U.S. DEPARTMENT OF ENERGY

PNNL-22941

# Transactional Network Platform: Applications

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October 2013

Pacific Northwest NATIONAL LABORATORY

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## Abstract

In FY13, Pacific Northwest National Laboratory (PNNL), with funding from the Department of Energy's (DOE's) Building Technologies Office (BTO), designed, prototyped and tested a transactional network platform to support energy, operational and financial transactions between any networked entities (equipment, organizations, buildings, grid, etc.). Initially, in FY13, the concept demonstrated transactions between packaged rooftop air conditioning and heat pump units (RTUs) and the electric grid using applications or "agents" that reside on the platform, on the equipment, on a local building controller or in the Cloud.

The transactional network project is a multi-lab effort with Oakridge National Laboratory (ORNL) and Lawrence Berkeley National Laboratory (LBNL) also contributing to the effort. PNNL coordinated the project and also was responsible for the development of the transactional network (TN) platform and three different applications associated with RTUs. This document describes two applications or "agents" in detail, and also summarizes the platform. The TN platform details are described in another companion document.

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# Transactional Network (TN) Platform Overview

The core of the TN platform is VOLTTRON Lite™ software, which integrates the various components of the TN platform. It also provides an environment for agent execution and serves as a single point of contact for interfacing with devices (rooftop air conditioning and heat pump units (RTUs), power meters, etc.), external resources, and platform services such as data archival and retrieval. The VOLTTRON Lite platform provides a collection of utility and helper classes, which simplifies agent development. VOLTTRON Lite is an open source version of the VOLTTRON™ software, developed at Pacific Northwest National Laboratory (PNNL). This newly developed codebase has replicated appropriate VOLTTRON functionality, added several new capabilities, and incorporated several open source projects to build a flexible and powerful platform. For more details on the platform, please refer to the companion report (Haack et al. 2013).

# RTU Agent Design, Development, and Testing

PNNL developed three agent or applications, to demonstrate the TN concept with RTUs: 1) automated fault detection and diagnostic (AFDD) agent, 2) demand response (DR) agent and 3) smart monitoring and diagnostic system (SMDS) application. The first two agents run on the platform, while the SMDS application runs in the Cloud but analyzes data from RTUs provided by the TN platform. This document only describes the implementation details for the three applications.

## Automated Fault Detection and Diagnostics (AFDD) Agent

The automated fault detection and diagnostic process is a two-step process where 1) a fault with equipment operation is detected and 2) the cause of the fault is isolated (Figure 1). The process generally relies on analytical or physical redundancies to isolate faults during the diagnostic step. Most RTUs on commercial buildings lack physical redundancy because heating, ventilation, and air conditioning (HVAC) systems in commercial buildings are considered non-critical. An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault.

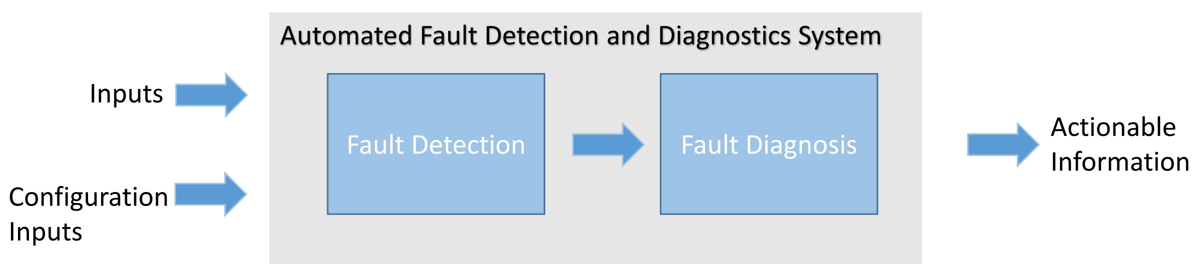


*Figure 1: Illustration of the Automated Fault Detection and Diagnostic Process*

Proactive AFDD is a process that involves automatically initiating changes to cause or to simulate operating conditions that may not occur for some time, thus producing results that might not be available for months otherwise. Such tests could be automated to cover a more complete range of conditions or to deepen diagnosis beyond what might be possible without this capability. The proactive diagnostic process can help diagnose and isolate faulty operations to a much greater extent than passive diagnostics, but it is intrusive. Some building owners and operators may consider this to be disruptive to the normal operation of their RTU systems. They may not, however, if such proactive tests can be conducted quickly enough to maintain acceptable control of the RTU systems. Proactive diagnostic procedures are capable of providing continuous persistence of performance if they are frequently triggered (e.g., once a day, once a week, once a month or perhaps seasonal). These procedures might be scheduled to occur during building startup hours or at the end of the day to further reduce their intrusiveness or could be scheduled on demand. The proactive diagnostic process described above is similar to functional testing that is performed during manual commissioning of systems.

Seven AFDD algorithms were developed and deployed on the TN platform for detecting and diagnosing faults with RTU economizer and ventilation operations using sensors that are commonly installed for control purposes. The algorithms utilize rules derived from engineering principles of proper and improper RTU operations. The seven algorithms include:

- Compare discharge-air temperatures (DAT) with mixed-air temperatures (MAT) for consistency (AFDD0)
- Check if the outdoor-air damper (OAD) is modulating (AFDD1)
- Detect RTU sensor faults (outdoor-air, mixed-air and return-air temperature sensors) (AFDD2)
- Detect if the RTU is not economizing when it should (AFDD3)
- Detect if the RTU is economizing when it should not (AFDD4)
- Detect if the RTU is using excess outdoor air (AFDD5)
- Detect if the RTU is bringing in insufficient ventilation air (AFDD6).

The intent of these algorithms is to provide actionable information to building owners and operations staff while minimizing false alarms.  Therefore, the algorithms have been designed to minimize false alarms. On the other hand, if HVAC systems and their controls start to fail, having an indicator (a.k.a. "check engine light") of a real problem is always helpful – especially if it allows operations and maintenance staff to be proactive, rather than reactive. The remainder of this section will provide a more detailed summary of the seven algorithms. Appendix contains more detailed information including implementation details, flowcharts, inputs required for the algorithms and the outputs from the algorithms.

To implement the algorithms, the RTUs must be configured with a number of temperature sensors (including outdoor-, return-, mixed- and discharge-air) and status signals (including fan, compressor, and outdoor-air damper). The outdoor-air temperature (OAT) sensor can be installed on an individual RTU, or a shared value across the network (network from inside the building or network from outside the building). . The typical location of these sensors is shown in Figure 2.

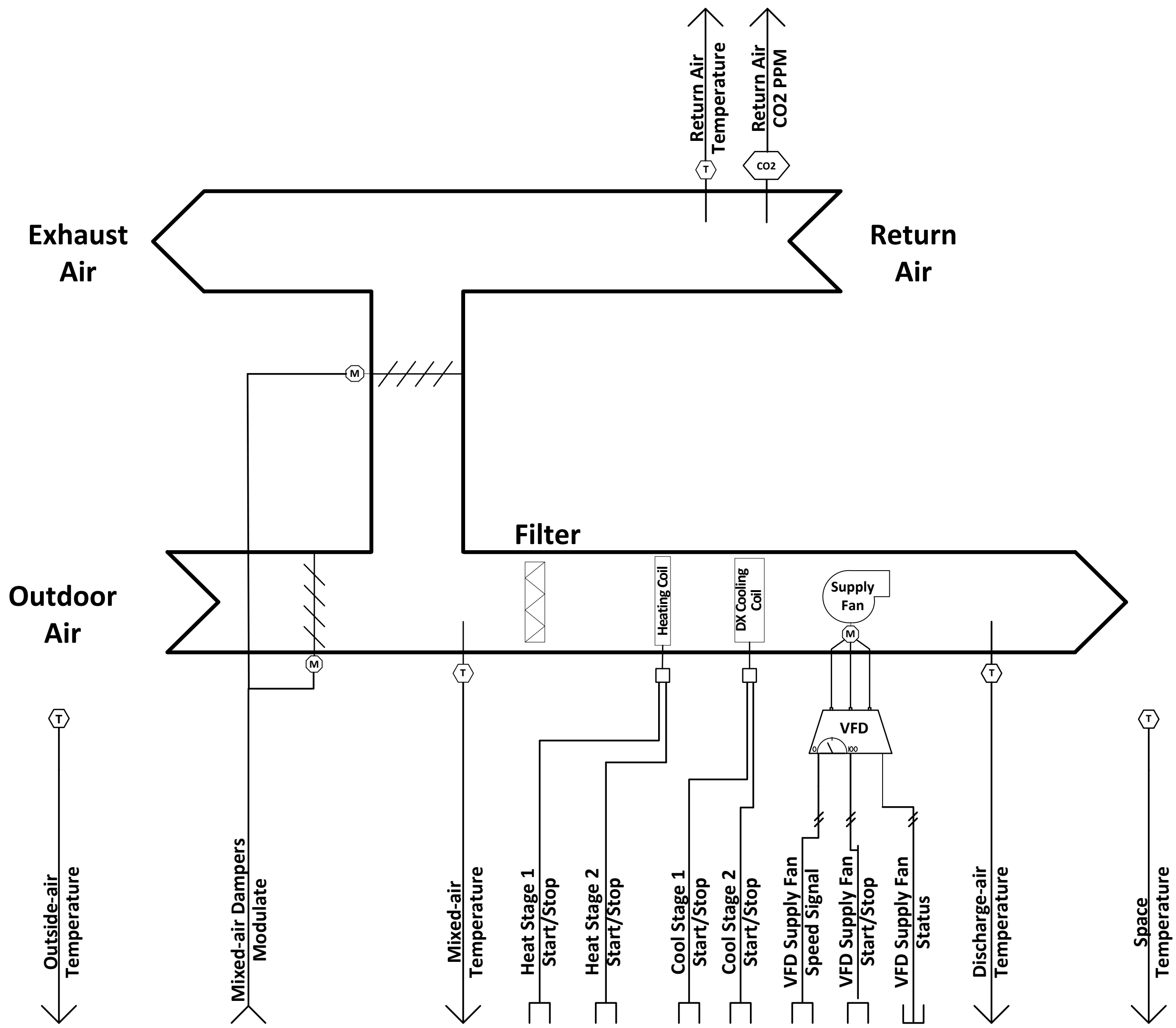


*Figure 2: Schematic of RTU Showing the Various Sensor Locations*

## AFFD0: Compare Discharge-air Temperatures With Mixed-air Temperatures for Consistency

The first diagnostic check is designed to compare the discharge-air and mixed-air temperature sensor readings with each other. When heating and cooling systems are turned off, (disabled) during this diagnostic check, the temperature sensors in the air streams upstream of the fan (mixed-air plenum) and downstream of the fan (discharge-air plenum) are compared to each other. The result of this comparison should have temperature readings within 2$^{o}$F to 4$^{o}$F (user-adjustable) of each other during steady-state conditions (user-adjustable time lag required after the heating and cooling systems are turned off). There usually is additional heat in the discharge–air stream from the fan and motor that would create the slight difference (higher discharge-air temperature is the expectation) when this check is made.

This test validates that these two temperature sensors are reading within a user-adjustable pre-set value (suggest 2$^{o}$F to 4$^{o}$F). This provides an initial confidence factor in the two sensors and their integrity. If the diagnostic check determines that the absolute value of the difference between the two temperature sensors is higher than the acceptable threshold, a fault will be generated. The fault does not identify which sensor is "faulty," only that there is a lack of confidence in one or both sensors and their accuracy.

This algorithm may consider additional fault analysis (future work) that finds that the mixed-air temperature sensor is consistently reading higher than the discharge-air temperature sensor. Typical causes include sensor fault, sensor location, sensor wiring, sensor software configuration, cooling coil control valve leak (where chilled water coils exist in the RTU), etc.

The schedule established on the TN platform determines when this fault analysis will run for an individual RTU. It is generally preferable not to schedule this test prior to normal occupancy or during morning warm up or cool down periods (because heating or cooling would be active). The best time of day to run this fault analysis is 15 to 30 minutes prior to a scheduled unoccupied period (if the intent is to not cause additional run time on the RTU). Each of the diagnostic process typically takes 20 to 30 minutes.

The building owner will determine the frequency of this fault analysis, but it is recommended at least once per week. A future enhancement of AFDD will be a data integrity flag. When the application returns a fault-free diagnostic, the flag will be set for a pre-determined amount of time. During this time, AFDD0 will not re-run and the sensors involved in that diagnostic will be assumed reliable.

If mixed-air temperature sensor value is not available because it is not typically measured, this test cannot be done.

### AFFD1: Check if the Outdoor-air Damper is Modulating

The second diagnostic check determines if the economizer damper is modulating properly. The fault analysis will use the economizer damper command to create two steady-state conditions in the mixed-air plenum.

The first steady-state condition is obtained by commanding the economizer damper to a fully open position (100% outside air). The outside-air temperature is compared to the mixed-air temperature. The time to reach steady state will be a user-adjustable parameter (recommended to be at least 5 minutes for greater accuracy and confidence in the results). If the damper is fully open, the difference between the outside air and the mixed air (discharge-air temperature if mixed-air temperature sensor is not installed) should be minimal (between 2$^{o}$F and 4$^{o}$F).

The second steady-state condition is obtained by commanding the economizer damper to a fully closed position (0% outside air). If the damper is fully closed, the difference between the return-air temperature (RAT) and the mixed-air temperature sensors (discharge-air temperature if mixed-air temperature sensor is not installed) should be minimal (between 2$^{o}$F and 4$^{o}$F).

The absolute difference between the sensor measurements is averaged over a user-adjustable number of minutes to obtain an average absolute difference for each of the steady state conditions. If the diagnostic check determines that the average absolute temperature difference is greater than the acceptable threshold, a fault is generated indicating the damper is not modulating properly.

If the RTU is missing the mixed-air temperature sensor, the discharge-air temperature sensor is used instead for both steady-state conditions with appropriate change in the threshold value. This fault test will also require that the heating and cooling functions be temporarily disabled (similar to “AFFD0” diagnostic check) for both steady-state condition checks.

The schedule established on the TN platform determines when this fault analysis will run for an individual RTU. In addition to the schedule, this test will not be run if the outside-air temperatures are extreme (too hot or too cold [OAT < 50°F or OAT > 90°F]) or when the outside-air temperatures are within 4°F to 5°F of the return-air temperature value.

The frequency of this fault analysis will be determined by the building owner, but it is recommended at least once a week. A future enhancement of the AFDD will be a data integrity flag. When the application returns a fault-free diagnostic, the flag will be set for a pre-determined amount of time. During this time, AFDD1 will not rerun and the damper will be considered functional (or modulating properly).

If the fault analysis returns a fault for an economizer damper that does not open 100% or close to 0%, the platform will recommend that the building owner or designated operations and maintenance (O&M) staff physically inspect the damper movements.

### AFDD2: Detect RTU Sensor Faults (Outside-, Mixed- and Return-air Temperature Sensors)

The third diagnostic check determines if the temperature sensors used on the RTU are reliable and within accepted tolerances. This diagnostic check requires the user/owner or designated staff to visually verify that the economizer dampers are working (when “AFDD1” indicates a fault) as previously described for one or both of the steady-state conditions (0% outside-air and 100% outside-air commands).

When the outdoor-air damper is commanded to a fully closed position (0% outside air), the temperature sensors in the return- and the mixed-air (discharge-air temperature sensor if mixed air temperature sensor is not installed) plenums are compared to each other. The result of this comparison should be within 2°F to 4°F after steady-state conditions are reached. The time to reach steady state will be a user-adjustable parameter (recommended to be at least 5 minutes for greater accuracy and confidence in the results).

The second steady-state condition is obtained by commanding the economizer damper to a fully open position (100% outside air). When the temperature in the mixed-air plenum is compared to the outside-air temperature, the result of this comparison should be within 2°F to 4°F after steady-state conditions are reached.

The schedule established on the TN platform determines when this fault analysis will run for individual RTUs. In addition to the schedule, the test will not run when outside-air temperatures are extreme (too hot or too cold [OAT < 50$^{o}$F or OAT > 90$^{o}$F]) or when the outside-air temperatures are within 4$^{o}$F to 5$^{o}$F of the return-air temperature value.

The building owner will determine the frequency of this fault analysis, but it is recommended at least once per week.

### AFDD3: Detect if the RTU is Not Economizing When it Should

The fourth diagnostic check determines if the economizer on the RTU is working properly when the conditions are favorable for economizing. The AFDD application can be configured to either a differential dry bulb economizer (economize when there is a call for cooling and OAT < RAT) or high-limit economizer (economize when there is a call for cooling and OAT < high limit). This document describes the AFDD configured for differential dry bulb economizer. This diagnostic check assumes that the sensors are reliable and that the damper is able to modulate (AFDD1 and AFDD2 are fault-free).

This diagnostic will look at the zone thermostat cooling call or RTU controller cooling call that is sent to the RTU. When there is a call for cooling and the outside-air temperature is less than the return-air temperature, the damper command should be close to 100% open (or at least greater than the minimum damper position (i.e., 20% open) to introduce cooler outside air than is inside the space being served. If not, a fault will be generated.

If mechanical cooling activates with the damper less than 100% open when outdoor conditions are favorable for economizing, the energy costs are higher because outdoor air is not utilized to the fullest extent. In many cases, outside air is cool enough to satisfy all the cooling loads without using mechanical cooling.

It is possible that the RTU controller was not configured properly (set points) or was never programmed to utilize the economizer. This fault diagnostic will alert the building owner or operator to possible failure of the economizer control function (or lack of economizer control function in cases where it was not programmed).

The schedule established on the TN platform will determine when this fault analysis will run. When the outdoor-air temperatures are not favorable for economizing, this test cannot be conducted. Therefore, the agent will induce an artificial condition by changing the outdoor-air temperature value that the controller sees. For example, if the outdoor-air temperature is 80$^{o}$F and the return-air temperature is 75$^{o}$F, the agent will set the outdoor-air temperature to 70$^{o}$F to induce a condition that is favorable for economizing. If the outdoor-air damper opens fully during this induced state, then there is no fault. On the other hand, if the outdoor-air damper does not open fully, a fault is issued.

### AFDD4: Detect if the RTU is Economizing When it Should Not

The fifth diagnostic check determines if the RTU economizer is introducing outside air beyond the minimum ventilation value when outdoor conditions are not favorable for economizing. This diagnostic check assumes that the sensors are reliable and that the damper is able to modulate (AFDD1 and AFDD2 are fault-free). Even though economizing has potential to reduce cooling energy consumption, economizing when not needed has the potential to increase heating and/or cooling energy consumption. The diagnostic will use the outdoor-air damper command from the controller to determine if it is appropriate during various heating and cooling events, as well as when there is no call for heating or cooling.

This diagnostic will look at the RTU heating and cooling commands and the outdoor-air damper's response to varying conditions. During occupied periods, there are at least three conditions that should be evaluated for this fault condition:

1. When there is no call for cooling or heating, the damper command should be at the minimum position.
2. When there is a call for heating, the damper command should be at the minimum position.
3. When there is a call for cooling, and the outside-air temperature is greater than the return-air temperature, the damper command should be at the minimum damper position.

During unoccupied periods when the controller is trying to maintain minimum or maximum space temperatures, the damper should be closed, unless the outside-air temperature is less than the return-air temperature. The same is also true during morning warm up periods and may also be true during morning cool down periods. This fault diagnostic will alert the building owner or operator to possible failure with the economizer control function.

The schedule established on the TN platform will determine when this fault analysis will be run. As there are so many possible configurations for when the damper should not be open or not be open beyond the minimum position, this diagnostic may need to run most of the time (at least during occupied periods). If natural conditions are not favorable for economizing, the outdoor-air temperatures can be temporarily changed to verify the test. However, some of the tests (items 1 and 2 above) will have to be conducted when they naturally occur.

### AFDD5: Detect if the RTU is Using Excess Outdoor Air

The sixth diagnostic check determines if the RTU is introducing excess outside air beyond the minimum ventilation value when it should not be. This diagnostic check assumes that the sensors are reliable and that the damper is able to modulate (AFFD1 and AFDD2 are fault-free). Excess outdoor air, when not needed, has the potential to increase heating and/or cooling energy consumption.

This diagnostic will calculate the outside air fraction (OAF), which is determined by the following equation:

$$\frac{\textbf{return-air temperature} - \textbf{mixed-air temperature}}{\textbf{return-air temperature} - \textbf{outside-air temperature}}$$

The accuracy of this equation is less reliable when the outside-air temperature and the return-air temperatures are within 4 to 5$^{o}$F. Therefore, the diagnostic will only run when this is not the case.

The calculated OAF is compared to an OAF threshold (adjustable) to determine if excess outdoor air is being introduced into the space. If the calculated outdoor air percent (OAF × 100) is **more than 25% to 50%** (user-adjustable) greater than the OAF threshold, a fault is issued.

The schedule established on the TN platform will determine when this fault analysis will be run. Like AFDD3 and AFDD4 if the conditions are not favorable for this test, the outdoor-air temperatures can be temporarily changed to validate the test. However, some of the tests have to be conducted when the conditions naturally occur.

### AFDD6: Detect if the RTU is Bringing in Insufficient Outdoor Air

The seventh and final diagnostic check determines if the RTU is introducing insufficient outdoor air below the minimum ventilation requirement. This diagnostic check assumes that the sensors are reliable and that the damper is able to modulate (AFDD1 and AFDD2 are fault-free).

Insufficient outdoor air has the potential to contribute to possible "sick building" syndrome effects, including increased levels of $CO_2$ gases and could also lead to potentially negative building pressurization problems, which can contribute to infiltration of unwanted dust, moisture, pollens, cold air or hot air (from other parts of the building). All of these unwanted infiltration issues can impact occupant health and in some cases the safety of the building (cold air infiltrating can freeze nearby pipes, if not adequately insulated). Moisture can contribute to the growth of molds, which is also unwanted. The intent is to ensure that ventilation air from outside is brought into the building via the RTUs outdoor-air dampers, which are designed with filtration systems, conditioning systems and moisture capture systems. If the dampers are verified to be working properly, this fault analysis will determine if there is an insufficient amount of outdoor air being introduced to the RTU's supply-air stream.

This diagnostic will calculate the outdoor-air fraction (OAF), similarly to AFDD5.
The accuracy of this equation is less reliable when the outside-air temperature and the return-air temperatures are within 4 to 5$^{o}$F. Therefore, the diagnostic will only run when this is not the case.

The calculated OAF is compared to a minimum OAF threshold to determine if insufficient ventilation air is being introduced into the space. If the calculated outdoor air percent is **more than 10% to 15%** (user-adjustable) less than the minimum OAF threshold, a fault is issued.

The schedule established on the TN platform will determine when this fault analysis will be run. Like AFDD3 and AFDD4, if the conditions are not favorable for this test, the outdoor-air temperatures can be temporarily changed to validate the test. However, some of the tests have to be conducted when the conditions naturally occur.

## Automated Demand Response (DR) Agent

Many utilities around the country have or are considering implementing dynamic electrical pricing programs that use time-of-use (TOU) electrical rates. TOU electrical rates vary based on the demand for electricity. Critical peak pricing (CPP), also referred to as critical peak days or event days, is an electrical rate where utilities charge an increased price above normal pricing for peak hours on the CPP day. CPP times coincide with peak demand on the utility; these events are generally called between 5 to 15 times per year and occur when the electrical demand is high and the supply is low. Customers on a flat standard rate who enroll in a peak time rebate program receive rebates for using less electricity when a utility calls for a peak time event. Most CPP events occur during the summer season on very hot days.

The initial implementation of the DR agent addresses CPP events where the RTU would normally be cooling. This implementation can be extended to handle CPP events for heating during the winter season as well. This implementation of the DR agent is specific to the CPP, but it can easily be modified to work with other incentive signals (real-time pricing, day head, etc.). The remainder of this section will offer a summary of the DR agent. More detailed information, including implementation details, flowcharts, inputs required for the algorithms and the outputs from the algorithms are provided in Appendix.

The main goal of the building owner/operator is to minimize the electricity consumption during peak periods on a CPP day. To accomplish that goal, the DR agent performs three distinct functions:

**Step 1 – Pre-Cooling:** Prior to the CPP event period, the cooling and heating (to ensure the RTU is not driven into a heating mode) set points are reset lower to allow for pre-cooling. This step allows the RTU to cool the building below its normal cooling set point while the electrical rates are still low (compared to CPP events). The cooling set point is typically lowered between 3 and 5°F below the normal. Rather than change the set point to a value that is 3 to 5°F below the normal all at once, the set point gradually lowered over a period of time.

**Step 2 – Event:** During the CPP event, the cooling set point is raised to a value that is 4 to 5°F above the normal, the damper is commanded to a position that is slightly below the normal minimum (half the of the normal minimum), the fan speed is slightly reduced (by 10% to 20% of the normal speed, if the unit has a variable frequency drive (VFD)), and the second stage cooling differential (time delay between stage one and stage two cooling) is increased (by few degrees, if the unit has multiple stages). The modifications to the normal set points during the CPP event for the fan speed, minimum damper position, cooling set point, and second stage cooling differential are user adjustable. These steps will reduce the electrical consumption during the CPP event. The pre-cooling actions taken in step one will allow the temperature to slowly float up to the CPP cooling temperature set point and reduce occupant discomfort during the attempt to shed load.

**Step 3 – Post-Event**. The DR agent will begin to return the RTU to normal operations by changing the cooling and heating set points to their normal values. Again, rather than changing the set point in one step, the set point is changed gradually over a period of time to avoid the “rebound” effect (A spike in energy consumption after the CPP event when RTU operations are returning to normal).

## VOLTTRON Lite Platform Services

The AFDD and the DR agents utilize several services provided by the VOLTTRON Lite software on the TN platform. Some of these services are summarized in this section and also be found on the project wiki[1].

### Communication with the RTU Controller

The AFDD and the DR agent make use of the publish/subscribe mechanism built on the ZeroMQ[2] Python library to access data for the RTU in which the AFDD and DR events are performed. The VOLTTRON Lite platform uses a Modbus[3] driver to obtain RTU data such as temperature sensor readings, status readings, and various set points for the RTU controller and "publishes" this information on the message bus for use by the agents. The Modbus driver, in conjunction with the actuator agent (a service agent for the VOLTTRON Lite platform), allows an agent to publish commands for the RTU to the platform message bus. The commands are then be accessed by the Actuator agent and using the Modbus driver, written to the registers on the RTU controller.

### Scheduling of the AFDD Agent and DR Agent

The AFDD agent runs on a daily basis during a scheduled time. The schedule is maintained within the launch file (configuration file) for the actuator agent. This simple daily schedule allows a user to determine the appropriate time to run the AFDD agent and to limit the effect on occupants' comfort. The AFDD agent can even be scheduled to run when the building is normally unoccupied. The AFDD agent subscribes to the message bus topic "schedule announce." The schedule announce message published by the actuator agent informs the other agents that they can currently acquire a device lock and how long they can hold the device lock. The lock is essential to control the RTU operations; without the lock, the agent will not be able to command the damper or change the set points, etc.

The DR agent responds to the OpenADR (Open Automated Demand Response) signal published to the message bus by the OpenADR agent. The OpenADR agent receives signals from the utilities and publishes the CPP event information from this signal to the VOLTTRON Lite message bus. This message contains CPP event data including a date and time for the start of a CPP event. Because the run time for the agent is not known in advance of the OpendADR signal being published, the agent is given 24 hour per day lock access to the RTU for which it is configured. The DR agent is configured with a schedule indicating the normal occupancy for each day of the week. The DR sequence will not be initiated on unoccupied days. During a CPP event, if a building goes into an unoccupied mode during the CPP period or during restoration of normal RTU controls, the DR sequence will be terminated and the RTU will go into the normal unoccupied mode of operation.

[1] https://svn.pnl.gov/RTUNetwork/wiki/

[2] http://zeromq.org/

[3] Modbus Protocol is a messaging structure developed by Modicon in 1979. It is used to establish master-slave/client-server communication between intelligent devices. It is a de facto standard, truly open and the most widely used network protocol in the industrial manufacturing environment. http://www.modbus.org

## Logging Service (sMAP Logging)

Results from the seven fault detection diagnostics performed by the AFDD agent are recorded to the sMAP[4] historian. The CPP event start time and end time for the DR agent are also recorded to the sMAP historian. The sMAP historian is a time series database. The logging agent facilitates the pushing of the AFDD results and the CPP event information to sMAP. To push data to the sMAP historian, an agent simply publishes a message on the VOLTTRON Lite message bus to the logging topic.

## AFDD Agent and DR Agent: Occupant Override

Due to the potential for occupant discomfort caused by the AFDD, best efforts should be made to perform these diagnostics at times when occupants will be least affected. To safeguard occupant comfort, an occupant override was implemented for the AFDD agent. During the fault detection and diagnostic sequence, occupants may push an override button on the thermostat within the space served by the RTU to end the fault detection and diagnostic sequence. When the override is initiated, the AFDD agent will return the controller to normal operations and will not attempt to perform the AFDD sequence until the following day.

The DR sequence of operations could potentially cause occupant discomfort. To safe guard occupant comfort, an occupant override was implemented for the DR agent. During the DR sequence, occupants may push an override button on the thermostat within the space served by the RTU to end the DR sequence. When this override is initiated, the DR agent will return the controller to normal operations and will not attempt to initiate the DR sequence again during that day.

## DR Agent Updating and Cancelling CPP Events

The DR agent subscribes to the “openadr” topic on the VOLTTRON Lite message bus. This message contains CPP information that the DR agent reacts to. When an OpenADR signal indicates that the time associated with a CPP event has been modified, the DR agent will reschedule the corresponding actions for the CPP event. When the OpenADR signal indicates that a CPP event has been cancelled, the DR agent will cancel any scheduled actions pertaining to the demand response event. If the DR agent is in the process of executing the cancelled event, it will return the RTU to its normal operations and cancel any further scheduled events corresponding to the cancelled CPP event.

## AFDD Agent and DR Agent Configuration

The AFDD and the DR agent require a configuration file for each RTU; this file contains information on the RTU such as the campus name, building name, and RTU name and should be the same names that were used when configuring the Modbus driver. These identifiers give the agent the necessary information to subscribe to the RTU data and publish RTU commands. The AFDD agent configuration also contains thresholds used when performing the diagnostics. Modifying these thresholds will affect the sensitivity of the diagnostic. The DR agent configuration file includes CPP parameters such as temperature set point values, damper command minimum set point values, fan speed reduction values, and other configurable parameters. Appendix includes a sample configuration file for the AFDD and DR agents.

[4] http://www.cs.berkeley.edu/~stevedh/smap2/index.html

## Appendix

## AFDD0: Mixed-air Temperature and discharge-air temperature are Not Consistent When the mechanical Cooling/Heating are Off

### Fault Description

Economizer systems typically use mixed-air temperature measurements for feedback control of the outdoor- and return-air dampers. In addition, diagnostic methods for both economizer systems and air-conditioning equipment require accurate measurements of the MAT. However, packaged equipment for small/medium commercial building applications typically have small chambers for mixing outdoor and return air, and can have very non-uniform temperature and velocity distributions at the inlet to the direct expansion (DX) coil. As a result, there can be significant bias errors associated with employing single-point. Furthermore, the mixing process can change significantly as the position of the dampers change with economizer operations. The purpose of this proactive diagnostic test is not to identify which sensor(s) is "faulty," but to establish that there is a lack of confidence in one or both sensors and their accuracy.

The compressor will be turned off to ensure the consistency of DAT and MAT readings. The MAT may increase between 2°F and 4°F after passing the supply fan chamber because of the heat from the supply fan motor. The afdd0_threshold can be adjusted to compensate for this during the diagnostic.

### Input Parameters

The following parameters should be available from the local RTU controller:

Analog Input (AI)

- Mixed-air temperature (MAT)
- Discharge-air temperature (DAT)

Digital Input (DI)

- Supply fan status (FanStat) for RTU

Digital Output (DO)

- Supply fan command (FanCmd) for the RTU if the FanStat is not available

### Prerequisite

The following conditions must be met before the fault detection process can be initiated.

- Supply fan status = “ON.” The proactive AFDD process will not be enabled if the supply fan status is still “OFF.” If the supply fan status is not available, the supply fan command will be used in the diagnostic.

## Configuration

The AFDD process and data processing configurations are defined in this section.

### Fault Detection and Diagnostics Process

AFDD tests generally rely on analytical or physical redundancies to isolate faults during diagnosis. Most RTU systems in commercial buildings lack physical redundancy because HVAC systems in the commercial buildings are considered non-critical. Additionally, there is ususally no outdoor-air damper feedback signal to the RTU controller. An AFDD test can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems. Packaged RTU equipment for small/medium commercial applications typically have small chambers for mixing outdoor and return air and can have very non-uniform temperature and velocity distributions at the inlet to the coil. This proactive AFDD test can be initiated by the VOLTTRON Lite schedule when all prerequistes are met. This schedule is configured in the Actuator agent (a VOLTTRON Lite platform agent) .

Steps in the AFDD test:

- Step 1: AFDD agent will disable the heating and cooling (compressor(s)) for the RTU.
- Step 2: The AFDD agent will send the damper open override command to the Catalyst controller. The AFDD agent will command the OAD to a fully open position and force it to remain in that position irrespective of the Catalyst control signal. After the damper is fully open and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the DAT and the MAT. If the MAT sensor is not present this test cannot be done. Compute the absolute difference between the mixed-air temperatures and discharge-air temperatures (DIFF1) averaged over 5 minutes (adjustable by the user).
- Step 3: If the difference between DAT and MAT is greater than afdd0_threshold, the AFDD agent can report the fault to the user and record the time of this fault. If no fault occurs, the agent will move on to next step.
- Step 4: Command the OAD to a fully closed position. After the OAD fully closes and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the DAT and the MAT. Compute the absolute difference between the MAT and DAT (DIFF2) averaged over 5 minutes (adjustable by the user).
- Step 5: If the difference between the DAT and MAT is greater than affd0_threshold, the AFDD agent can report the fault to the user and record the time of this fault.
- Step 6. If performing the the entire AFDD sequence (AFDD0 through AFDD6) continue to AFDD1. Otherwise, send the release commands to the local controller so the dampers return to their “normal” control configuration. The heating and cooling commands will also need to be released so they return to their normal configuration.

### Threshold of this Configuration

AFDD0 threshold = 5°F (adjustable by building operator).

## Discussion

This section discusses possible causes, re-tuning opportunities, saving estimation methods, etc.

### Possible Causes

The possible causes of the DAT and MAT sensor inconsistencies can be mechanical failure or a control failure:

- Sensor failure or communication failure.
- MAT sensor is out of calibration or improperly located.
- The return air and outdoor air are not well-mixed in the mixing chamber.
- The MAT sensor uses a point measurement instead of a temperature averaging sensor
- Temperature stratification: Outside air may stay at the bottom of the duct without good mixing.

### Possible Corrective Actions

- Use an averaging temperature sensor instead of the point measurement for mixed-air temperature.
- Possible ways to improve the mixing:
    - Rotate the damper sections so that the damper blades direct the air streams into each other as they close. This creates turbulence and helps to promote the mixing process.
    - Add baffles to divert the air stream several times before it reaches the coils. This also creates turbulence, which promotes mixing. If the baffles are arranged so that the velocity through them is low (800-1,000 fpm), then significant benefits can be realized without significant additional pressure drop.

## Implementation Details

Figure A - 1 shows the fault detection flow chart for the fault "MAT and DAT are not consistent when mechanical cooling/heating is off."

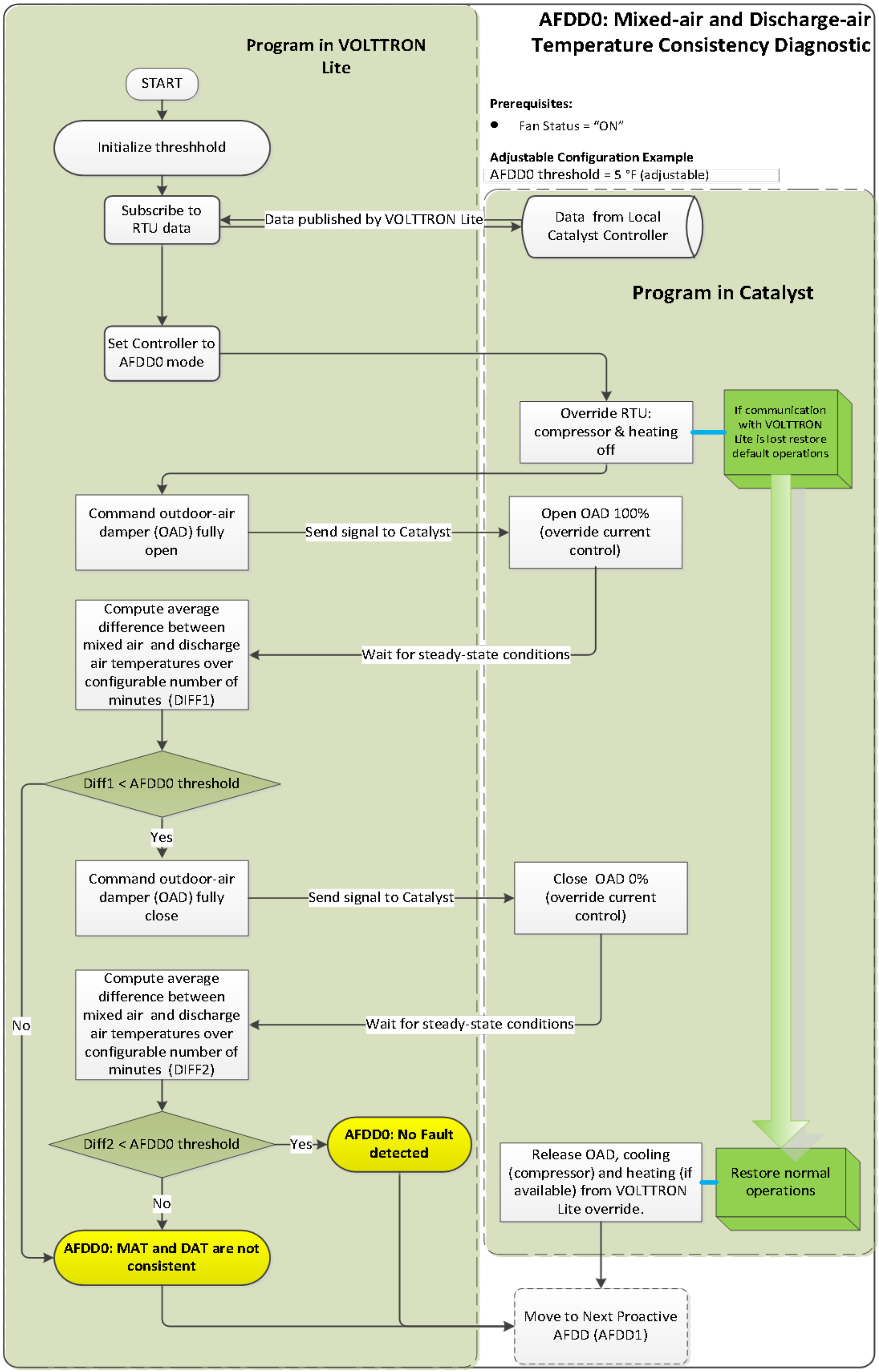


*Figure A - 1: Fault Detection Flow Chart: MAT and DAT are Not Consistent*

## AFDD1: No Outdoor-air damper modulation

### Fault description

The purpose of this proactive diagnostic is to identify faulty OAD systems on an RTU. When the OAD (economizer damper) is not modulating, there is the potential for energy waste or insufficient ventilation to the space(s) served by the RTU. For example, if the damper is stuck in a fully closed position, the RTU will fail to provide the necessary ventilation, and opportunities for free cooling when outdoor conditions are favorable for economizing will be missed, causing energy to be wasted.

A broken or stuck actuator or linkage that affects damper positioning can cause an economizer to fail. In addition, a temperature sensor or damper control system may fail and cause improper amounts of outdoor-air (OA) intake. Damper faults can increase energy consumption at the RTU in two ways; 1) too much OA is admitted on a cold day, this unnecessarily increases the heating load and 2) too much OA intake on a hot or humid day unnecessarily increases the energy expended to cool or dehumidify the air. In both cases, improper damper positioning can waste significant amounts of energy and increase system pressure drop across the filter. On a hot day, additional load may prevent the mechanical cooling system from maintaining desired space temperature and/or humidity, causing occupant discomfort. Furthermore, an OAD that fails and is stuck closed may reduce the outdoor-air ventilation rate to levels less than those required by ANSI/ASHRAE Standard 62, *Ventilation for Acceptable Indoor Air Quality*, potentially causing indoor air quality (IAQ) problems and a related liability risk.

### Approach

The OAD will be commanded fully open and fully closed in sequence through a proactive diagnostic approach. Sufficient time will be allowed between opening and closing the damper to ensure conditions at the RTU have reached steady state. By comparing the temperatures, conclusions can be drawn as to the state of the OAD.

### Input Parameters

The following parameters should be available from the local RTU controller:

Analog Input (AI)

- Mixed-air temperature (MAT)
- Outdoor-air temperature (OAT)
- Return-air temperature (RAT)
- Discharge-air temperature (DAT) if MAT is not available

Digital Input (DI)

- Supply fan status (FanStat) for RTU

Digital Output (DO)

- Supply fan command (FanCmd) for RTU if the FanStat is not available

If the MAT sensor for the RTU is not available, the DAT sensor can be used and the cooling/heating systems for the RTU should be turned off temporarily during the testing.

## Prerequisite

The following conditions must be met before the fault diagnostic process can be initiated.

- Supply fan status = "ON." The proactive AFDD process will not be enabled if the supply fan status is still "OFF." If supply fan status is not available, supply fan command will be used in the testing.

- The OAT is not too close to the RAT. For example, the proactive fault diagnostics process will not be initiated if the absolute value of (RAT-OAT) < AFDD1 temperature threshold (4 °F by default and user adjustable).

The modbus driver will publish Catalyst controller data points to the VOLTTRON Lite message bus at 1-minute intervals. The AFDD agent will subscribe to the needed data points for use in fault diagnostics. If the MAT sensor is not available, the discharge-air temperature sensor can be used for the diagnostic. The heating and cooling (compressor) will be disabled during the diagnostic.

- Performing a limit check on temperature sensors can detect a hard failure and should be performed prior to the damper modulation diagnostic. Ensure that the current OAT is not outside the expected range for the sensor. If the OAT is above OAT high-limit or below the OAT low-limit, then the fault diagnostic should not proceed. Check that the RAT is not outside the expected range for the sensor. If the RAT is above RAT high-limit or below the RAT low-limit, the fault diagnostic should not proceed. Check that the MAT is not outside the expected range for the sensor. If the MAT is above MAT high-limit or below the MAT low-limit, the fault diagnostic should not proceed.

- All of the temperature high-limit and temperature low-limit settings for OAT, MAT, and RAT are user configurable.

- Please refer to Figure A - 2 and Figure A - 3 for implementation of temperature limit checks.

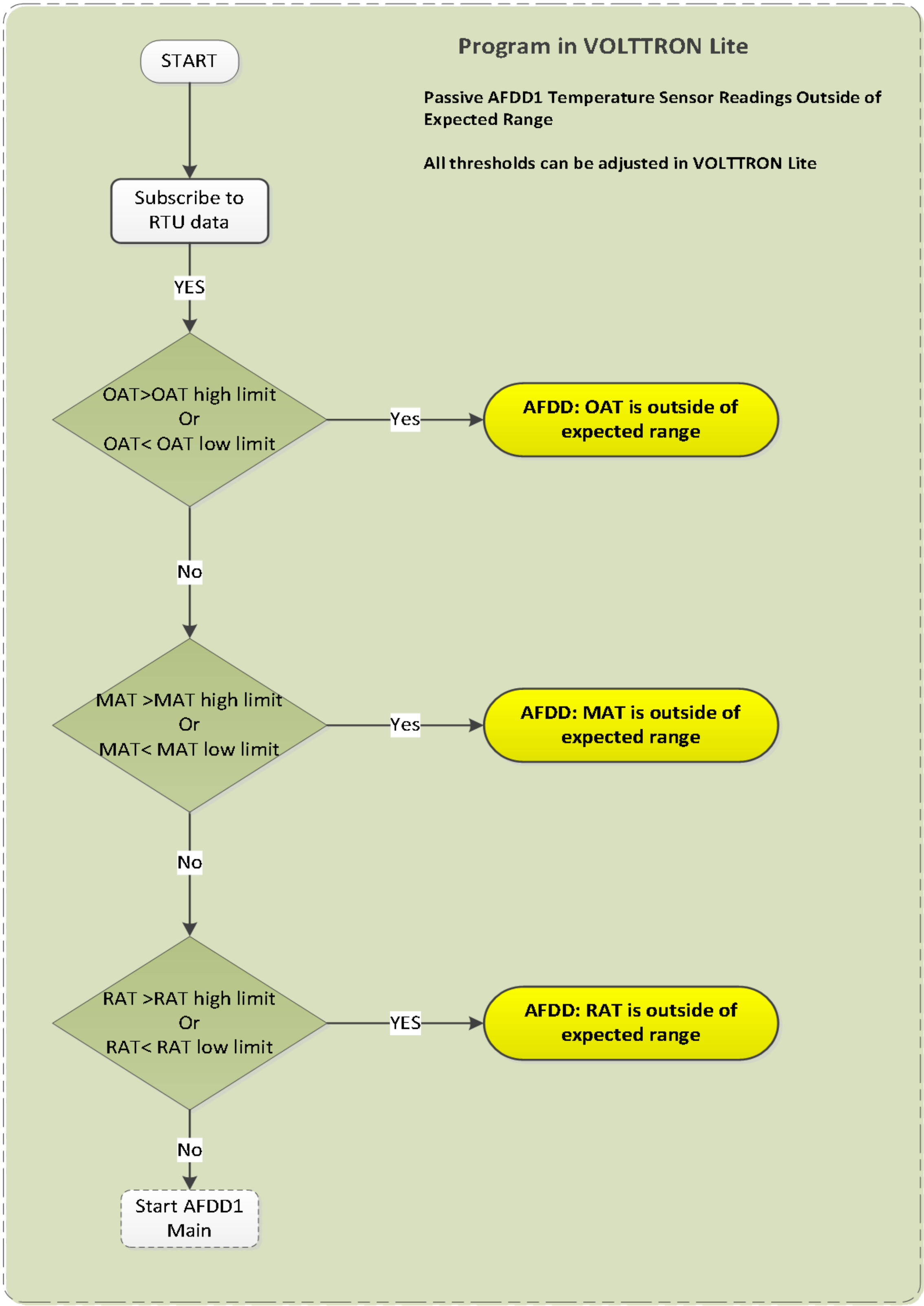


*Figure A - 2: Flow Chart for Temperature Sensor Measurements Outside of Expected Range in Proactive AFDD1*

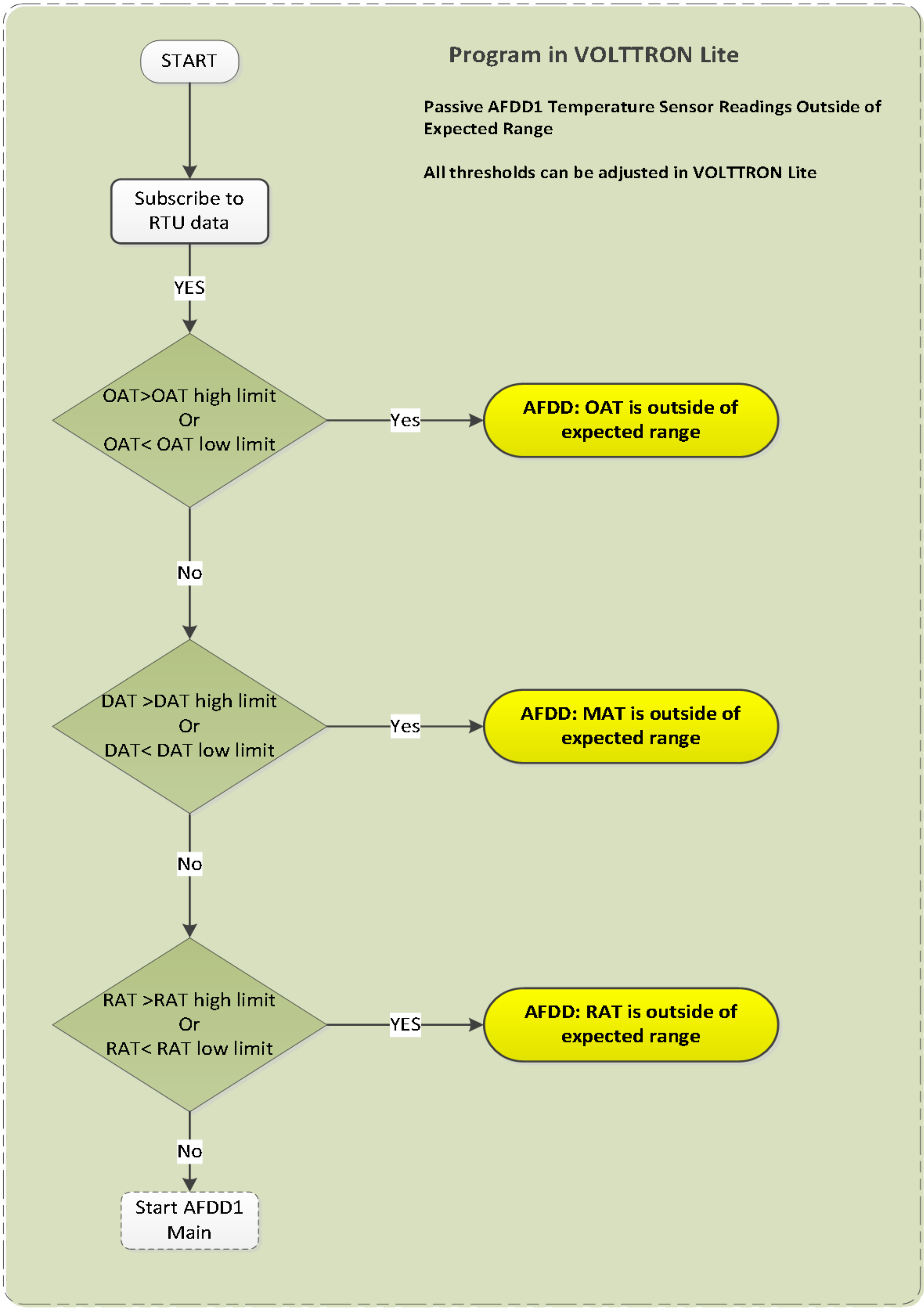


*Figure A - 3: Flowchart for Temperature Sensor Measurements Outside of Expected Range in Proactive AFDD1 (when mixed-air temperature is not available)*

## Configuration

AFDD process and data processing configurations are defined in this section.

### Fault Detection & Diagnostics Process

AFDD tests generally rely on analytical or physical redundancies to isolate faults during diagnosis. Most RTU systems in commercial buildings lack physical redundancy because HVAC systems in the commercial buildings are considered non-critical. Also, there is ususally no OAD feedback signal to the RTU controller. An AFDD test can use proactive diagnostic processes to create analytical redundancies to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems. If the MAT sensor is not available for the RTU, the DAT sensor can be used instead.

The proactive AFDD test can be initiated when all prerequistes are met.

Steps in the AFDD1 test:

- Step 1: AFDD agent will disable the heating and cooling (compressor) for the RTU.
- Step 2: The AFDD agent will send the damper open override command to the Catalyst controller. The AFDD agent will command the OAD to a fully open position and force it to remain in that position irrespective of the Catalyst control signal. After the damper is fully open and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the OAT and the MAT (DAT if MAT is not available). Compute absolute difference between MAT and OAT (DIFF1) averaged over 5 minutes (the number of minutes the difference is averaged over is adjustable by the user).
- Step 2: Command the OAD to a fully closed position. After the OAD fully closes and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the RAT and the MAT (DAT if MAT is not available). Compute absolute difference between MAT and RAT (DIFF2) averaged over 5 minutes (the number of minutes the difference is averaged over is adjustable by the user).
- Step 3: Compute the average of DIFF1 and DIFF2 (DIFF1+DIFF2)/2. If this value is greater than AFDD1 damper threshold, the AFDD agent can report the fault to the building operator and record the time the fault.
- Step 4: If no fault is detected for AFDD0 and if performing the the entire AFDD sequence (AFDD0 through AFDD6) continue to AFDD2. Otherwise, send the release command(s) to the local controller so the dampers return to their normal control configuration. The heating and cooling commands are also released so they return to their normal configuration.

### Threshold of this Configuration

AFDD1 damper threshold = 3°F (adjustable by the user).

## Discussion

This section discusses possible causes and corrective measures.

### Possible Causes

The causes of no damper modulation can be a mechanical failure or a control failure:

- Broken linkage between damper actuator and damper.
- Damper or damper actuator mechanical (and/or electrical) failure (including damper seals, damper power or blockage/binding).
- Electrical connection (control wiring) fault between the local controller and the damper actuator (no signal or wrong signal).
- Actuator not rotating correct direction when signal is applied or not sequenced correctly with other actuator(s) when multiple actuators exist (first actuator has rotated 50% of travel before other actuator(s) start moving).

### Possible Corrective Actions

- Fix the damper and actuator connection.
- Make sure the control wiring and data points are mapped correctly.
- Make sure the actuator sequencing and calibration set up are correct.

## Implementation Details

Figure A - 4 shows the fault detection flow chart for the fault “No outdoor-air damper modulation.”

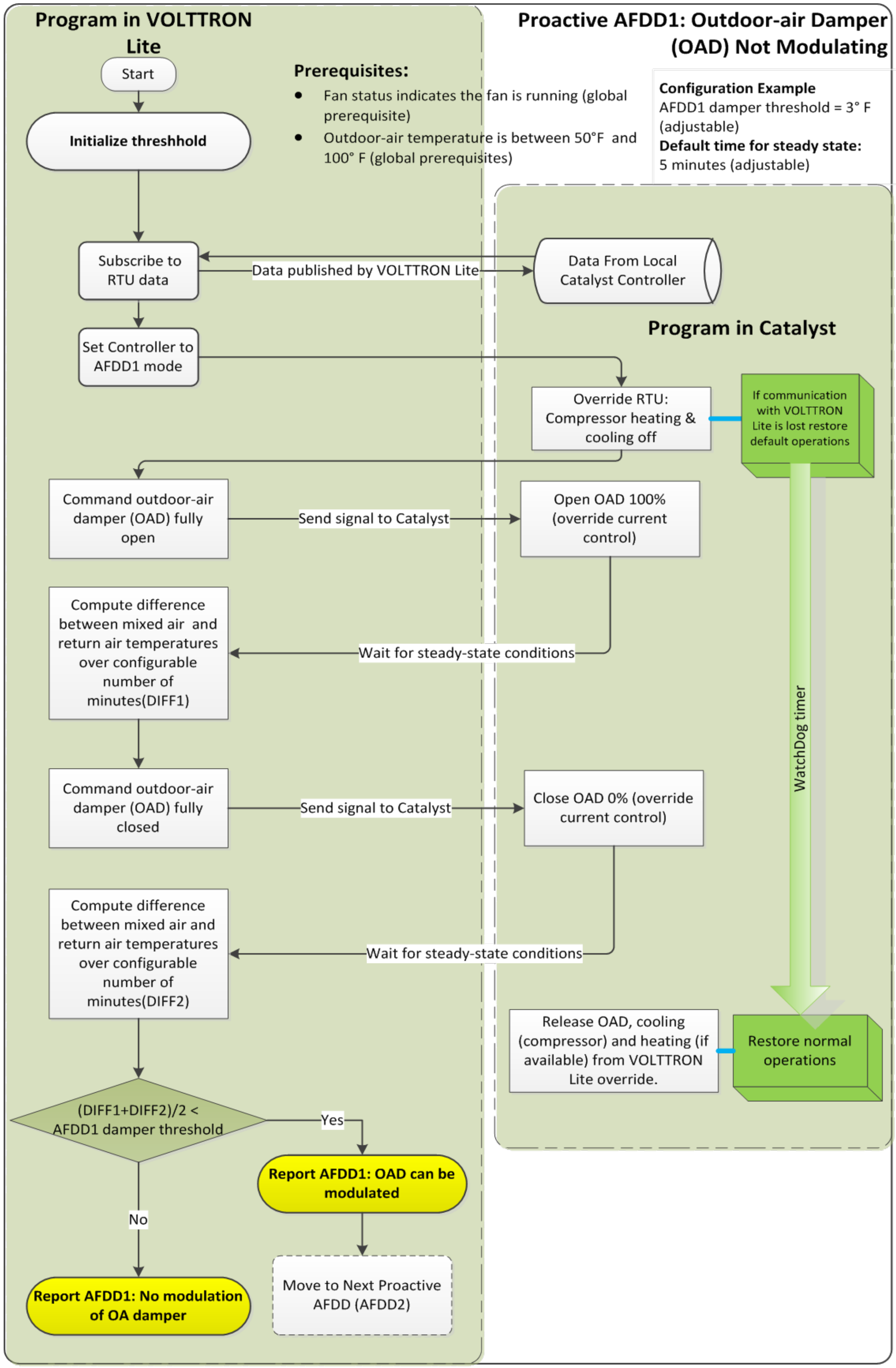


*Figure A - 4: Flowchart to Detect Outdoor-air Damper not Modulating*

## AFDD2: Air-side Temperature Sensors (Outdoor-air, Mixed-air and Return-air) Failure/Fault

### Fault Description

The purpose of this proactive diagnostic measure is to identify temperature sensor faults (OAT, RAT, and MAT sensors).

Damage, disconnected wiring, or mis-calibration of air-temperature sensors can cause an RTU to operate in inefficient modes, such as failing to actuate an economizer when outside air can provide free cooling, or remaining in a high-capacity mode in an attempt to maintain the DAT when a more energy-efficient stage could provide adequate cooling. Accurate and reliable sensors are essential to automate the building re-tuning process because automated methods depend on sensor measurements to verify proper operation or identify improper operations. In reality, however, sensor measurements are corrupted by inappropriate sensor location, random noise, and degradation over time. To overcome these shortcomings, sensor data must be validated to assess the integrity of the information.

Although the effects of faulty sensors on energy consumption (Kao and Pierce 1983)[5], monitoring and control optimization (Usoro et al. 1985)[6], and FDD applications (Katipamula, Pratt, and Braun 2000)[7] are well known in the HVAC industry, the quality of sensors in RTU systems is not comparable to that of sensors in critical applications such as aeronautics, nuclear power, and chemical processing. A primary concern of building owners and operators is cost. Therefore, fewer sensors (usually the minimum required) and inexpensive sensors are usually used. In addition, the sensors might be installed by low-bid or insufficiently-trained technicians.

The aerospace, nuclear, and process industries have been concerned about the accuracy and reliability of sensors for many years because of the critical role of sensors in system control, monitoring, and supervision. These processes require high reliability and operational safety, so they tend to have reliable and redundant sensors. If an application has redundant sensors, an automated diagnostic process can easily detect and isolate a faulty sensor and still continue to detect and diagnose other faults with the system. However, if there is no physical redundancy, the automated process must rely on other methods to detect and isolate faults (and to verify proper operation). Because it is not common to have redundant sensors in HVAC applications, methods that do not rely on physical redundancy to isolate faults must be used.

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[5] Kao, J.Y. and Pierce, E.T. 1983: Sensor errors: their effects on building energy consumption. *ASHRAE Journal*, December 42–45.

[6] Usoro, P.B., Schick, L.C. and Negahdaripour, S. 1985: An innovation-based methodology for HVAC system fault detection. *Journal of Dynamic Systems, Measurement, and Control. Transactions of the ASME* 107, 284–85.

[7] Katipamula, S., R.G. Pratt, and J. Braun. 2000. "Building Systems Diagnostics and Predictive Maintenance." CRC Handbook of Heating Ventilation, and Air Conditioning. Ed. Jan F. Kreider CRC Press, New York.

In general, sensor faults fall into two broad categories: 1) complete failure (hardware faults) and 2) partial failure (software faults). Sensors with hard faults are relatively easy to detect and diagnose, while soft faults are difficult. The most common soft faults are sensor bias and gradual drift. Unlike hard faults, soft faults can go undetected and adversely affect the health of occupants (through inadequate ventilation and increased energy consumption).

Most FDD methods rely on two basic approaches to detect and diagnose faulty sensors: 1) physical redundancy and 2) analytical redundancy (PECI and Battelle 2003)[8]. All procedures developed as part of this research effort use analytical redundancy to isolate faulty sensors.

### Input Parameters

The following parameters should be available from the local RTU controller:

Analog Output (AO)

- Outdoor-air damper command (OAD)

Analog Input (AI)

- Outdoor-air temperature (OAT)
- Return-air temperature (RAT)
- Mixed- air temperature (MAT)

If the MAT is not available for the RTU, discharge-air temperature (DAT) can be used in the testing.

Digital Input (DI)

- Supply fan status (FanStat) for RTU

Digital Output (DO)

- Supply fan command (FanCmd) for RTU if the FanStat is not available

### Prerequisite

The following conditions must be met before the fault pattern recognition process can be initiated.

- Supply fan status = “ON.” If the supply fan status for the RTU is not available, the FanCmd can be used in the analysis.
- The OAT is at acceptable weather condition (for example 50 °F < OAT < 90 °F). If the OAT is within the acceptable weather condition, the proactive fault diagnostics process will be

[8] PNNL & PECI. 2003. Methods for Automated and Continuous Commissioning of Building Systems. *Prepared for The Air-Conditioning and Refrigeration Technology Institute (US).*

initiated. The user can adjust the acceptable temperature limits. The MAT and RAT readings should also lie within some acceptable range, where the high and low limit of this range is configurable for both MAT and RAT.

- There is no fault for AFDD1. If there is no OAD modulation, the faulty temperature sensors cannot be isolated.

## Configuration

AFDD process and data processing configurations are defined in this section.

### Fault Detection & Diagnostics Process

A number of temperature sensors faults, especially hard faults, can be detected by performing simple limit checks, so the first step is to verify the range of the measured temperature sensors data. For some temperature sensors, tight limits can be specified so the temperature sensors deviations can be easily detected. However, for some other sensors, such as outdoor-air temperature sensor, there is a large range of valid values. In such cases, the high and the low limits must be seasonally adjusted, reset using a condition (day of year, for example), or sufficiently wide so that adjustment is not necessary (although this decreases the value of the limits). These limit checks are performed as a prerequisite to the AFDD process and documented in AFDD1.

Before the proactive diagnostic process is initiated, the presence of a temperature sensor fault must be established.

Steps in the AFDD2 test:

- Step 1: Determine if a temperature sensor fault exists. If MAT < OAT and MAT < RAT or MAT > OAT and MAT > RAT, then a temperature sensor fault exists, and continue with the diagnostic to isolate the faulty temperature sensor. If there is not a temperature sensor fault, then report no temperature sensor fault to the user and move to the next AFDD diagnostic (AFDD3).

- Step 2: The AFDD agent will disable the heating and cooling (compressor(s)) for the RTU.

- Step 3: The AFDD agent will send the damper open override command to the Catalyst controller. The AFDD agent will command the OAD to a fully open position and force it to remain in that position irrespective of the Catalyst control signal. After the damper is fully open and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the OAT and the MAT (DAT if MAT is not available). Compute the absolute difference between the MAT and OAT (DIFF1) averaged over 5 minutes (adjustable by the user).

- Step 4: If DIFF1 < AFDD2 OAT/MAT threshold, then report that there is a RAT sensor fault to the user.

- Step 5: If the RAT sensor is not faulty then the AFDD agent will command the OAD to a fully closed position. After the OAD fully closes and steady-state conditions are reached (minimum 5 minutes delay time, which can be adjusted by the user), monitor and record the RAT and the MAT (DAT if MAT is not available). Compute the absolute difference between the MAT and RAT (DIFF2) averaged over 5 minutes (adjustable by the user).

- Step 6: If DIFF2 < AFDD2 RAT/MAT threshold, report that there is a OAT sensor fault to the user. If the both the OAT sensor and the RAT sensor are not found to be faulty then there is a MAT sensor fault.

- Step 4: If no fault is detected for AFDD2 and if performing the the entire AFDD sequence (AFDD0 through AFDD6) continue to AFDD3. Otherwise, send the release command(s) to the local controller so the dampers return to their normal control configuration. The heating and cooling commands are also released so they return to their normal configuration.

### Threshold of this Configuration

AFDD2 OAT/MAT threshold = 4F (adjustable by the user).

In an RTU, the positioning of the OAD at specific positions provides the analytical redundancy, which provides sufficient additional information to identify the fault.

As shown in Figure A - 5, the first step in the proactive diagnostic process is to open the OAD completely and wait for the conditions to reach steady state.

While keeping the OAD fully open, the OAT and MAT are sampled over a few minutes and compared. If the average value of the absolute difference between the MAT and OAT are approximately equal, this indicates that the OAT and MAT sensors are consistent with one another and the RAT sensor is faulty.

If the OAT and the MAT are not approximately equal, command the outdoor-air damper to a closed position and wait until steady-state conditions are achieved. When the outdoor-air damper is closed, the average MAT should nearly equal the average RAT during the sampling period. If the average value of the absolute difference between the MAT and RAT are approximately equal, this indicates that the RAT and MAT sensors are consistent with one another and the OAT sensor is faulty.

If the OAT sensor and RAT sensor are not found to be faulty, then the MAT sensor is faulty (because earlier the RAT sensor was not found to be faulty).

The mixed-air chamber is small for RTUs in general. Temperature stratification in the mixing chamber due to insufficient mixing of outdoor and return air is one potential source of error in the measurement of the MAT. The MAT measured at a single point may not accurately represent the true average MAT and could lead to misleading diagnoses. Therefore, the MAT should always be measured across the duct and averaged using an averaging sensor.

## Implementation Details

Figure A - 5 shows the fault detection flow chart for the fault "Air-side Temperature (outdoor air, mixed-air and return-air) Fault.

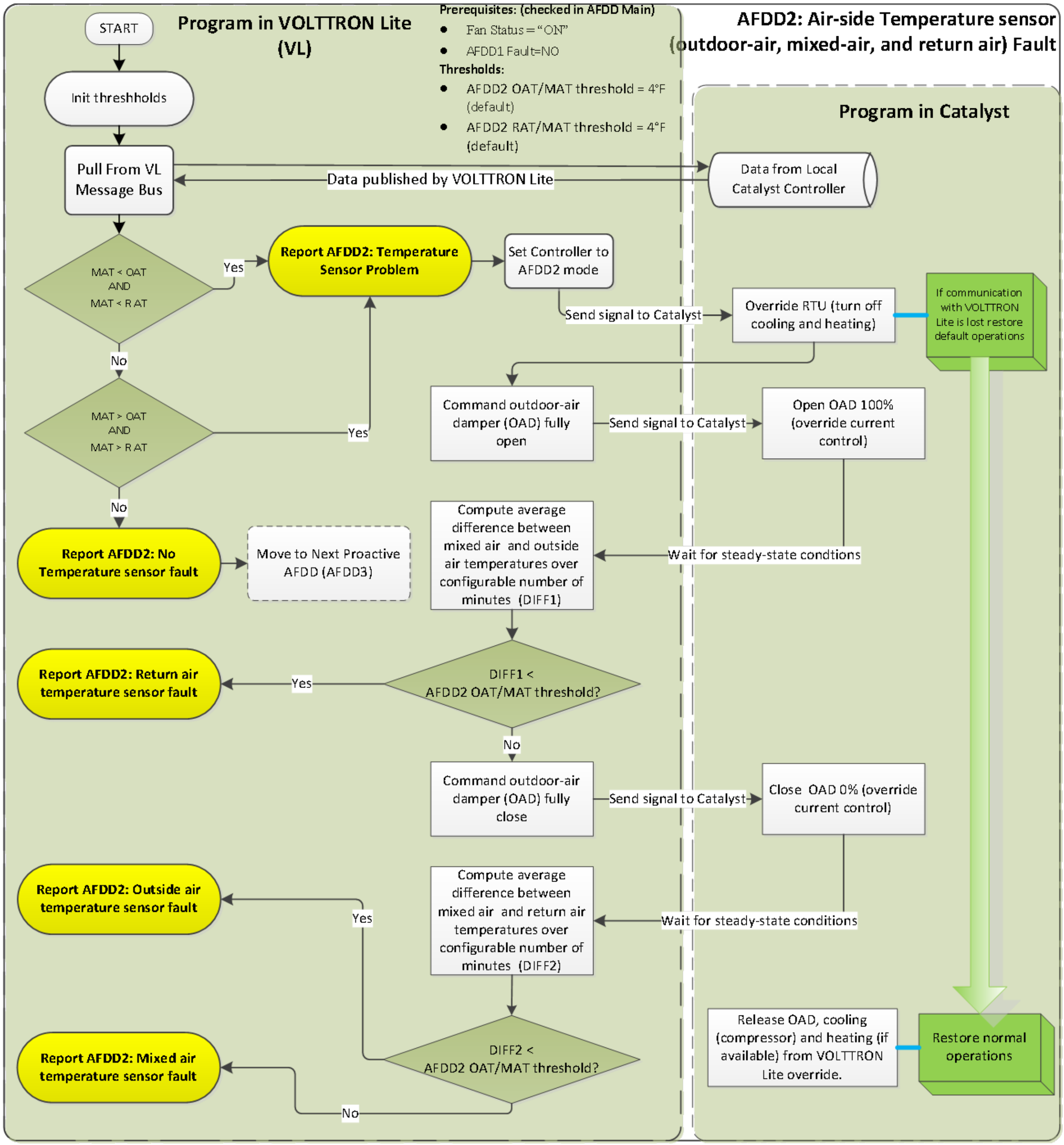


*Figure A - 5: Air-side Temperature Sensor (outdoor-air, mixed-air and return-air) Fault*

## Discussion

A similar process could be employ on air-handling unit (AHU) systems to detect faulty temperature sensors. The remainder of this section discusses possible causes and corrective measures.

### Possible Causes

The possible causes of the temperature sensors failure/fault can be a mechanical failure or a control failure:

- Sensor is physically broken or damaged.
- Connection fault between the local controller and the temperature sensors (no signal or wrong signal).
- Sensor is not connected to local controller.
- The temperature sensor is out of calibration.

### Possible Corrective Actions

- Replace the sensor if the sensor is broken or damaged.
- Fix the sensor and RTU controller connection.
- Make sure the control wiring and sensor points are mapped are correctly.
- Make sure sensors are properly calibrated.

## AFDD3: Not Economizing When RTU Should

### Fault Description

The purpose of this proactive diagnostic measure is to identify the fault of not economizing or fully utilizing the economizer when outdoor conditions are favorable for economizing. When the economizer damper does not operate as intended, the unit fails to provide free cooling, thus causing an energy penalty during periods when free cooling is available.

The failure of the RTU to economize when it should can be caused by improper control parameter settings, improper building pressurization or failure of the actual economizer actuator and/or economizer damper components (blades, seals, linkages, etc). Because economizers can fail in many ways, it may seem like an overwhelming task to design them to operate successfully. Yet most problems can be avoided by specifying economizers with higher-quality components and by commissioning (and periodically re-tuning) them so malfunctions can be readily identified and resolved.

When economizers fail to operate properly, their poor performance may go unnoticed for a long time. Few symptoms of failure are perceptible to building occupants because if the economizer is not working, the compressors usually just work harder. Even the most seasoned building engineer has probably never received a tenant complaint about the economizer, at least not directly. Only in extreme cases does a malfunctioning economizer result in unacceptable space temperatures or poor indoor air quality. The proactive AFDD process can help to minimize such problems.

The outdoor-air temperature can be overridden to test the economizer when the outdoor-air temperature is not favorable for economizing.

### Input Parameters

The following parameters should be available from the local RTU controller:

Analog Input (AI)

- Mixed-air temperature (MAT)
- Discharge-air temperature (DAT can be used if MAT is not available and if mechanical cooling is disabled)
- Outdoor-air temperature (OAT)
- Return-air temperature (RAT)
- Outdoor-air damper signal (OAD)

Analog Output (AO)

- Outdoor-air damper command (OADCmd)

Digital Input (DI)

- Supply fan status (FanStat) for RTU

Digital Output (DO)

- Supply fan command (FanCmd) for RTU if the FanStat is not available

## Prerequisite

The following conditions must be met before the fault pattern recognition process can be initiated.

- Fan Status = "ON." The proactive AFDD process will not be enabled if the fan status is still "OFF." If the fan status is not available, the fan command can be used.

- No fault is identified for proactive AFDD1 "No Outdoor-air Damper Mdulation."

- No fault is identified for proactive AFDD2 "Air Temperature Sensor Failure/Fault."

- The economizer high limit (EcoHigh) should be pre-determined. When employing a high limit economizer control logic optimizing economizer operations comes down to choosing the optimal high limit option for any given climate zone. Table A - 1 (Table 6.5.1.1.3B of ASHRAE 90.1-2007) provides a list of allowed and prohibited high limits. Table 6.5.1.1.3B also provides us with the control settings to employ, by climate zone, for the various high limit options. We assume the dry-bulb temperature sensors have been installed in all RTUs. The fixed dry-bulb temperature high limit can be used in our proactive AFDD for the RTUs.

- The Catalyst controller enables economizing whenever there is a call for cooling and the OAT is less than 70 °F. When the OAT is greater than 70 °F and there is a call for cooling, the Catalyst uses differential dry-bulb economizer logic. This control logic has been accounted for in the AFDD process.

*Table A- 1: High Limit of Shutoff Control Settings for Air Economizers (ASHRAE 90.1-2007[9])*

| Device Type | Climate | Required High Limit (Economizer Off When): | |
|---|---|---|---|
| | | Equation | Description |
| Fixed dry bulb | 1b, 2b, 3b, 3c, 4b, 4c, 5b, 5c, 6b, 7, 8 | $T_{OA} > 75°F$ | Outdoor air temperature exceeds 75°F |
| | 5a, 6a, 7a | $T_{OA} > 70°F$ | Outdoor air temperature exceeds 70°F |
| | All other zones | $T_{OA} > 65°F$ | Outdoor air temperature exceeds 65°F |
| Differential dry bulb | 1b, 2b, 3b, 3c, 4b, 4c, 5a, 5b, 5c, 6a, 6b, 7, 8 | $T_{OA} > T_{RA}$ | Outdoor air temperature exceeds return air temperature |
| Fixed enthalpy | All | $h_{OA} > 28$ Btu/lb[a] | Outdoor air enthalpy exceeds 28 Btu/lb of dry air[a] |
| Electronic enthalpy | All | $(T_{OA}, RH_{OA}) > A$ | Outdoor air temperature/RH exceeds the "A" setpoint curve[b] |
| Differential enthalpy | All | $h_{OA} > h_{RA}$ | Outdoor air enthalpy exceeds return air enthalpy |
| Dew-point and dry-bulb temperatures | All | $DP_{oa} > 55°F$ or $T_{oa} > 75°F$ | Outdoor air dry bulb exceeds 75°F or outside dew point exceeds 55°F (65 gr/lb) |

[a] At altitudes substantially different than sea level, the Fixed Enthalpy limit shall be set to the enthalpy value at 75°F and 50% relative humidity. As an example, at approximately 6000 ft elevation the fixed enthalpy limit is approximately 30.7 Btu/lb.
[b] Setpoint "A" corresponds to a curve on the psychrometric chart that goes through a point at approximately 75°F and 40% relative humidity and is nearly parallel to dry-bulb lines at low humidity levels and nearly parallel to enthalpy lines at high humidity levels.

[9] ASHRAE. 2007. ASHRAE Standard 90.1-2007: Energy Standard for Buildings Except Low-Rise Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. Atlanta, GA

## Configuration

Proactive AFDD process and data processing configurations are defined in this section.

### Fault Detection & Diagnostics Process

Automated fault detection and diagnosis (AFDD) processes generally rely on analytical or physical redundancies to isolate faults during diagnosis. Most RTU systems in commercial buildings lack physical redundancy because HVAC systems in the commercial buildings are considered non-critical. There is no outdoor-air damper feedback signal to the RTU controller either. An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems.

Steps in the AFDD3 test:

**a.** Check if there was a fault detected for modulation of the OAD (AFDD1) or temperature sensor (AFDD2).

If no faults for the OAD or temperature sensors are identified, the AFDD process for the economizer can be initiated.

**b.** When there is a call for cooling from space served by RTU and outside conditions are favorable for economizing:

- Check the OAD signal. If 100 –OAD signal < AFDD3 damper threshold, then the damper is open and the RTU is economizing. Proceed to the next step in the diagnostic process. Otherwise, report that the RTU is not economizing when the unit should be economizing.
- If the RTU is economizing properly, the OAF will be calculated. If 1.0 – OAF >AFDD3 OAF threshold, then the RTU is not bringing in sufficient outdoor air and is not fully realizing the energy savings potential of economizing. Report to the building operator that insufficient outdoor air is being brought in by the RTU when economizing.

**c.** When there is a call for cooling from the space served by the RTU and the conditions are not favorable for economizng:

- VOLTTRON Lite will send an override command to RTU local controller and set the outdoor-air temperature bias to simulate conditions favorable for economizing (the RTU should open the damper fully).
- Check the OAD signal after 5 minutes. If 100–OAD signal < AFDD3 damper threshold. Proceed to the next step in the diagnostic process. Otherwise, report that the RTU is not economizing when the unit should be economizing.

- If the unit is economizing properly, the OAF will be calculated. If 1.0 – OAF > AFDD3 OAF threshold, then the RTU is not bringing in sufficient outdoor air and is wasting energy. Report to the building operator that insufficient outdoor air is being brought in by the RTU when economizing.

d. If there is not a call for cooling from the space served by the RTU, retry the diagnostic later.

If a fault is detected the energy impact can be determined by using first principle energy conservation relationships, an estimated flow rate for the supply-air provided by the supply-air fan, and RTUs EER rating.

### Threshold of this Configuration

AFDD3 OAF threshold = 0.25

AFDD3 damper threshold =5

## Implementation Details

Figure A - 6 shows the fault detection flow chart for the fault "Not Economizing when RTU Should".

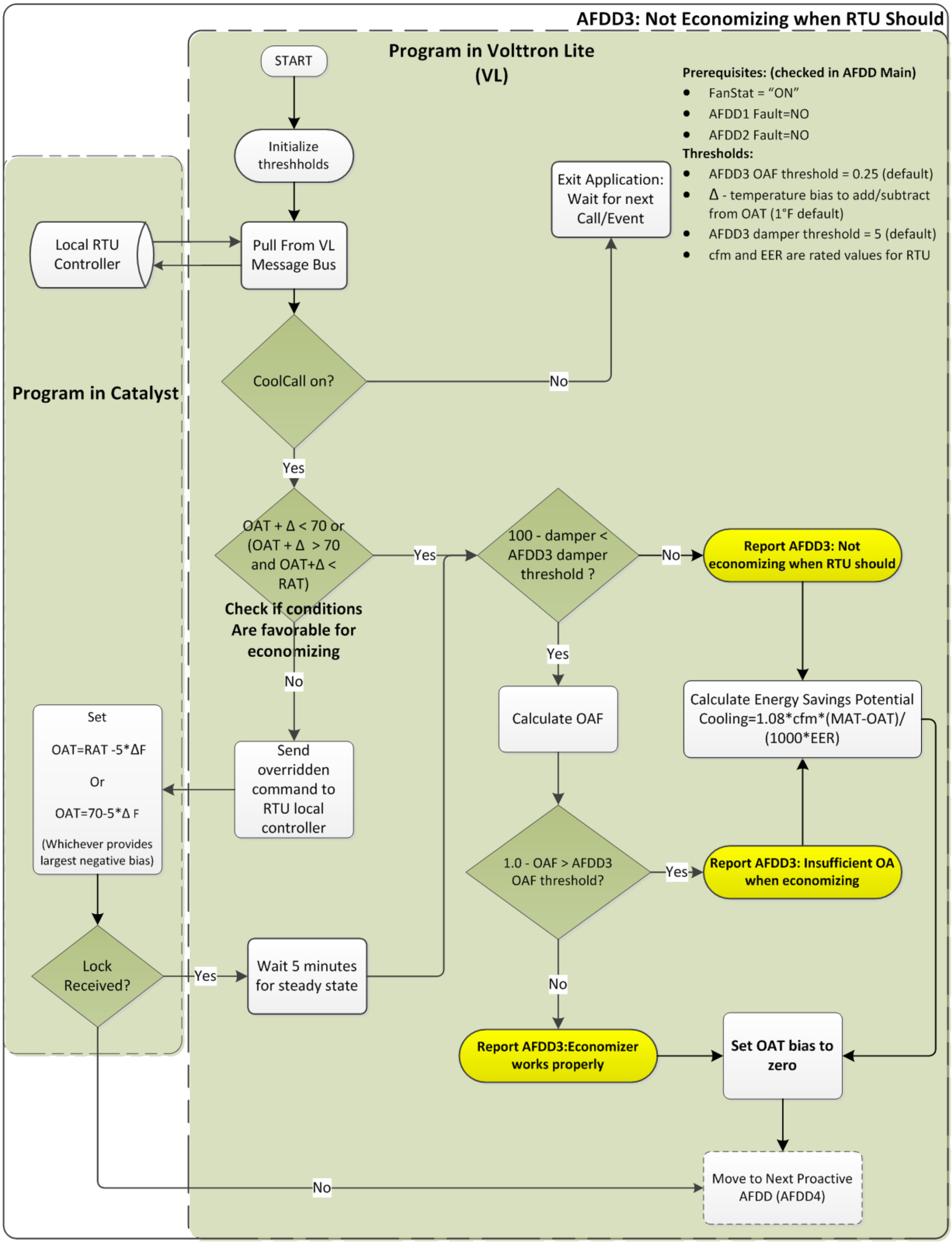


*Figure A - 6: Flowchart for Detecting Economizer Faults (not economizing when it should)*

## Discussion

This section discusses possible causes, re-tuning opportunities, saving estimation methods, etc.

### Lockout by Over-cooled Discharge Air

Economizer systems shall be integrated with the mechanical cooling system and be capable of providing partial cooling even when additional mechanical cooling is required to meet the remainder of the cooling load. However, there are exceptions allowed in ASHRAE 90.1, they are:

- DX system with controls that reduce outdoor air to prevent coils from frosting at the lowest compressor operating condition, and the lowest part-load condition is not more than 25% of the total capacity.
- DX system with capacities less than 65,000 Btu/hr with controls that do not allow integrated operation.
- Systems in climate zones 1, 2, 3a, 4a, 5a, 5b, 6, 7, and 8

When the discharge-air temperature is too low, the economizer might be locked out.

### Possible Causes

The causes of not economizing when the RTU should can be mechanical failure or a control failure:

- *The economizer high limit is too low*. A basic economizer controller with dry-bulb temperature sensor and high limit used to define the temperature below which the outside-air damper can be fully opened. If the dry-bulb temperature high limit is set too low, the economizer will operate less often than it could, leading to higher DX-cooling costs.
- *Improper control of building pressure.* For an economizer to work effectively, a nearly equal amount of air must be exhausted from the building as is taken in. Slightly more supply air is usually taken in so that the building will be somewhat pressurized. If the return or exhaust fan does not keep up with the supply delivery rate, the building will become over-pressurized, and the security door cannot be opened. When the return or exhaust fan exceeds the supply delivery rate, air may be heard to whistle as it breezes through the stairwells, and the front doors may be hard to close.
- Damper or damper actuator mechanical (and/or electrical) failure (including damper seals, damper power or blockage/binding).
- Connection fault between the local controller and the damper actuator (no signal or wrong signal)
- Actuator not rotating in the correct direction when signal is applied or not sequenced

correctly with other actuator(s) when multiple actuators exist (first actuator has rotated 50% of travel before other actuator(s) start moving)

### Possible Corrective Actions

- Input a reasonable economizer high limit based on ASHRAE 90.1 recommendations
- Fix the damper and actuator connection.
- Make sure the control wiring and points mapping are correct.
- Make sure the actuator sequencing and calibration set up are correct

## AFDD4: Economizing When It Should Not

### Fault Description

The purpose of this proactive diagnostic measure is to identify the fault of economizing when the RTU should not (the OAT is not favorable for economizer in the cooling season). When the economizer damper is partially open or fully open, DX-cooling costs will increase during warm weather. Occupant comfort may be compromised if this extra load exceeds the available cooling capacity. Similarly heating costs will increase during cold weather and occupant comfort may be compromised if this extra load exceeds the available heating capacity.

The fault of economizing when the RTU should not can be caused by following: 1) The economizer high limit is too high; 2) The outdoor-air temperature sensor fault/failure. When economizers fail to operate properly, their poor performance may go unnoticed for a long time. Few symptoms of failure are perceptible to building occupants, because if the economizer is working when it should not in warm weather, the compressor will usually just work harder. Some economizers have adjustable set points, while others do not, but it is common that set points are not configured correctly, resulting in missed opportunities for economizer cooling. The opposite problem can occur as well. When a set point is higher than recommended or when an OAD is stuck open, heating and cooling energy will increase significantly.

The outdoor-air temperature can be overridden to test the economizer when the outdoor-air temperature is favorable for economizing.

### Input Parameters

The following parameters should be available from the local RTU controller:

Analog Input (AI)

- Mixed-air temperature (MAT)
- Discharge-air temperature (DAT)
- Outdoor-air temperature (OAT)
- Return-air temperature (RAT)
- Outdoor-air damper signal (OAD)

Analog Output (AO)

- Outdoor-air damper command (OADCmd)

Digital Input (DI)

- Supply fan status (FanStat) for RTU

Digital Output (DO)

- Supply fan command (FanCmd) for RTU if the FanStat is not available

## Prerequisite

The following conditions must be met before the fault pattern recognition process can be initiated.

- Supply fan status = "ON." The proactive AFDD process will not be enabled if the fan status is still "OFF." If the fan status is not available, the fan command can be used.

- No fault is identified for proactive AFDD1 "No Outdoor-air Damper Modulation" (FAULT=NO).

- No fault is identified for proactive AFDD2 "Air Temperature Sensor Failure/Fault" (FAULT=NO).

- Minimum OAD set point (MinOAD) is available in the system.

- The economizer high limit (EcoHigh) should be pre-determined. When employing a high limit economizer control logic optimizing economizer operations comes down to choosing the optimal high limit option for any given climate zone. Table A - 1 (Table 6.5.1.1.3B of ASHRAE 90.1-2007) provides a list of allowed and prohibited high limits. Table 6.5.1.1.3B also provides us with the control settings to employ, by climate zone, for the various high limit options. We assume the dry-bulb temperature sensors have been installed in all RTUs. The fixed dry-bulb temperature high limit can be used in our proactive AFDD for the RTUs.

- The Catalyst controller enables economizing whenever there is a call for cooling and the OAT is less than 70 °F. When the OAT is greater than 70 °F and there is a call for cooling, the Catalyst uses differential dry-bulb economizer logic. This control logic has been accounted for in the AFDD process.

*Table A - 2: High Limit of Shutoff Control Settings for Air Economizers (ASHRAE 90.1-2007[9])*

| Device Type | Climate | Required High Limit (Economizer Off When): | |
|---|---|---|---|
| | | **Equation** | **Description** |
| Fixed dry bulb | 1b, 2b, 3b, 3c, 4b, 4c, 5b, 5c, 6b, 7, 8 | $T_{OA} > 75°F$ | Outdoor air temperature exceeds 75°F |
| | 5a, 6a, 7a | $T_{OA} > 70°F$ | Outdoor air temperature exceeds 70°F |
| | All other zones | $T_{OA} > 65°F$ | Outdoor air temperature exceeds 65°F |
| Differential dry bulb | 1b, 2b, 3b, 3c, 4b, 4c, 5a, 5b, 5c, 6a, 6b, 7, 8 | $T_{OA} > T_{RA}$ | Outdoor air temperature exceeds return air temperature |
| Fixed enthalpy | All | $h_{OA} > 28$ Btu/lb[a] | Outdoor air enthalpy exceeds 28 Btu/lb of dry air[a] |
| Electronic enthalpy | All | $(T_{OA}, RH_{OA}) > A$ | Outdoor air temperature/RH exceeds the "A" setpoint curve[b] |
| Differential enthalpy | All | $h_{OA} > h_{RA}$ | Outdoor air enthalpy exceeds return air enthalpy |
| Dew-point and dry-bulb temperatures | All | $DP_{oa} > 55°F$ or $T_{oa} > 75°F$ | Outdoor air dry bulb exceeds 75°F or outside dew point exceeds 55°F (65 gr/lb) |

[a] At altitudes substantially different than sea level, the Fixed Enthalpy limit shall be set to the enthalpy value at 75°F and 50% relative humidity. As an example, at approximately 6000 ft elevation the fixed enthalpy limit is approximately 30.7 Btu/lb.
[b] Setpoint "A" corresponds to a curve on the psychrometric chart that goes through a point at approximately 75°F and 40% relative humidity and is nearly parallel to dry-bulb lines at low humidity levels and nearly parallel to enthalpy lines at high humidity levels.

## Configuration

Proactive AFDD process and data processing configurations are defined in this section.

### Fault Detection & Diagnostics Process

AFDD processes generally rely on analytical or physical redundancies to isolate faults during diagnosis. Most RTU systems in commercial buildings lack physical redundancy because HVAC systems in the commercial buildings are considered non-critical. There is no OAD feedback signal to the RTU controller either. An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems.

**a.** Check if there were faults detected for modulation of outdoor-air damper or air-temperature sensors.

If no faults for modulation of OAD and temperature sensors were identified, the AFDD process for the economizer can be initiated. Otherwise, fix the outdoor-air damper or the temperature sensors.

**b.** If there is a call for cooling from the space served by the RTU and outdoor conditions are not favorable for economizing (OAT > RAT and OAT > 70).

- If the OAD signal > AFDD4 minimum damper, report the fault to the building operator. Otherwise, no fault is detected. Proceed to the next diagnostic (AFDD5)

**c.** If there is a call for cooling from the space and outdoor conditions are favorable for economizing (OAT < RAT or OAT < 70).

- The AFDD agent will send an override command to RTU local controller and set the OAT bias to simulate conditions not favorable for economizing (the RTU should close the damper to the minimum damper set point).

- Check the OAD signal after 5 minutes. If the OAD signal > AFDD4 minimum damper report, the fault to the user. Otherwise, no fault is detected. Proceed to the next diagnostic (AFDD5).

**d.** If there is a not call for cooling from the space served by the RTU.

- If the OAD signal > AFDD4 minimum damper, report the problem to the user. Otherwise, no fault is detected. Proceed to the next diagnostic (AFDD5).

#### Threshold of this Configuration

AFDD4 minimum damper = 0.25

## Discussion

This section discusses possible causes, re-tuning opportunities, saving estimation methods, etc.

### Possible Causes

The causes of economizing when the RTU should not can be mechanical failure or a control failure:

- *The economizer high limit is too high*. A basic economizer controller with dry-bulb temperature sensor and high limit used to define the temperature below which the outside-air damper can be fully opened. If the dry-bulb temperature high limit is set too high, DX-cooling costs will increase during warm weather because of higher ventilation rates, and comfort may be compromised if this extra load exceeds available cooling capacity.
- *The outdoor-air temperature sensor fault or failure.* Refer to AFDD2 for more details.
- *If the controls include demand control ventilation (DCV) sequences that rely on one or more $CO_2$ sensor(s), and if the sensors have failed or are out of calibration (reading at the high end of the sensor), this can result in the controls commanding the outside dampers to be open more than required.*

### Possible Corrective Actions

- Input a reasonable economizer high limit based on ASHRAE 90.1 recommendations.
- Replace or calibrate the OAT sensor.
- Verify $CO_2$ sensors (if used with DCV sequences) are calibrated

## Implementation Details

Figure A - 7 shows the fault detection flow chart for the fault "Economizing When it Should Not".

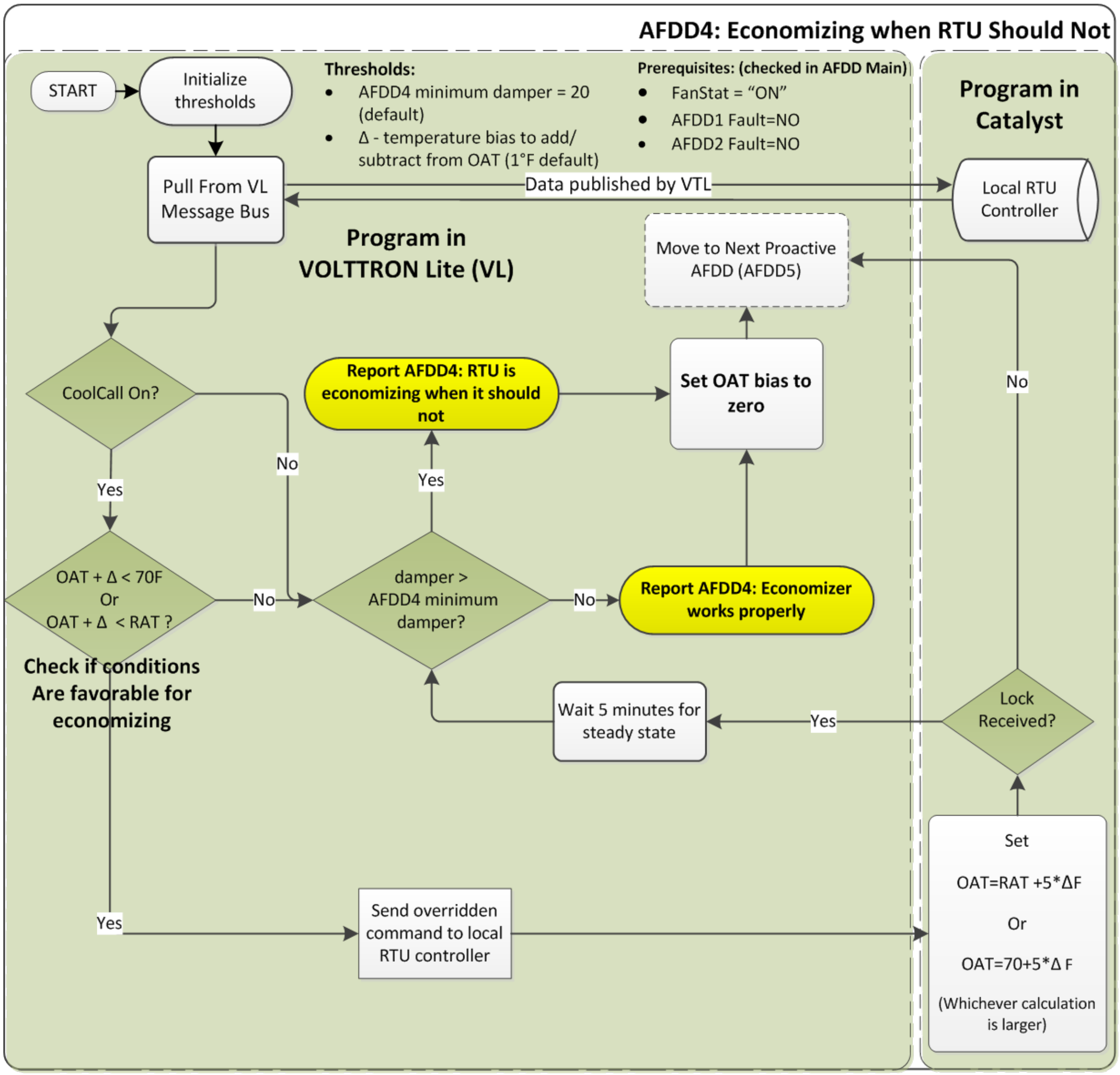


*Figure A - 7: Flowchart for Detecting Economizer Faults (Economizing when RTU Should Not)*

## AFDD5: Excessive outdoor air intake

### Fault Description

The purpose of this proactive diagnostic measure is to identify the fault of excessive outdoor-air intake. When the outdoor-air intake is much more than the required air flow, DX-cooling costs will increase during warm weather because of higher ventilation rates, and comfort may be compromised if this extra load exceeds available cooling capacity. Heating costs will increase during cool weather because of higher ventilation rates, and comfort may be compromised if this extra load exceeds the available heating capacity during periods when free cooling is not desired.

The fault of excessive outdoor air can be caused by following: 1) Minimum OAD position is too high. 2) The OAD cannot be closed to minimum position because of the mechanical failure. When the outdoor-air intake is excessive, the poor performance may go unnoticed for a long time. Few symptoms of failure are perceptible to building occupants because if the outdoor-air intake is excessive, the compressors usually just work harder in the cooling season and the compressors (heat pump application) and/or gas/electric heating systems usually work harder in the heating season. When a minimum OAD set point is higher than recommended or when an OAD is stuck open, heating and cooling energy will increase significantly. If the control sequence includes DCV , the outside-air dampers may be responding to a fault in the $CO_2$ sensor reading (reading excessively high). This can also contribute to excessive outdoor-air intake.

The OAT can be overridden to test the minimum outdoor-air intake when the OAT is favorable for economizing.

### Input Parameters

The following parameters should be available from the local RTU controller:

Analog Input (AI)

- Mixed-air temperature (MAT)
- Outdoor-air temperature (OAT)
- Return-air temperature (RAT)

Analog Output (AO)

- Outdoor-air damper command (OADmpr)

Digital Input (DI)

- Supply fan status (FanStat) for RTU

Digital Output (DO)

- Supply fan command (FanCmd) for RTU if the FanStat is not available

## Prerequisite

The following conditions must be met before the fault pattern recognition process can be initiated.

- Supply fan status = "ON." The proactive AFDD process will not be enabled if the fan status is still "OFF." If the supply fan status is not available, the fan command can be used.
- No fault is identified for proactive AFDD-1 "No outdoor-air damper modulation" (FAULT=No).
- No fault is identified for proactive AFDD-2 "Air temperature sensor failure/fault" (FAULT=No).
- Minimum OA intake ratio (MinOA%) is available in the system (i.e., 20%).
- The economizer high limit (EcoHigh) should be pre-determined.
- The OAT is not too close to the RAT. For example, the proactive fault diagnostics process will not be initiated if the absolute value of (RAT-OAT) < AFDD5 temperature threshold. Default value of AFDD5 temperature threshold is $4\,^{o}$F (adjustable), can be adjusted by the building operator.

## Configuration

Proactive AFDD process and data processing configurations are defined in this section.

### Fault Detection & Diagnostics Process

An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems.

**a.** Check if there were faults detected for modulation of OAD or air-temperature sensors.

If no faults for the OAD and temperature sensors are identified, the AFDD process for the economizer can be initiated. Otherwise, fix the OAD or the temperature sensors.

**b.** If there is a call for cooling from the space served by the RTU and outdoor conditions are not favorable for economizing (OAT > RAT and OAT > $70\,^{o}$F).

- Calculate the OAF using the OAT, RAT, and MAT.
- Compare the OAF with the pre-defined minimum outdoor-air intake ratio (MinOA%).
- If (OAF- MinOA%) > AFDD5 OAF threshold, report the fault of excessive outdoor-air intake to building operator. Otherwise, no fault is detected. Proceed to the next diagnostic (AFDD6).

**c.** If there is a call for cooling from the space and outdoor conditions are favorable for economizing (OAT < RAT or OAT < 70).

- The AFDD agent will send an override command to RTU local controller and set the OAT bias to simulate conditions not favorable for economizing (the RTU should close the damper to the minimum damper set point).
- Check the OAD signal after 5 minutes. Calculate the OAF using the OAT, RAT, and MAT.
- Compare the OAF with the pre-defined minimum outdoor-air intake ratio (MinOA%).
- If (OAF- MinOA%) > AFDD5 OAF threshold, report the fault of excessive outdoor-air intake to building operator. Otherwise, no fault is detected. Proceed to the next diagnostic (AFDD6).

**d.** If there is not a call for cooling from the space,

- Check to make sure the OAD is commanded to the minimum position.
- Calculate the OAF using the OAT, RAT, and MAT.
- Compare the OAF with the pre-defined minimum outdoor-air intake ratio (MinOA%).
- If (OAF- MinOA%) > AFDD5 OAF threshold, report the fault of excessive outdoor-air intake to building operator. Otherwise, no fault is detected. Proceed to the next diagnostic (AFDD6).

If a fault is detected the energy impact can be determined by using first principle energy conservation relationships, an estimated flow rate for the supply-air provided by the supply-air fan, and RTUs EER rating.

#### Threshold of this Configuration

AFDD5 OAF threshold = 25%

MinOA = 5%

## Discussion

This section discusses possible causes, re-tuning opportunities, saving estimation methods, etc.

### Possible Causes

The causes of excessive outdoor-air intake can be mechanical failure or a control failure:

- *The minimum OAD set point is too high.* If the minimum damper position is set too high, DX-cooling costs will increase during warm weather because of higher ventilation rates, and comfort may be compromised if this extra load exceeds available cooling capacity. Heating costs will increase during cool weather because of higher ventilation rates, and comfort may be compromised if this extra load exceeds available heating capacity.

- The OAD cannot be closed to the minimum position
- $CO_2$ DCV sensors are out of calibration or DCV control sequence parameters are not configured properly

### Possible Corrective Actions

- Check the outdoor-air intake requirements based on the existing occupancy. Input a reasonable minimum OAD.
- Fix the OAD if it cannot be closed to the minimum position.

## Implementation Details

Figure A - 8 shows the fault detection flow chart for the fault “Excessive Outdoor-air Intake”.

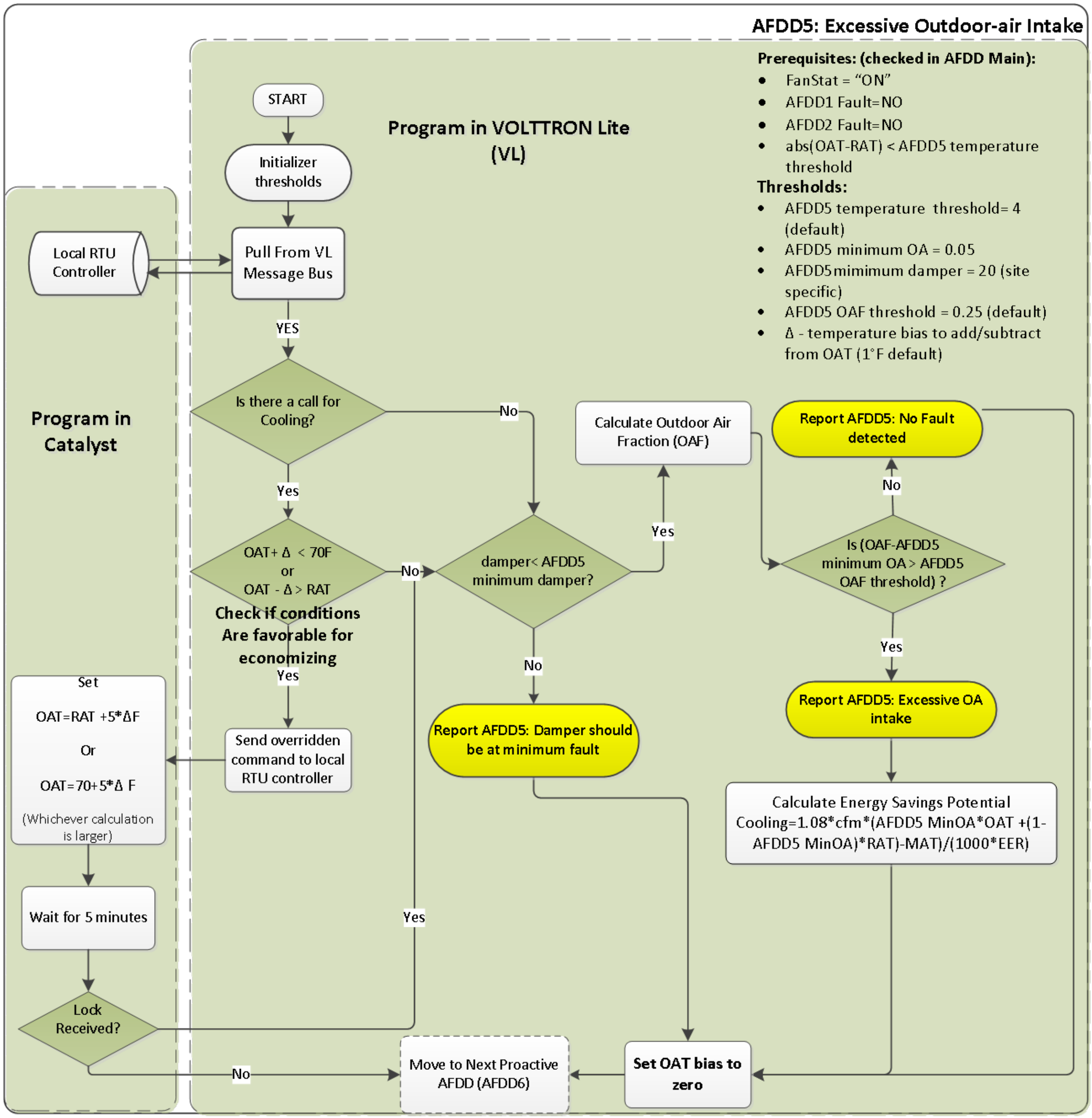


*Figure A - 8: Flowchart for Detecting Excessive Outdoor-Air Intake*

## AFDD6: Insufficient Outdoor-air Intake

### Fault Description

The purpose of this proactive diagnostic measure is to identify the fault of insufficient outdoor-air intake when the outdoor-air temperature is not favorable for economizing. When the outdoor-air intake is insufficient to meet ventilation requirements, it might result in sick building syndrome (SBS) or negative building pressure. Infiltration can have many negative effects on the building, especially when it brings moisture into the building during the cooling season. This moisture can condense, causing damage to the building structure and to the insulation, and promoting growth of mold and mildew (Shakun 1990)[10]. Other negative effects of infiltration include freezing of piping (sprinkler or other) that contains stagnant water in exterior zones, particularly during very cold weather) and introduction of air pollutants into the building.

The fault of insufficient outdoor air can be caused by the following: 1) Minimum outdoor-air damper position is too low (almost closed). 2). The outdoor-air damper cannot be opened because of the mechanical failure. 3) The static pressure in mixed-air chamber is positive because of a plugged intake screens/filters on RTUs or improper return/exhaust fans control (over-powering supply fans).

The OAT can be overridden to a higher value to test the minimum outdoor-air intake when the outdoor-air temperature is favorable for economizing.

### Input Parameters

The following parameters should be available from the local RTU controller:

Analog Input (AI)

- Mixed-air temperature (MAT)
- Outdoor-air temperature (OAT)
- Return-air temperature (RAT)
- Damper signal

Analog Output (AO)

- Outdoor-air damper command (OADmpr)

Digital Input (DI)

- Supply fan status (FanStat) for RTU

[10] Shakun, Wallace. A review of water migration at selected Florida hotel/motel sites. Proceedings of the biennial symposium on improving building practices in hot & humid climates. October 1990. Texas A&M University, College Station, TX.

Digital Output (DO)

- Supply fan command (FanCmd) for RTU if the FanStat is not available

## Prerequisite

The following conditions must be met before the fault pattern recognition process can be initiated.

- Supply fan status = "ON." The proactive AFDD process will not be enabled if the fan status is still "OFF." If the supply fan status is not available, the supply fan command can be used.

- No fault is identified for proactive AFDD-1 "No outdoor-air damper modulation" (FAULT=No).

- No fault is identified for proactive AFDD-2 "Air temperature sensor failure/fault" (FAULT=No).

- Minimum OA intake ratio (MinOA%) is available in the system (i.e., 20%).

- The economizer high limit (EcoHigh) should be pre-determined.

- The outdoor-air temperature is not too close to the return-air temperature. For example, the proactive fault diagnostics process will not be initiated if the absolute value of (RAT-OAT) < AFDD6 temperature threshold 4 $^{o}$F (user adjustable)

## Configuration

Proactive AFDD process and data processing configurations are defined in this section.

### Fault Detection & Diagnostics Process

An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems.

**a.** Check if there is fault for outdoor-air damper modulation (AFDD1) or air-temperature sensor (AFDD2).

**b.** If no faults for OAD and temperature sensors are identified, the AFDD process for economizer can be initiated. Otherwise, fix the outdoor-air damper or the temperature sensors.

**c.** If there is a call for cooling from the space and outdoor conditions are not favorable for economizing (OAT < RAT or OAT < 70 $^{o}$F):

- If the OAD is greater than the minimum OAD set point (afdd6 minimum damper), report the problem to operator. Otherwise, proceed to next step.

- Calculate the OAF using the OAT, RAT, and MAT.

- Compare the OAF with the pre-defined minimum outdoor-air intake ratio (MinOA%).

- If (MinOA% - OAF) > AFDD6 OAF threshold, report the fault of insufficient outdoor-air intake to operator.

**d.** If there is a call for cooling from the space and outdoor conditions are favorable for economizing (OAT < RAT or OAT < 70 $^{o}$F):

- The AFDD agent will send an override command to RTU local controller and set the OAT bias to simulate conditions not favorable for economizing (the RTU should close the damper to the minimum damper set point).
- Check the outdoor-air damper siganl after 5 minutes. If the OAD is greater than the minimum OAD set point (AFDD6 minimum damper), report the problem to operator. Otherwise, proceed to next step.
- Calculate the OAF using the OAT, RAT, and MAT.
- Compare the OAF with the pre-defined minimum outdoor-air intake ratio (MinOA%).
- If (MinOA% - OAF) > AFDD6 OAF threshold, report the fault of insufficient outdoor-air intake to the building operator. Otherwise report no fault detected.

**e.** If there is not a call for cooling from the space served by the RTU:

- If the OAD is greater than the minimum OAD set point (AFDD6 minimum damper) report the problem to operator. Otherwise, proceed to next step.
- Calculate the OAF using the OAT, RAT, and MAT.
- Compare the OAF with the pre-defined minimum outdoor-air intake ratio (MinOA%).
- If (MinOA% - OAF) > AFDD6 OAF threshold, report the fault of insufficient outdoor-air intake to the building operator. Otherwise report no fault detected.

**f.** Release all controller locks (overrides) so the RTU returns to normal operations.

### Threshold of this Configuration

AFDD6 minimum damper= 20% (adjustable)

AFDD6 OAF threshold = 0 (adjustable)

MinOA% =5% (adjustable)

## Discussion

This section discusses possible causes, re-tuning opportunities, saving estimation methods, etc.

### Possible Causes

The causes of “Insufficient outdoor-air intake” can be mechanical/electrical failure or a control failure:

- The minimum outdoor air damper set point is close to 0% open. If the minimum outdoor-air damper is at almost close position.
- The outdoor-air damper cannot be opened because of the mechanical/electrical failure.
- The static pressure in mixed-air chamber is positive.
- The intake screens and/or filters can be plugged
- The return fan or powered exhaust fan can be over coming the supply fan, causing the mixed-air chamber pressure to be the wrong pressure

### Possible Corrective Actions

- Check the outdoor-air intake requirements based on the existing occupancy. Input a reasonable minimum outdoor-air damper position.
- Fix the outdoor-air damper if it cannot be opened.
- Fix screens or filters
- Fix control of powered exhaust fan or return fan, if contributing to problems

## Implementation Details

Figure A - 9 shows the fault detection flow chart for the fault “Insufficient Outdoor-air Intake”.

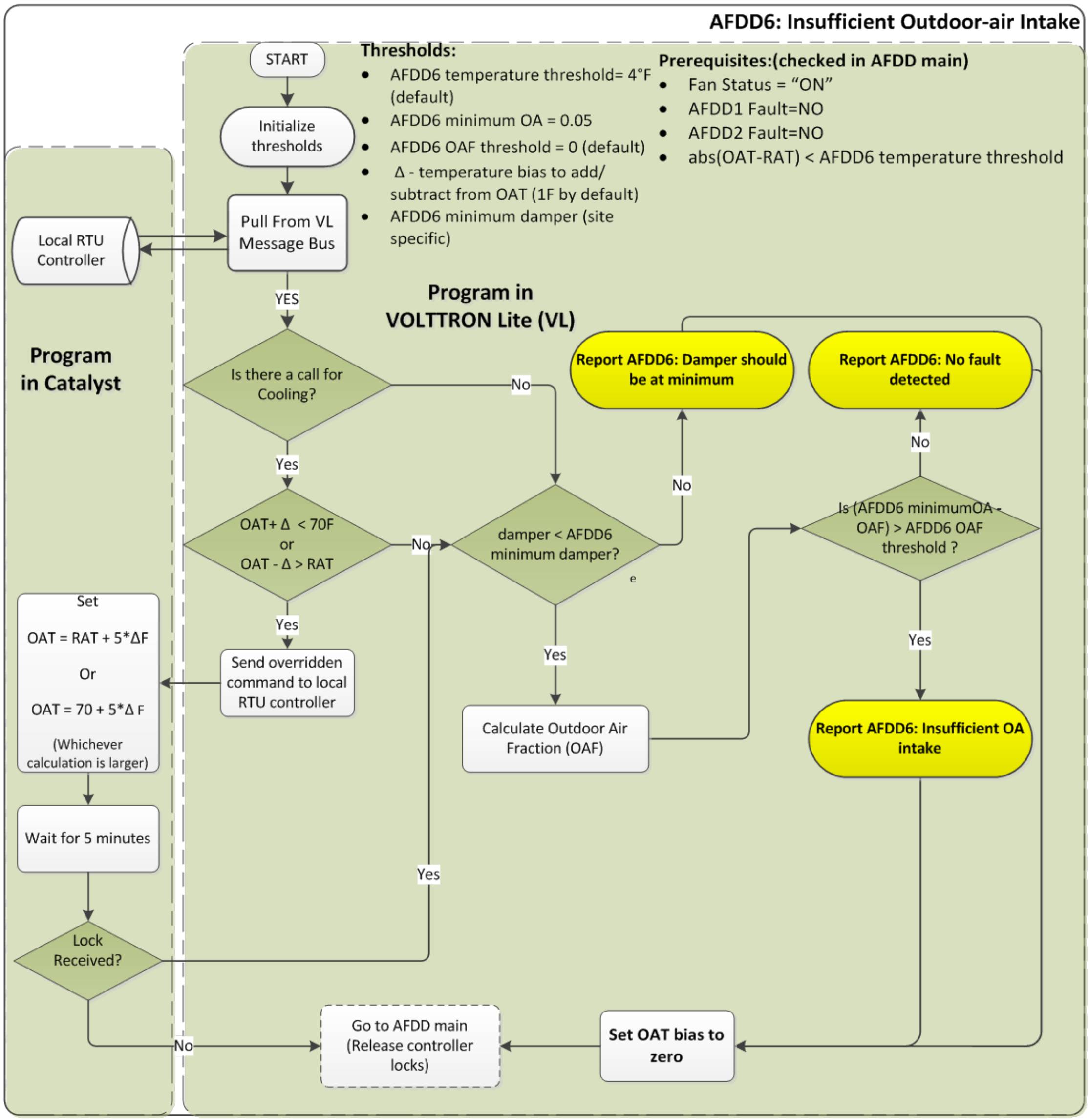


*Figure A - 9: Flowchart for Detecting Ventilation Faults (Insufficient Outdoor-air Intake)*

## Automated Fault Detection and Diagnostic Agent Example Configuration File

{

"agent": {

"exec": "afddagent-0.1-py2.7.egg --config \"%c\" --sub \"%s\" --pub \"%p\""

}

"agentid": "AFDD1",

"campus": "Campus1",

"building": "Building1",

"unit": "RTU1",

"smap_path": "datalogger/log/AFDD Messages/Campus1/Building1/RTU1", **#/datalogger/log/smap path**

**#Controller point names**

"volttron_flag": "VoltronFlag",

"oat_point_name":  "OutsideAirTemperature",

"mat_point_name": "MixedAirAverage", #"DischargeAirTemperature"

"dat_point_name": "DischargeAirTemperature",

"rat_point_name": "ReturnAirTemperature",

"oat_virtual_point_name": "ReturnAirCO2Stpt",

"damper_point_name": "DamperSignal",

"damper_command_name": "DamperCommand",

"cool_call1_point_name": "CoolCall1",

"cool_call2_point_name": "CoolCall2",

"cool_cmd1_point_name": "CoolCommand1",

"cool_cmd2_point_name": "CoolCommand2",

"fan_status_point_name": "FanStatus",

"heat_command1_point_name": "HeatCommand1",

"heat_command2_point_name": "HeatCommand2", "oat_bias": "OutsideAirTemperatureBias",

"fan_command_name": "SupplyFanSpeed",

"mixed_air_sensor_missing": 1, **#set to '0' if MAT sensor is present,  set to '1' if MAT sensor is missing**

"economizertype": 1, **#'1' for catalyst override to standard mode (high limit 55F), '0' is ddb economizer ESMMode (high limit 70F)**

"high_limit": 55.0, **#for ESMMode on controller the high limit is lowest temperature for differential dry bulb economizer control**

#Global thresholds

"min_oa_temperature": 50,

"max_oa_temperature": 100,

"min_ra_temperature": 50,

"max_ra_temperature": 100,

"min_ma_temperature": 50,

"max_ma_temperature": 100,

"minutes_to_average": 5, #5

"seconds_to_steady_state": 360,

"cfm": 5000 , **#supply fan rated cfm**

"EER": 10, **#site specific**

**#AFDD0 DAT and MAT consistency check**

"afdd0_mat_dat_consistency _threshold": 5, **#degrees F**

**#AFDD1 Outdoor-air damper modulation diagnostic**

"afdd1_econ_temp_differential": 4, **#degrees F**

"afdd1_damper_modulation_threshold": 3, **#degree F**

**#AFDD2 Temperature sensor diagnostic**

#"afdd2_tempsensorfault_threshold": 4,

"afdd2_oat_mat_consistency_threshold": 4, **#degrees F**

"afdd2_rat_mat_consistency_threshold": 4, **#degrees F**

**#AFDD3 RTU is not economizing when it should**

"afdd3_oaf_threshold": 0.3,

"afdd3_econ_temp_differential": 1,

"afdd3_oat_rat_temperature_difference_threshold": 2,

"afdd3_open_damper_threshold": 5,

**#AFDD4 RTU is economizing when it should not**

"afdd4_econ_temp_differential": 1,

"afdd4_minimum_damper_command": 20, **#site specific**

**#AFDD5 Excess outdoor-air ventilation diagnostic**

"afdd5_oat_rat_temperature_difference_threshold": 4,

"afdd5_econ_temp_differential": 1, **#degrees F**

"afdd5_oaf_threshold": 0.25,

"afdd5_minimum_damper_command": 20, **#site specific**

"afdd5_minimum_oa": 0.05, **#minimum outdoor air fraction (used in AFDD5 and AFDD6)**

**#AFDD6 Insufficient outdoor-air ventilation**

"afdd6_oat_rat_temperature_difference_threshold": 4,

"afdd6_oaf_threshold": 0,

"afdd6_min_oa": 0.05,

"afdd6_minimum_damper_command": 20, **#site specific**

"afdd6_econ_temp_differential": 1

}

## Automated Demand Response Agent

Many utilities around the country have or are considering implementing dynamic electrical pricing programs that use time-of-use electrical rates. Time-of-use electrical rates vary based on the demand for electricity. Critical peak pricing (CPP), also referred to as critical peak days or event days, is an electrical rate where utilities charge an increased price above normal pricing for peak hours on the CPP day. CPP times coincide with peak demand on the utility, these events are generally called between 5 to 15 times per year and occur when the electrical demand is high and the supply is low. When a CPP event occurs, these customers can reduce their electrical consumption and receive a utility incentive. Most CPP events occur during the summer season on very hot days.

The purpose of the DR agent as implemented in the transactional network will target RTUs and reduce the electrical demand of the RTUs during a CPP event. The main goal of the building owner/operator is to minimize the electricity consumption during the peak periods on a CPP day. DR agent will help accomplish that goal. The initial implementation of the DR agent only addresses CPP events where the packaged rooftop units (RTU) would normally be cooling. This implementation can be extended to handle CPP events for heating, during the winter season. Also, this implementation of the DR agent is specific to the CPP, but it can be easily modified to work with other incentive signals (real-time pricing, day head, etc.). In this section, implementation details including flowcharts, inputs required of the algorithms and the outputs from the algorithms are presented.

## User Configurable Inputs

The user configurable inputs are highlighted in this section followed by an example configuration file.

- Pre-cooling temperature set point (Pre_CSP)
- CPP cooling temperature set point (CPP_CSP)
- Reduction in supply fan speed during the CPP event (for RTUs with variable-frequency-drives)
- Minimum damper command during the CPP event (CPPD)
- Building thermal constant (BTC -°F/hr)
    - Approximate temperature drop of space when RTU is actively cooling.
- Cooling stage differential (difference is actual space temperature and space set point before the second stage cooling is allowed to come on - CSD)
- Daily occupied/unoccupied schedule
    - This is an example of a Monday through Friday occupied schedule and Saturday and Sunday unoccupied schedule, default [1, 1, 1, 1, 1, 0, 0].
- How far in advance pre-cooling is allowed to start (default 5 hours)
- Pre-cool and after event time step size (time step)
- Normal occupied cooling temperature set point (NCTSP)
- Length of time between temperature modifications in pre-cooling and post-event (LT – default 15 minutes)
- Normal first stage cooling fan speed
- Normal second stage cooling fan speed
- Normal minimum damper set point

### Example DR Agent Configuration File

{

"agent": {

"exec": "DRAgent-0.1-py2.7.egg --config \"%c\" --sub \"%s\" --pub \"%p\""

},

**#Agent Parameters**

"agentid": "DR1", **#Agent ID used by actuator agent for control of RTU**

"campus": "Campus1", **#campus name as known by VOLTTRON Lite**

"building": "Building1", **#Building name as known by VOLTTRON**

"unit": "RTU1", **#RTU/Controller name as known by VOLTTRON**

"smap_path": "datalogger/log/testing/twt/catalyst2" , **#/datalogger/log/your path here**

**#Catalyst Controller point names**

"cooling_stpt": "CoolingTemperatureStPt"**, # second value in quotes in name from your controller as specified in you Catalystreg file**

"heating_stpt": "HeatingTemperatureStPt",

"min_damper_stpt": "MinimumDamperPositionStPt",

"cooling_stage_diff": "CoolingStageDifferential",

"cooling_fan_sp1": "CoolSupplyFanSpeed1",

"cooling_fan_sp2": "CoolSupplyFanSpeed2",

"override_command": "VoltronPBStatus",

"occupied_status": "Occupied",

"space_temp": "SpaceTemp",

"volttron_flag": "VoltronFlag",

**#DR cooling Set Points**

"csp_pre": 65.0, **#Pre-cooling zone temperature set point**

"csp_cpp": 80.0, **#CPP event zone temperature set point**

**#Normal set points**

"normal_firststage_fanspeed": 75.0,

"normal_secondstage_fanspeed": 90.0,

"normal_damper_stpt": 5.0,

"normal_coolingstpt": 74.0,

"normal_heatingstpt": 67.0,

**#DR Parameters**

"fan_reduction": 0.1, **#fractional reduction in fan command 0.1 = 10%**

"damper_cpp": 0, **#minimum damper command during CPP event**

"timestep_length": 900, **#number of seconds between csp modifications in Pre and After event (default 900 seconds = 15 min.)**

"max_precool_hours": 5, **#maximum pre-cooling window in hours**

"building_thermal_constant": 4.0, **#Building thermal constant F/hr (site specific estimate to calculate** needed pre-cooling time)

"cooling_stage_differential": 1.0, **#during CPP event (normal is 0.5)**

"Schedule": [1,1,1,1,1,1,1] **#[Mon, Tue, Wed, Thu, Fri, Sat, Sun] 1 is occupied day and 0 is unoccupied day**

}

## Catalyst Controller Points that the DR Agent can Command

The DR agent is allowed to command/change certain points on the RTU controller, these include:

- Cooling temperature set point (CSP)
- Heating temperature set point (HSP)
- Minimum damper position set point (MDSP)
- First stage cooling fan speed (FSCFS)

- Second stage cooling fan speed (SSCFS)
- Cooling stage differential (CSD)

## DR Agent Modes of Operation

When deployed at a site each RTU has a separate instance of the DR agent. This instance of the DR agent is configured to monitor and control a single RTU. The DR agent application has several distinct modes of operation: idle, pre-cooling, CPP event, post-event, and override.

### Idle Mode

During the idle mode of operation, the DR agent receives data from the RTU via the VOLTTRON Lite message bus. The DR agent stores the current space temperature (*CST*) and the occupancy status of the RTU; these values are updated each time new RTU data is published to the VOLTTRON Lite message bus. The DR agent subscribes to the OpenADR topic on the VOLTTRON Lite message bus. An OpenADR message will contain the date/time for the start (*CPPST*) and end (*CPPET*) of a CPP event. When an OpenADR message is published on the VOLTTRON Lite message bus the DR agent schedules its first DR action to start pre-cooling before the CPP event time (start of the CPP event as indicated in the OpenADR message). If the user-configured schedule indicates that the current date is an unoccupied day then the DR agent does not schedule any DR actions and remains in the idle mode. The default is to schedule this initial DR event for five hours prior to the start of the CPP event if the user configured schedule indicates that the current day is an occupied day. The firing of this scheduled event will send the DR agent into the pre-cool mode and the remainder of the DR actions will be scheduled in the beginning of the pre-cool mode.

### Pre-cool Mode

The first action the DR agent takes when entering the pre-cool mode is to request a device lock from the Actuator agent. The Actuator agent is a VOLTTRON Lite platform agent that acts as intermediary between the VOLTTRON Lite platform and the RTU. By acquiring a device lock for the RTU, the DR agent will be the only agent on the VOLTTRON Lite platform that will be allowed to issue commands to the RTU. During the pre-cool mode the duration of pre-cooling window (*PCW*) is determined. The *PCW* is calculated using the current space temperature to determine the time necessary to cool the space to the *Pre_CSP* (Equation 1). If cooling begins too early the space will be maintained at the *Pre_CSP* longer than necessary and will waste energy. Beginning the pre-cooling actions too early can also increase occupant discomfort caused by the space being too cool for a longer period. The pre-cooling start time (*PCST*) is determined as the difference in time between the CPP start time and the pre-cooling window as shown in Equation 2. The DR agent will set the cooling temperature set point to the pre-cooling temperature set point two time step lengths (default 30 minutes) prior to the CPP event. This should ensure that the space reaches the pre-cooling temperature set point before the CPP event starts. The number of steps in the pre-cooling sequence (*NCS*) is determined by taking the pre-cooling window and dividing by the time step length and subtracting one as shown in Equation 3. The temperature reduction to be applied to the cooling temperature set point at each time step is denoted as *dTP* and is determined by dividing the difference between the normal cooling temperature set point and the *Pre_CSP* by the number of cooling steps, shown in Equation 4.

$$PCW = \frac{CST - Pre\_CSP}{BTC} \text{ (evaluated as an integer)} \quad (1)$$

$$PCST = CPPST - PCW \quad (2)$$

$$NCS = \frac{PCW}{TL} - 1 \quad (3)$$

$$dTP = \frac{(NCTSP - PreCSP)}{NCS} \quad (4)$$

The pre-cooling schedule is updated every 15 minutes until the pre-cooling temperature set point modifications start. Because the schedule is dependent on the difference between the current space temperature and the pre-cooling set point, updating the schedule every 15 minutes will more accurately reflect the cooling needs. During the pre-cooling mode, if an updated OpenADR message is received and it is determined the pre-cool event should have already begun then then pre-cool event will begin immediately following the conclusion of scheduling the remainder of the DR actions (CPP event actions and post-event actions). The CPP event and post event will proceed normally. If the OpenADR message indicates that the CPP event should have already begun then the pre-cooling event will be skipped and the CPP event will fire immediately. The post-event will then proceed normally. If the OpenADR message indicates the CPP event is over then the DR agent will release the device lock from the Actuator agent and return to the idle mode.

During this period, before the pre-cooling temperature set point modifications, the CPP event actions and post-event actions are also scheduled. The DR event is scheduled to begin at the start time specified in the OpenADR message and end is scheduled at the end time specified in the OpenADR message. The post event actions are scheduled to start at the end time for the CPP event. Similar to the pre-cool actions, rather than changing the cooling temperature set point in one step, the set point is changed gradually over a period of time to avoid the "rebound" effect caused by the RTUs beyond the first stage cooling because the space temperature is far above the cooling set point. The length of time to restore the cooling temperature set point to the normal set point after the CPP event (*RCL*) is determined by dividing the difference between the CPP cooling temperature set point and the normal cooling temperature set point and dividing by the building thermal constant. The post-event end time is the *RCL* time added to the end time of the CPP event (Equation 6). The number of temperature steps or restore steps (*NRS*) in the post event is determined by dividing the *RCW* by the time step length (*TL*) as shown in Equation 7. The temperature reduction to be applied to the cooling temperature set point at each time in the post event step is denoted as *dTR* and is determined by dividing the difference between the CPP cooling temperature set point and the normal cooling temperature set point by the number of restore steps as shown in Equation 8.

$$RCW = \frac{CPP\_CSP - NCTSP}{BTC} \text{ (evaluated as an integer)} \quad (5)$$

$$RCET = CPPET + RCL \quad (6)$$

$$NRS = \frac{RCL}{TL} \quad (7)$$

$$dTR = \frac{CPP\_CSP - NCTSP}{NRS} \quad (8)$$

When the pre-cooling temperature set point modifications begin for the pre-cool event, the space heating set point (HSP) is set to 5°F below the pre-cool temperature set point. This ensures that while reducing the cooling temperature set point the RTU is not driven into a heating mode. During the pre-cool event the temperature is reduced by *dTP*, as calculated in the last updated pre-cooling schedule before the pre-cool event began. The pre-cool steps are executed as scheduled until the unit reaches the *Pre_CSP*, default is 30 minutes before the start of the CPP event.

### CPP Event Mode

At the time indicated in the OpenADR message as the start of the CPP event, the cooling temperature set point is increased to the CPP_CSP, the first stage cooling fan speed is reduced by the fractional fan reduction percent (default is 10% reduction), the second stage cooling fan speed is reduced by the fractional fan reduction percent (default is 10% reduction), and minimum damper command set point is reduced to the CPP minimum damper command (default is 0). If during the CPP event the occupied flag associated with the RTU indicates the space is no longer occupied the DR application restores the RTU to normal operations and releases the device lock.

### Post Event Mode

When the post-event temperature set point modifications begin, the heating temperature set point, the minimum damper command set point, the first stage cooling fan speed, and second stage cooling fan speed are all restored to the normal values. During the post-event the cooling temperature set point is reduced by *dTR* at the scheduled time steps until the normal cooling temperature set point is reached. If during the post-event the occupied flag associated with the RTU indicates the space is no longer occupied the DR application restores the RTU to normal operations, releases the device lock with the Actuator agent, and the DR agent returns to the idle mode. Upon completion of the DR sequence the RTU controller resets all set points to normal values (redundancy to ensure restoration of normal RTU controls).

### Override Mode

During a DR event, occupants may push an override button on the thermostat within the space served by the RTU to end the DR sequence. When an occupant override is initiated, the DR agent will restore all set points modified during the DR sequence to normal values. The RTU controller will also reset all set points to normal values (redundancy to ensure restoration of normal RTU controls). The DR application then releases the device lock with the Actuator and schedules a return to the idle mode for midnight of that day. No further DR action can be initiated until the DR agent returns to the idle mode.

### Cancelled Events

If the DR agent receives an OpenADR signal indicating that a CPP event has been cancelled the DR agent will cancel any scheduled action pertaining to that CPP event. If the DR agent has made any command modifications to set points on the RTU for the CPP event cancelled, then the normal default set points for the RTU will be restored. If the DR agent currently holds the device lock for a RTU and the CPP event that triggered the lock request is cancelled the DR agent will release the device lock with the Actuator agent and return to the idle mode.

## Updating DR Events

When an OpenADR signal indicates that the time associated with a CPP event has been modified the DR agent will update the schedule for executing the DR sequence based on the modified time. Any actions scheduled based on the previous message will be cancelled.

Figure A-10 shows a state diagram for the DR agent including the various modes of operation or states and the triggers to put the DR agent into that mode.

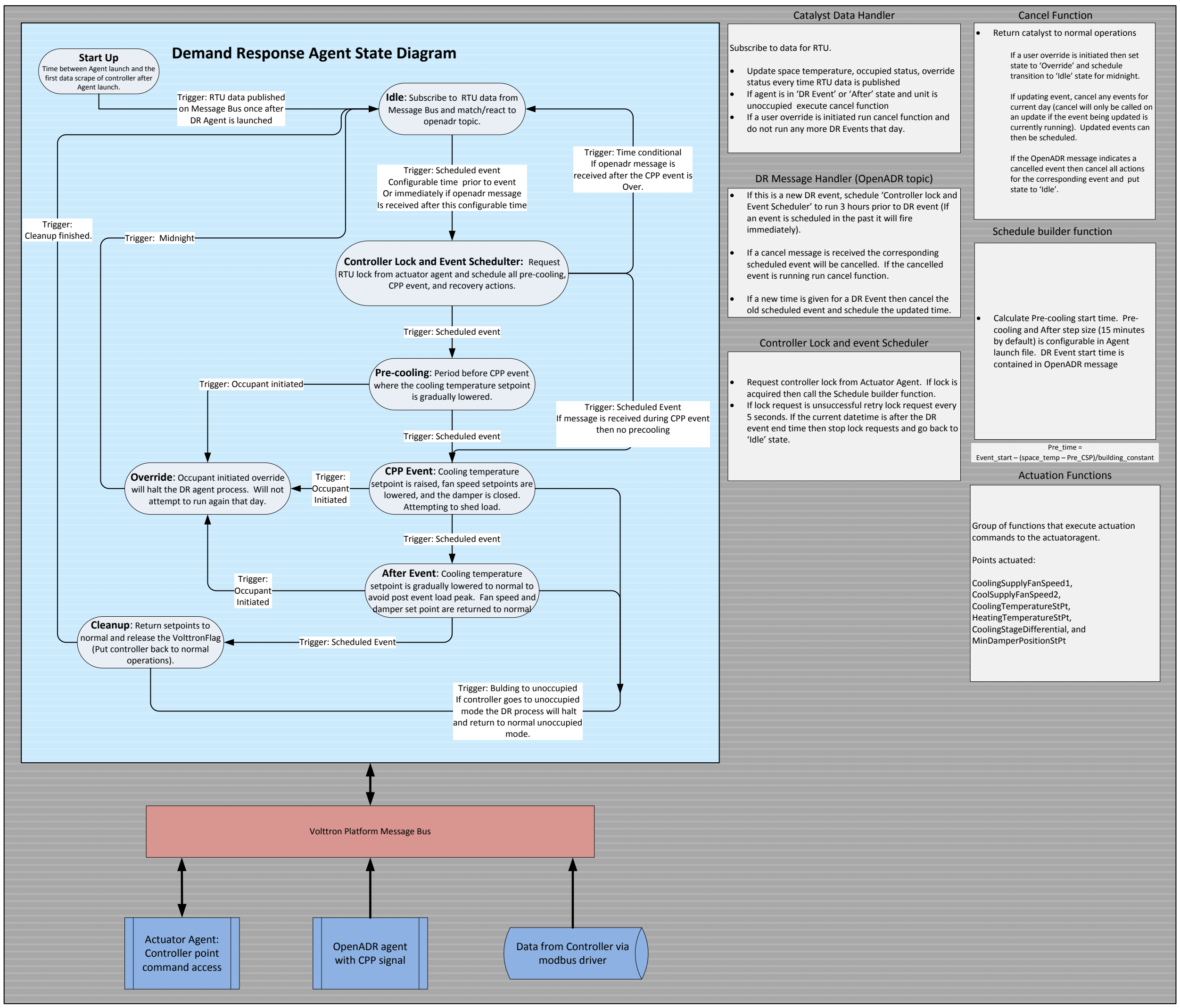


*Figure A – 10: Demand Response Agent Mode (State) Diagram*