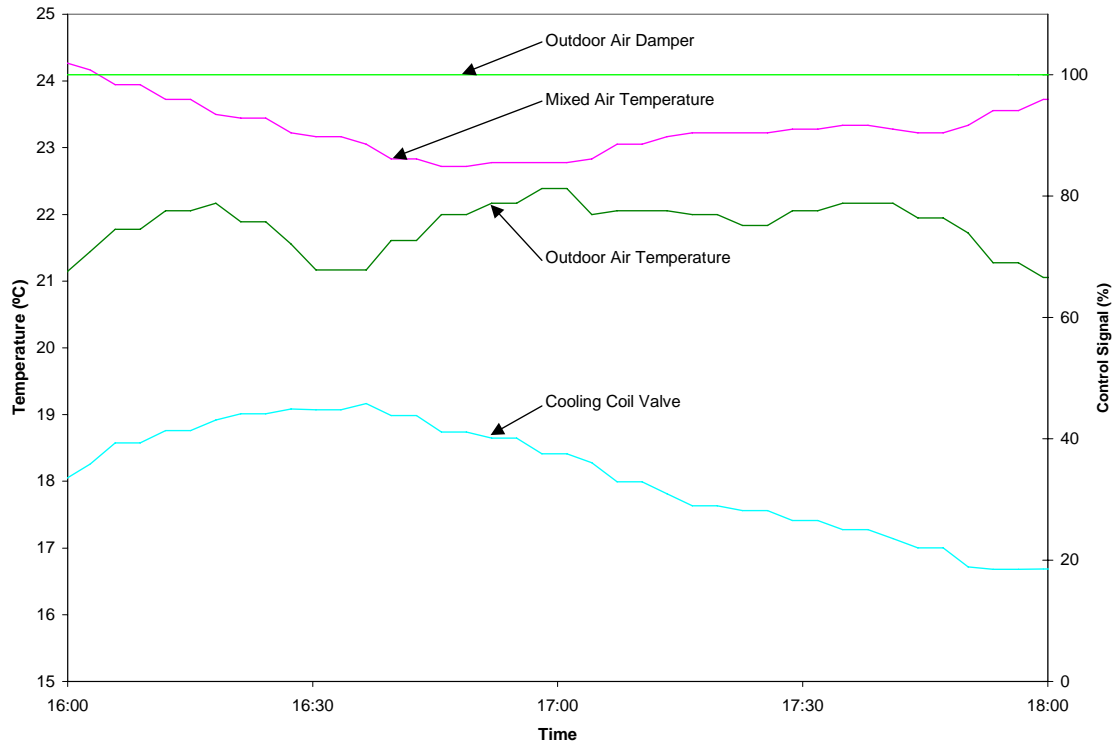
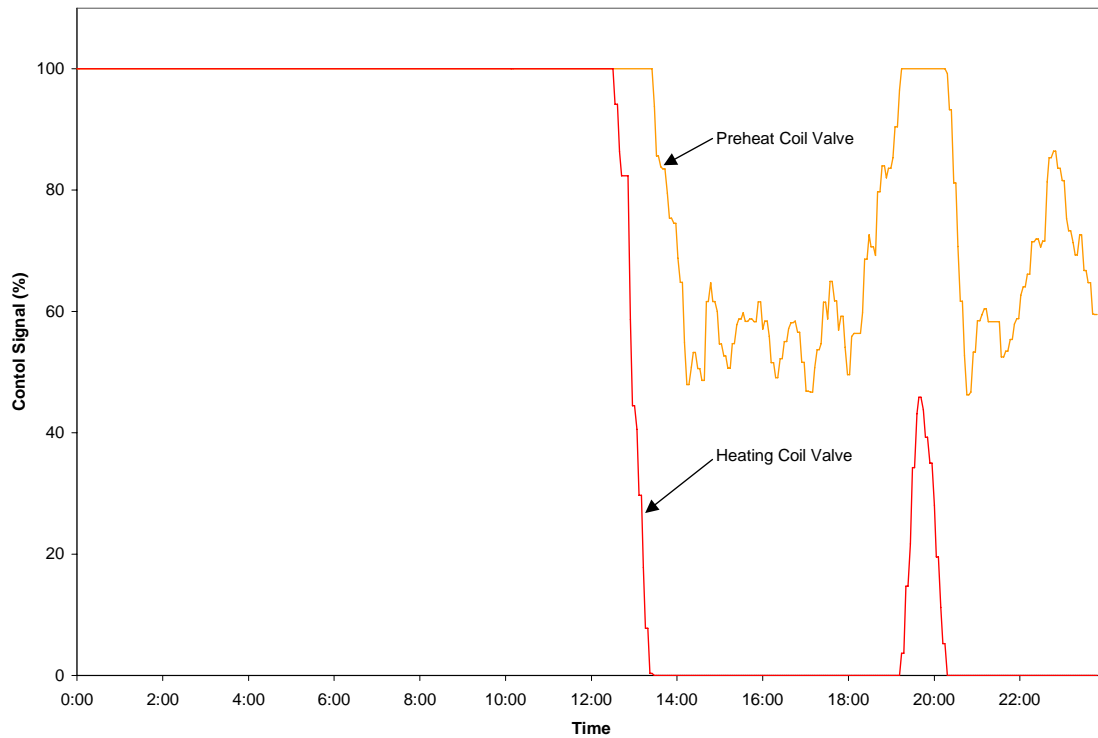


Figure 5.17. Manual Override of Outdoor Air Damper.

Figure 5.17 shows a plot of temperature and control signal data from the AHU at SITE-4. The preheat and heating coil valves (not shown) remain fully closed and the mixing box dampers are positioned for 100 % outdoor air. The cooling coil valve is modulated to meet the cooling load. This combination of control signals corresponds to Mode 3: mechanical cooling with 100 % outdoor air. One of the rules for Mode 3 is Rule 10, which states that the outdoor air and mixed air temperatures should be nearly the same. Figure 5.17 shows that the mixed air temperature is greater than the outdoor air temperature by as much as 3 °C. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 10. As shown in Table 2.2, the possible causes of this fault are an outdoor or mixed air temperature sensor error or a stuck or leaking mixing box damper. Onsite personnel explained that the fault was due to a manual override of the outdoor air damper which had been made in response to a design flaw. The sequence of operations for this AHU specifies that the outdoor air damper open fully during occupied periods. However, under some weather conditions, the AHU does not have sufficient capacity to meet both the space heating/cooling load and the ventilation load. A manual override keeps the outdoor air damper partially closed, thereby reducing the ventilation load so that the AHU has sufficient capacity to maintain the space temperature and humidity at setpoint.

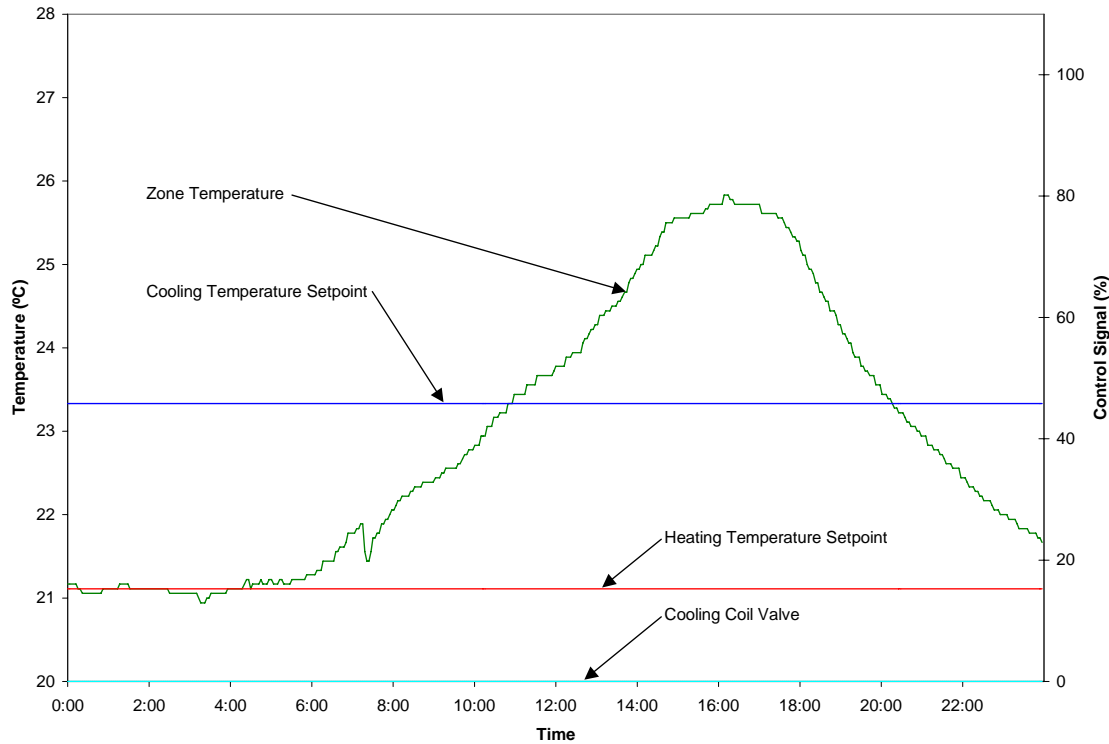
### 5.4.3 Steam Outage



**Figure 5.18. Sitewide Steam Outage.**

Figure 5.18 shows a plot of temperature and control signal data from the AHU at SITE-4. This AHU has a preheat coil and a heating coil, which are sequenced as described in Section 5.4.1. Figure 5.18 shows the AHU operating in Mode 1: heating. One of the rules for Mode 1 is Rule 4, which warns that the heating coil valve is saturated fully open. For the first 12 hours of the day shown, both the preheat and heating coil valves are saturated at 100 % open. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 4. As shown in Table 2.2, the possible causes of this fault are either a supply air temperature sensor error, a stuck or leaking cooling coil valve, a stuck heating coil valve, an undersized heating coil, a fouled heating coil, hot water supply temperature too low, a problem with the hot water circulating pump, or a controller tuning error. Onsite personnel investigated and determined that the fault was due to a sitewide steam outage which caused the hot water supply temperature to fall too low. Figure 5.18 shows that the fault disappeared when the steam supply was brought back online at approximately 12:00.

#### 5.4.4 Incorrect Cooling Coil Valve Actuator Configuration

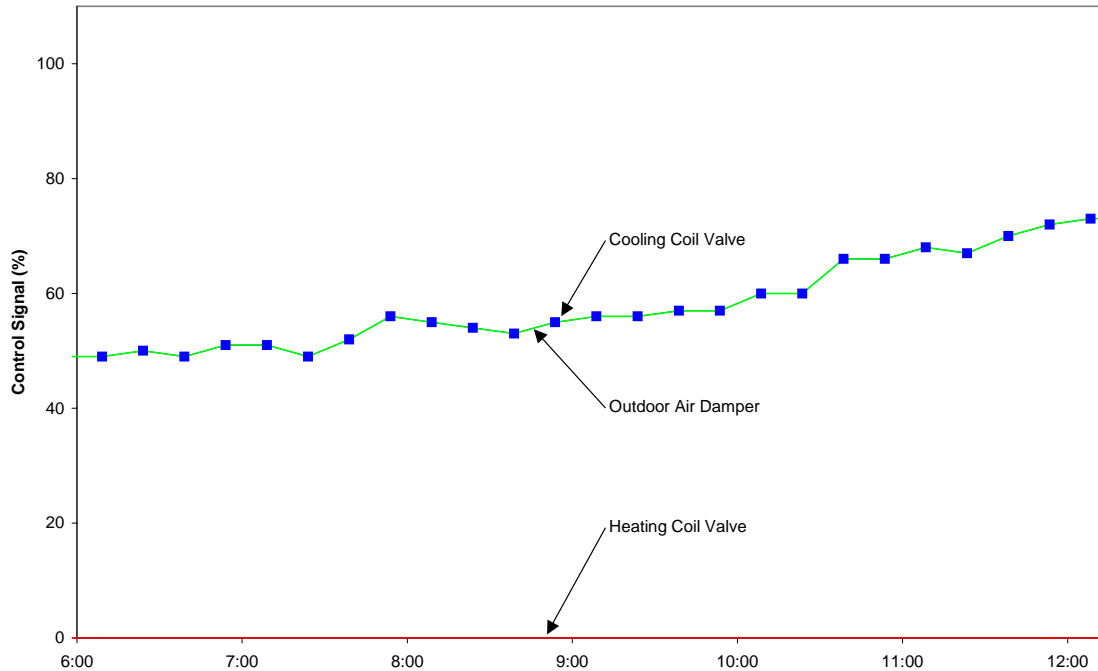


**Figure 5.19. Incorrect Cooling Coil Valve Actuator Configuration.**

Figure 5.19 shows a plot of temperature and control signal data from the AHU at SITE-4. It shows the AHU operating in Mode 5: unknown mode of operation. One of the rules which applies to all modes of operation is Rule 25, which states that the supply air temperature should be nearly equal to the supply air temperature setpoint. The sequence of operations for this single-zone AHU modulates the cooling coil valve to maintain the zone temperature between the heating and cooling setpoints, so Rule 25 was rewritten to state that the zone temperature should be between the cooling and heating setpoints. Figure 5.19 shows that the zone temperature exceeded the cooling setpoint by as much as 5.5 °C, yet the cooling coil valve remained closed. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 25. As shown in Table 2.2, the possible causes of this fault are either a controller tuning or logic error. Onsite personnel investigated and determined that the fault was due to an incorrect configuration of the AHU controller output to the cooling coil valve actuator. The controller output was configured for 0 – 10 V, but the actuator was 2 – 10 V. As a result, the valve remained closed for controller output values from 0 – 2 V. The fault was repaired by reconfiguring the controller output for 2 – 10 V.

## 5.5 SITE-5

### 5.5.1 Simultaneous Mechanical Cooling and Economizing

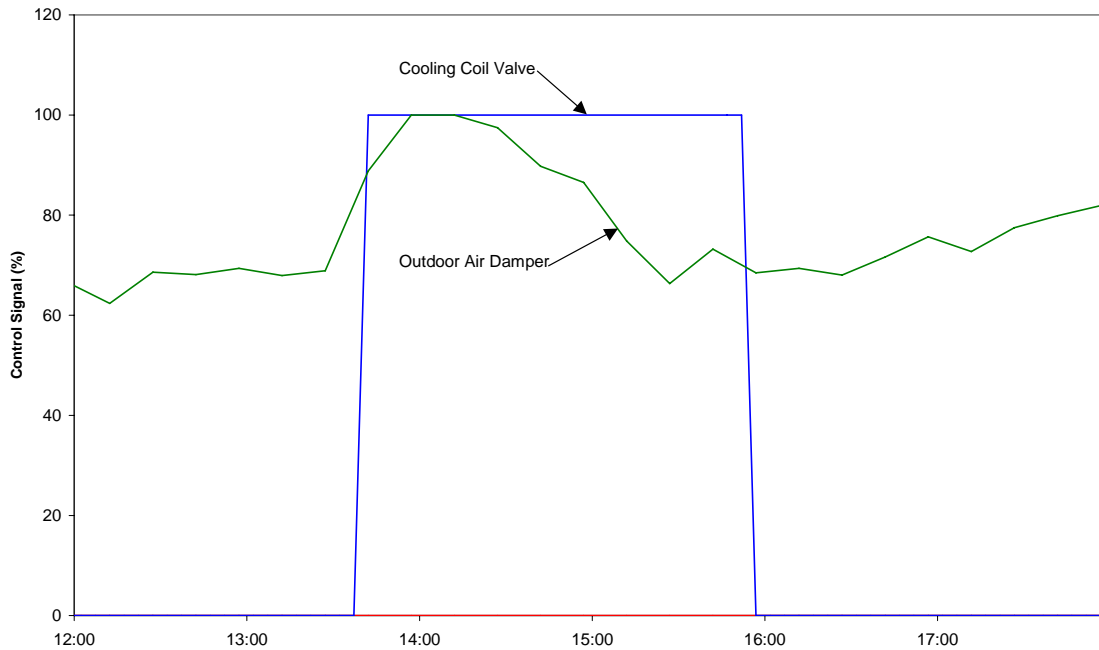


**Figure 5.20. SITE-5 Simultaneous Mechanical Cooling and Economizing.**

Figure 5.20 shows a plot of control signal data from one of the AHUs at SITE-5; it shows the AHU operating in Mode 5: unknown mode of operation. One of the rules for Mode 5 is Rule 24, which states that the AHU is simultaneously modulating the cooling coil valve and the economizer. As shown in Figure 5.20, the cooling coil valve and outdoor air damper move in concert from 50% to 75% open over the course of the morning. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 24. As shown in Table 2.2, the possible causes of this fault are a controller tuning or logic (sequencing and scheduling) error. Since this fault was reported for both AHUs at SITE-5, a logic error was the most likely explanation. A review of the control logic revealed that the output of the temperature control PID loop was sent to both outputs simultaneously, which caused a greater load on the chiller and increased chiller run time, both contributing to increased energy consumption. Proper sequencing for conditions that meet the criteria for economizer operation would position the outdoor air damper to maintain the supply air temperature at its setpoint while keeping the cooling coil valve closed, thus meeting the cooling load without using mechanical cooling. If the cooling load is too great, the outdoor air damper will saturate at 100% open, and the cooling coil valve will open to maintain the supply air temperature at its setpoint. By keeping the outdoor air damper fully open, the load on the cooling coil will be minimized.

## 5.6 SITE-6

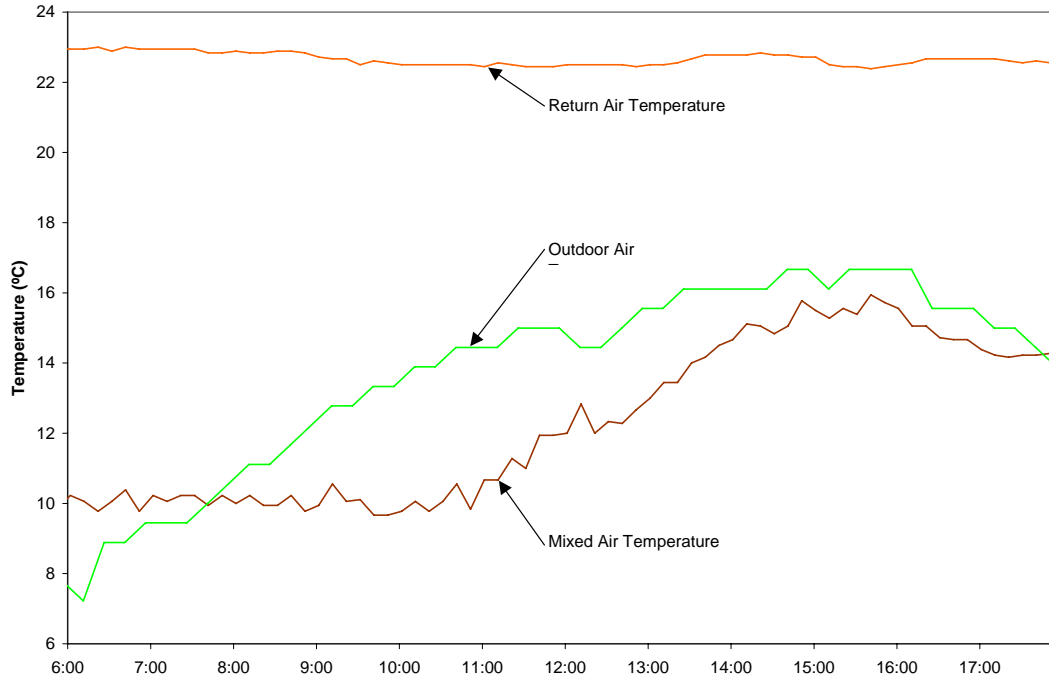
### 5.6.1 Simultaneous Mechanical Cooling and Economizing



**Figure 5.21. SITE-6 Simultaneous Mechanical Cooling and Economizing.**

Figure 5.21 shows a plot of control signal data from one of the AHUs at SITE-6; it shows the AHU operating in Mode 5: unknown mode of operation. One of the rules for Mode 5 is Rule 24, which states that the AHU is simultaneously modulating the cooling coil valve and economizer. As shown in Figure 5.21, the cooling coil valve opens while the outdoor air damper is modulating. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 24. As shown in Table 2.2, the possible causes of this fault are a controller tuning or logic (sequencing and scheduling) error. As in the simultaneous cooling and economizing fault for SITE-5, the AHU sequencing logic was the cause. In this case, two separate PID loops were used to position the cooling coil valve and the outdoor air damper. No interlocks or other logic was present to coordinate outdoor air damper operation with the heating and cooling coil valves.

## 5.6.2 Outdoor Air Temperature Sensor Error



**Figure 5.22. SITE-6 Outdoor Air Temperature Sensor Error.**

Figure 5.22 shows a plot of temperature data from one of the AHUs at SITE-6. Rules 26 and 27 apply to all modes of operation and state that the mixed air temperature should be between the outdoor air and return air temperatures. Rule 26 checks whether the mixed air temperature is greater than the maximum of the outdoor air and return air temperatures, while Rule 27 checks whether the mixed air temperature is less than the minimum of the outdoor air and return air temperatures. Figure 5.22 shows that the mixed air temperature is less than the minimum of the outdoor air and return air temperatures by as much as 5 °C. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 27. As shown in Table 2.2, the possible causes of this fault are an outdoor or mixed air temperature sensor error or a stuck or leaking mixing box damper. Onsite personnel investigated and determined that the fault was due to an outdoor air temperature sensor error caused by a difference in temperature between the location of the outdoor air temperature sensor and the AHU's outdoor air intake.

### **5.6.3 VAV Box Controller Hardware Failure**

When VPACC was initially installed in the VAV box controllers at SITE-6, there was a delay of several weeks before the trendlogs could be configured. During that time, several alarms were generated based on faults detected by VPACC. Although there is insufficient data to show plots and fully describe these faults, they were each confirmed and repaired by the maintenance staff. In one case, high airflow alarms were reported for two of the VAV boxes at the site. A follow up by the maintenance staff determined that both of the VAV box controllers had failed. The controllers were replaced and the alarms did not recur.

### **5.6.4 Disconnected VAV Box Supply Air Duct**

Another fault reported shortly after the initial installation of VPACC was a low airflow alarm for a VAV box. The maintenance staff determined that the flexible duct connecting the main supply air duct to the inlet of the VAV box had partially slipped from the VAV box inlet connection. The flexible duct was moved into the correct position and secured in place. After this repair, the alarm did not recur.

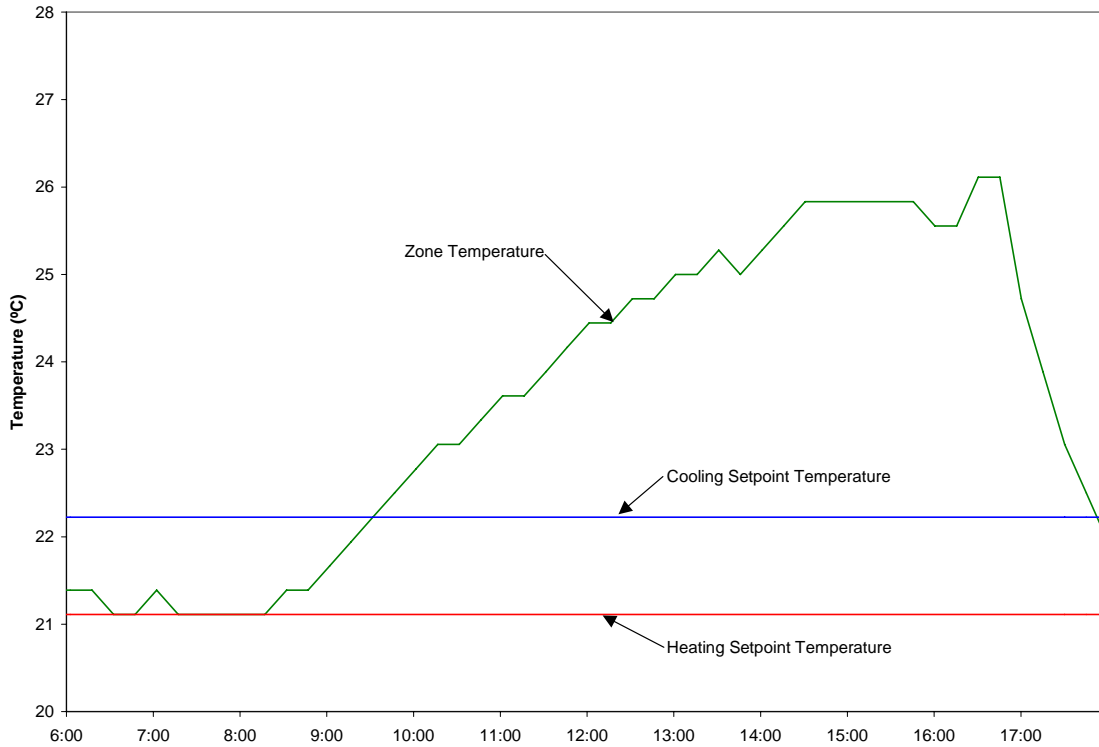
### **5.6.5 VAV Box Damper Actuator Failure**

A third fault reported shortly after the initial installation of VPACC was a high airflow alarm for one of the VAV boxes at SITE-6. A follow up by the maintenance staff determined that the damper actuator shaft was bent. The shaft was replaced and the alarm did not recur.

### **5.6.6 Disconnected VAV Box Flow Sensor Tubing**

A final fault reported shortly after the initial installation of VPACC was another high airflow alarm for a VAV box. In this case, the fault was caused by one of the flexible tubing connections from the velocity probe (flow ring) in the VAV box inlet to the differential pressure sensor on the VAV box controller. The tubing had slipped off of the connection at the controller. The tubing was moved back into the correct position and the alarm did not recur.

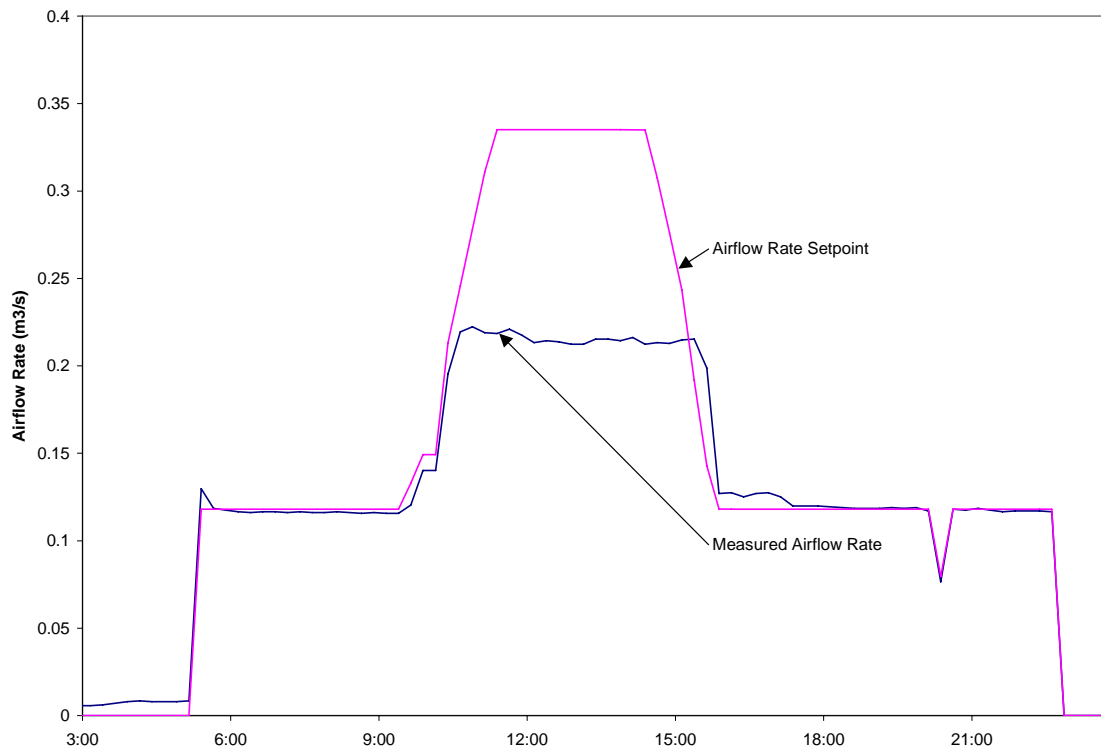
### 5.6.7 Undersized VAV Box



**Figure 5.23. SITE-6 Undersized VAV Box.**

Figure 5.23 shows a plot of temperature data from one of the VAV boxes at SITE-6. It shows a large positive zone temperature error, since the zone temperature is greater than the cooling setpoint temperature. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a high zone temperature alarm. Table 2.3 lists the possible causes of this fault, including a zone temperature sensor error, airflow (DP) sensor error, reheat coil valve or actuator stuck or failed, supply air too warm, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a maximum airflow setpoint that is too low, and a sequencing logic error. Onsite personnel investigated and determined that the fault was due to a high solar heat gain to the conditioned space, which is a lobby with large windows. The VAV box is not large enough to provide a sufficient supply airflow rate to meet the load.

## 5.6.8 Undersized Supply Fan

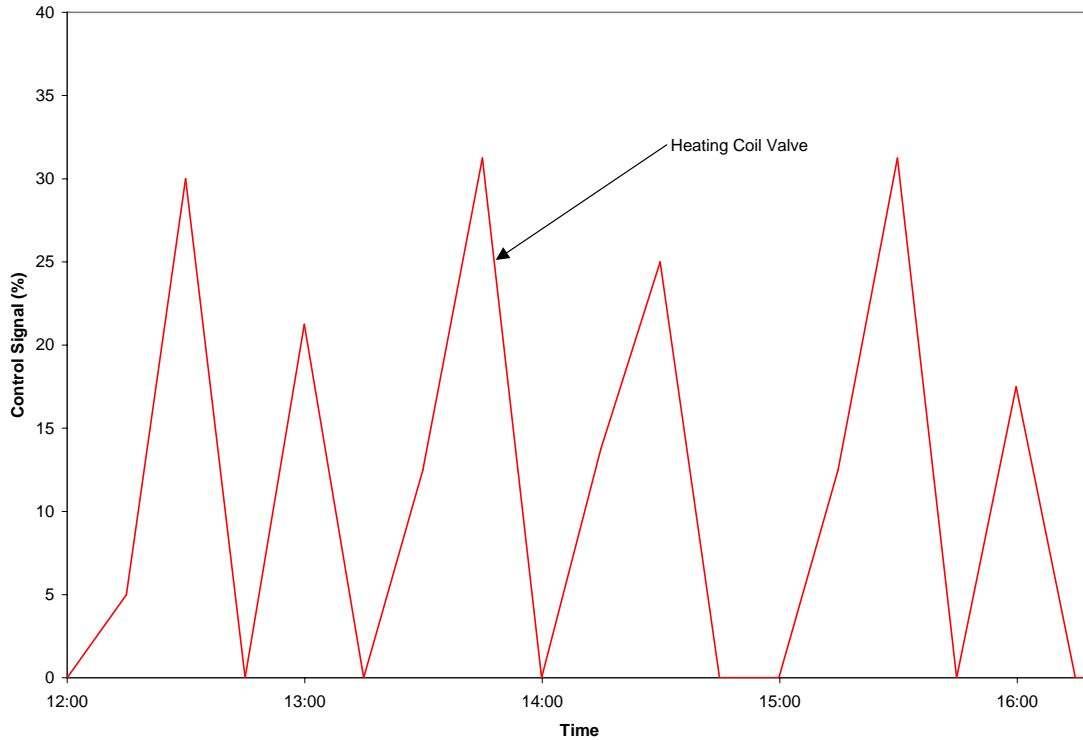


**Figure 5.24 SITE-6 Undersized Supply Fan.**

Figure 5.24 shows a plot of airflow data from one of the VAV boxes at SITE-6. The plot shows that the measured airflow rate was substantially less than the airflow rate setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low airflow alarm. Table 2.3 lists the possible causes of this fault, including an airflow (DP) sensor error, a stuck or failed damper or damper actuator, low static pressure in the supply air duct, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control PID loop, a maximum airflow setpoint that is too high, and a sequencing logic error. Onsite personnel investigated and determined that the fault was due to low static pressure in the supply air duct caused by an undersized supply fan in the AHU that serves this VAV box. Figure 5.24 illustrates that early and again later in the day, the airflow rate setpoint was at the minimum and the supply fan was able to maintain sufficient static pressure. When the airflow setpoint increased in the middle of the day, the actual airflow fell below the setpoint as the supply fan was not able to maintain the static pressure at the setpoint. The problem was corrected by replacing the sheaves on the supply fan and motor to increase the fan speed.

## 5.7 SITE-7

### 5.7.1 AHU PID Loop Tuning Error



**Figure 5.25. SITE-7 AHU PID Loop Tuning Error.**

Figure 5.25 shows a plot of control signal data from one of the AHUs at SITE-7. Both stages of DX cooling remain off (not shown) and the economizer is positioned for minimum outdoor air (not shown), while the heating coil valve repeatedly cycles open and closed. The actual rate of valve cycling was observed by the researcher and the maintenance staff to be several times greater than that shown on Figure 5.25. An aliasing effect is present due to the relatively large trendlog sample interval time of 15 min. Whenever the heating coil valve is closed, the AHU is in Mode 5 (unknown mode of operation) and when the heating coil valve is open, the AHU is in Mode 1 (heating). Rule 28, which applies to all modes of operation, counts the number of mode switches per hour. If the count exceeds the threshold (seven mode switches per hour) then a fault has occurred. Although it does not appear so in Figure 5.2, Rule 28 is violated several times on the day shown. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated several fault reports due to Rule 28. As shown in Table 2.2, the possible causes of this fault are a controller or logic error. Onsite personnel investigated and determined that the fault was due to the value of the parameters used to sequence the heating coil valve, stages of DX cooling, and the economizer.

## **6 Summary**

Multiple field sites were established to test APAR and VPACC embedded in commercial HVAC equipment controllers. The test was quite successful: a variety of mechanical and control faults have been detected, diagnosed, and in many cases, repaired. The viability of deploying FDD as an integral component of the HVAC control system has been demonstrated. Based on feedback from users at the field sites, modifications have been made to enhance the usability and robustness of the FDD tools. In some cases, the local representative of the manufacturer of the control system was involved in the setup and operation of the test site. Feedback from these manufacturers' representatives, who will ultimately be responsible for installing FDD in their customers' buildings, was used to make the installation procedure more time- and resource-efficient and minimize the amount of site-specific configuration required.

## 7 References

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