

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

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**Final Report on Robust Parameters for Air  
Handling Unit and Variable Air Volume Box  
Fault Detection and Diagnostics**

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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 report describes a research effort to establish robust sets of parameters for APAR and VPACC. The goal of the study was to enable the commercial use of FDD without the collection and analysis of trend data from each potential installation.

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).

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].

There are a wide variety of disturbances that can cause an HVAC system to deviate from ideal “normal operation” conditions, but are not actual faults and should not be reported as such [4]. These include variations in outdoor temperature, wind velocity and direction, solar radiation, internal heat sources, and changes in system mode of operation or schedule. Normal non-idealities of the HVAC system, such as minor sensor drift, errors due to analog-to-digital or digital-to-analog converter resolution, noise, small deviations from setpoint, actuator hysteresis, etc. also should not be reported as faults. Many FDD methods, including APAR and VPACC, employ a set of parameters that collectively define the severity of a fault needed in order to report an alarm. If the cutoff severity needed to trigger an alarm is too great, real faults will remain undetected (false negatives). However, if the cutoff severity is too small, false alarms (false positives) will be generated. FDD parameters must be selected carefully to minimize both false positives and false negatives. This report describes the development and selection of these parameters for APAR and VPACC.

## 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 [5].

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 built-in 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 [5].

**Table 2.1: APAR Rule Set**

<b>Mode</b>	<b>Rule #</b>	<b>Rule Expression</b> (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			
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 [6].

VPACC implements an algorithm known as a CUSUM (cumulative sum) chart [7]. 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 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.

**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 Robust FDD Parameters

In previous research, the FDD parameters for APAR and VPACC were determined on a site-specific basis. For each data source, whether it was a simulation, emulation, laboratory, or field test site, initial guess values of the parameters were refined through trial and error [1,2,3,5,6]. It is expected that for most control system integrators and building owners, the need to develop a site-specific set of parameters presents a major barrier to the adoption of FDD, both in terms of a detailed understanding of the APAR and VPACC algorithms as well as the time and resources required. To overcome this obstacle, a set of robust FDD parameters was developed. These parameters were found to be effective for a variety of mechanical system types, building uses, and weather conditions based on application to previous work [2] as well as to multiple test sites in a field demonstration of APAR and VPACC concurrent with the study described in this report.

In the development of any set of FDD parameters, there is an inherent tradeoff between false negatives (real faults remain undetected) and false positives (false alarms). For the tabulated set of parameters, this tradeoff is biased toward minimizing false alarms, if necessary at the expense of missing some real faults. Most facilities have limited manpower available to follow up on reported faults, so by reporting only relatively severe faults, technician productivity is maximized as repairs are made to the most serious problems. Minimizing false alarms is crucial since too many false alarms will cause O&M staff to waste time and lose confidence in the FDD algorithms, ultimately causing real faults to be ignored. Furthermore, a large number of fault reports, whether real or false, may be more information than the O&M staff can process.

The recommended FDD parameters are presented in Tables 3.1 for APAR and 3.2 for VPACC.

**Table 3.1. APAR Recommended Parameters.**

<i>Parameter</i>	<i>Value</i>
Heating Coil Threshold	0.02
Cooling Coil Threshold	0.02
Mixing Box Damper Threshold	0.02
Temperature Threshold	2.0 °C (3.6 °F)
Flow Threshold	0.3
Enthalpy Threshold	3.0 kJ/kg (1.3 Btu/lbm)
Supply Fan Temperature Rise	1.1 °C (2.0 °F)
Return Fan Temperature Rise	1.1 °C (2.0 °F)
Minimum Temperature Difference for Ventilation Rules	5.6 °C (10.0 °F)
Maximum Number of Mode Switches Per Hour	7
Occupancy Delay	90 min
Mode Switch Delay	60 min
Rule Delay	60 min
Smoothing Constant	0.1

**Table 3.2. VPACC Recommended Parameters.**

<i>Parameter</i>	<i>Value</i>
Expected Zone Temperature Error	0.0 °C (0.0 °F)
Zone Temperature Error Standard Deviation	0.6 °C (1.0 °F)
Expected Airflow Rate Error	0 m <sup>3</sup> /s (0 cfm)
Airflow Rate Error Standard Deviation	0.02 * VAV Box Maximum Airflow Rate <sup>1</sup>
Expected Discharge Temperature Error	1.1 °C (2.0 °F)
Discharge Temperature Error Standard Deviation	1.1 °C (2.0 °F)
Slack Parameter	3
Alarm Limit	1000
Occupancy Delay	90 min
Reheat Coil Delay	60 min
CUSUM Reset Interval	360 min

<sup>1</sup>By scaling the airflow rate error standard deviation to the maximum airflow rate through the box, the same code can be used for any size VAV box.

## 4 Tuning FDD Parameters for Optimum Performance

In most cases it is expected that the tabulated FDD parameters will be used. However, some building operators may need to develop their own parameter values. For example, a particular facility may find that, although the faults that are reported are legitimate, there are too many for the O&M staff to handle. In this case, the parameters will be adjusted so that the threshold severity for a fault to be reported is increased. Or, in a facility that has more resources available and is particularly interested in reducing energy consumption, the parameters might be adjusted so that the threshold severity is reduced. To enable users to make these adjustments, guidelines for tuning the FDD parameters are included.

### 4.1 Tuning APAR Parameters

Some of the parameters can be determined directly by evaluating the mechanical system. The values for supply and return fan temperature rise can be determined from design data or field measurements.

The minimum temperature difference for ventilation rules can be determined by evaluating trendlogs of the return, outdoor, and mixed air temperatures, and the mixing box damper control signal. For each logged data sample, the actual outdoor air fraction can be compared with the calculated outdoor air fraction based on the temperature data. Correlating the accuracy of the calculated outdoor air fraction with the difference between the return and outdoor air temperatures will yield the minimum temperature difference for ventilation rules.

The occupancy delay can be determined by evaluating trendlogs of the supply air temperature and setpoint. The occupancy delay parameter should be set equal to the time from the onset of the occupancy until the supply air temperature is reasonably close to the setpoint. Then a margin of safety should be added. The mode switch delay can be determined similarly, by observing the time for the system to “settle out” after a change from one mode of operation to another.

The heating coil, cooling coil, mixing box damper, temperature, flow, and enthalpy thresholds, and the maximum number of mode switches per hour are best determined by analysis of particular rules that are causing false alarms or are not reporting actual faults when the recommended parameter values are used. Although it is possible to apply a standard uncertainty analysis as described in [8] to the rule, better results are obtained from trial and error. Trendlogs of the data relevant to the rule combined with a spreadsheet analysis of the rule can be very helpful for understanding why a particular rule is or is not reporting a fault, and then to help select better parameter values.

A detailed analysis of a particular rule will also reveal incorrect results that are due to poor values of the rule delay or the smoothing constant. If the rule delay is too short, transient conditions that are not true faults will cause false alarms, while a rule delay that is too long will cause real faults to be missed. If the smoothing constant is too great, noisy data or transient conditions that are not true faults will cause false alarms, while a smoothing constant that is too small will not allow real faults to be reported. A smoothing constant that is too small can also cause false alarms if the smoothed data still reflect the transient conditions from the most recent mode switch.

## 4.2 Tuning VPACC Parameters

Ideally, initial guesses for the expected value and standard deviation of the zone temperature, airflow, and discharge temperature errors should be calculated from data collected from the VAV boxes at the site. Data from unoccupied periods and from the first two hours of occupied periods should be removed from the set before computing the statistics. It is important to use data that is equally representative of heating and cooling conditions. If data are not available, the initial guesses for the expected zone temperature or airflow errors should both be set equal to zero. The initial guess for the expected discharge temperature should be set equal to the duct heat gain, which can be determined from the design documents or from measurements from a few typical VAV boxes. Sensor accuracies or typical observed variations can be used as initial guesses for the standard deviations. The recommended values from Table 3.2 can serve as initial guesses for the remaining parameters.

Once initial guesses have been determined, the parameters can be tuned by observing the faults reported by VPACC compared to the actual performance of the system. If there are false alarms or missed faults from two or more of the errors, the alarm limit should be adjusted accordingly. If the missed faults or false alarms are from one error only, the standard deviation of that error should be adjusted instead. To eliminate false alarms early in the occupied period of the day, the occupancy delay should be increased. If false alarms occur late in the day, the CUSUM reset interval should be decreased.

The following example demonstrates the relationships between the parameters. In this example, the recommended values from Table 3.2 are used. Consider a VAV box with a maximum airflow rate of  $0.472 \text{ m}^3/\text{s}$  (1000 cfm) and a constant airflow rate error of  $0.07 \text{ m}^3/\text{s}$  (150 cfm). The expected airflow rate error is zero and the airflow rate error standard deviation is equal to  $0.02$  \* the maximum airflow rate, or  $0.009 \text{ m}^3/\text{s}$  (20 cfm). The normalized error will be constant:

$$z_i = (x_i - x_{exp}) / \sigma_{exp} = (0.07 \text{ m}^3/\text{s} - 0 \text{ m}^3/\text{s}) / 0.009 \text{ m}^3/\text{s} = (150 \text{ cfm} - 0 \text{ cfm}) / 20 \text{ cfm} = 7.5$$

Since the error is positive, only the positive ( $S$ ) sum is accumulated.  $S$  is defined as:

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

The expression is evaluated once per minute beginning 90 min (the occupancy delay) after the beginning of occupancy. Since all the terms are constant,  $S$  increases by

$$z - k = 7.5 - 3 = 4.5$$

each minute. After 223 minutes,  $S$  reaches a value of 1003.5, which is greater than the alarm limit of 1000. The CUSUM reset interval is 360 min, which is greater than the time to reach the alarm limit, so the alarm will be reported before  $S$  is reset to zero.

## **5 Summary**

A study was conducted to establish robust sets of parameters for APAR and VPACC. The goal of the study was to enable the commercial use of these FDD tools without the collection and analysis of trend data from each potential installation. Robust values for the parameters were determined through trial and error at multiple field test sites and the resulting values were compiled and tabulated. For users who need or prefer to determine site-specific parameters, procedures to do so were developed and documented.

## 6 References

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