Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

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Project 2.7 – Enabling Tools

Task 2.7.4 – Develop a Test Plan for Testing WBD Features Under Controlled Conditions

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1 Introduction

The last decade has seen a tremendous growth and interest in the development of methodologies to detect and to diagnose performance degradation and faults in building systems (Katipamula et al. 2000). However, only a few fault detection and diagnostic (FDD) systems developed actually have been deployed in the field. Most of the development, testing and prototyping of FDD systems, with a few exceptions, has been limited to work in research laboratories and universities.

Furthermore, the building automation and controls industry has been slow to integrate FDD systems with their products primarily because of the first cost and lack of demand from building owners and operators. Third party developers are reluctant to develop FDD systems because different building automation systems and control devices generally do not interoperate and effectively communicate with one another. To develop and deploy FDD systems in such an environment would have required getting access to proprietary information and the difficult task of developing tools that communicate with diverse systems and controllers.

As the cost of sensors and computing technology decreases, interest in FDD systems increases, and as building automation system capabilities advance and interoperable industry standards become widely adopted, the development and deployment of automated commissioning and FDD tools will become much easier.

The objectives of this project are to test: 1) the ability to transfer data from BACnet® (ANSI/ASHRAE 2001) devices/controllers and the Whole Building Diagnostician (WBD) through NIST's Virtual Cybernetic Building Test-bed (VCBT) and FDD test shell, 2) the ability of the VCBT and FDD Test Shell to generate test data for both fault free and faulty operating states and 3) the automated diagnostic capabilities of Battelle's WBD diagnostic modules.

The VCBT consists of a variety of simulation models that together emulate the characteristics and performance of a building system. The simulation models are interfaced to real state-of-the-art BACnet-speaking control systems to provide a hybrid software/hardware test bed that can be used to develop and evaluate control strategies and control products that use the BACnet communication protocol. The FDD Test Shell is a data-sharing tool that was developed to enable side-by-side testing and comparison of two or more FDD tools and to support the integration of information from multiple FDD tools.

The WBD is a production-prototype software package with two modules providing automated diagnostics for air-handling systems and energy use of major building systems (Brambley et al. 1998 and Katipamula et al. 1999). The data for the WBD are generally collected from a direct-digital control (DDC) system employed in the building. The WBD has two diagnostic modules: 1) Outdoor Air Economizer (OAE), and 2) Whole Building Energy (WBE).

The OAE module diagnoses whether air handlers in a building are supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air whenever it is appropriate to do so, and not wasting energy by supplying excess outdoor air when it should not. Few, if any, sensors other than those used to control most economizers are required, making the tool practical in near-term markets because of its low cost.

The WBE module monitors variations in energy use at the whole-building or subsystem levels. It does this by tracking actual consumption and comparing it to estimated expected consumption as a function of up to five independent variables including time of day, day of week, and weather conditions. The WBE automatically constructs a baseline model for estimating expected consumption using historical energy consumption data from the system being tracked and values for the relevant independent variables specified by the user. Using this baseline model, the WBE alerts the user when the actual measured consumption deviates significantly from the estimated expected consumption. The tool requires up to 9 months of data to build a model adequate for use during an entire year; however, useful results become available with about 6 weeks of data.

Both tools provide information to users in simple, graphical displays that indicate the presence or absence of faults at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the faults detected.

This document provides a summary and background on the VCBT/FDD Test shell, the WBD and its modules, and the plan for testing and evaluating the WBD's performance using data from the VCBT/FDD Test Shell. In Section 2, the various steps in the testing process are outlined, followed by Section 3, provides a description of the capabilities of the VCBT/FDD Test Shell. The detection and diagnostic capabilities of the OAE and WBE diagnostic modules are described in Sections 4 and 5, respectively, followed by a detailed description of the data gathering process in Section 6. Potential faults for testing the OAE and the WBE modules are described in Section 7. The test plan is described in Section 8, the evaluation process is described in Section 9, and references are provided in Section 10.

2 Testing Process

As mentioned in the previous section, there are three main goals for the task. The process that will be used to realize the goals is as follows:

1. First, Battelle and NIST will work jointly to develop a process that will enable data exchange between BACnet® devices/controllers and the WBD through the VCBT and the FDD Test Shell.
2. Battelle will specify the capabilities of the WBD tool and provide NIST with lists of possible faults for the two modules.
3. NIST will specify how the faults will be instigated and the duration of the faulty operation for all possible fault scenarios.
4. NIST will make the necessary modifications to the VCBT simulation engine and the simulation models (used to generate data for the WBE module) to generate fault-free data.
5. Battelle will validate the fault-free data by processing it with the WBD modules. This will ensure that the data being generated is as specified and the modules are properly configured.
6. NIST will generate at least six months of fault-free data for training the WBE module.

7. Battelle and NIST will verify that the VCBT/FDD Test Shell and the simulation models are simulating the faulty operations accurately, before the OAE and the WBE modules process the simulated data from faulty operations.
8. NIST will generate data for faulty operation for the two WBD modules. The faults will be selected by NIST, based on the list provided by Battelle.
9. Battelle will then automatically process the data generated for blind tests. Battelle will also process the data through additional semi-automated graphically routines. The semi-automated graphically routines are not part of the WBD. They were developed for advanced users and can provide additional details not provided by the automated methodology.[1]
10. Battelle will report the results obtained directly from the automated detection as well as from the semi-automated detection to NIST.
11. The results from Battelle will be compared to the expected results by NIST to assess the performance of the WBD module.

3 VCBT/FDD Test Shell

The two tools developed by NIST, the Virtual Cybernetic Building Testbed (VCBT) and the FDD Test Shell will be used in this project to generated data corresponding to fault free and faulty operation of building systems for use in testing the capabilities of the two modules in the WBD (WBE and OAE). The VCBT consists of a variety of simulation models that together emulate the characteristics and performance of a building system. The simulation models are interfaced to real state-of-the-art BACnet- speaking control systems to provide a hybrid software/hardware testbed that can be used to develop and evaluate control strategies and control products that use the BACnet communication protocol. The FDD Test Shell is a data-sharing tool that was developed to enable side-by-side testing comparison of two or more FDD tools and to support the integration of information from multiple FDD tools. For more details on the two tools refer to report by Busby et al. (2001).

3.1 VCBT AHU Control Strategies

There are three AHUs in the VCBT setup, two constant air volume (CAV) systems and one variable air volume (VAV) system. The fan and temperature control strategies for the three AHUs are described in the following sections.

3.1.1 AHU-1 and AHU-2 Fan Control

Both AHU-1 and AHU-2 are VAV systems and the supply-air fan speed in both systems is controlled to maintain the supply-air pressure at its desired set point. The return-air fan speed is controlled to maintain a constant differential between the supply-air and return-air flow rates.

3.1.2 AHU-1 Temperature Control

AHU-1 uses a single control loop to generate a temperature control signal to maintain the supply-air temperature at its desired set point. Depending on the magnitude of the signal, it is mapped to one of three outputs which control the: heating coil, cooling coil, or mixing-box dampers. Additional logic sets the position of the other two outputs appropriately depending on which one

[1] They also represent additional diagnostics, which could be added to the tools in the future.

is active. For example, if the cooling coil valve is active, the heating coil valve will be fully closed and the mixing box damper will be set fully open if the return air enthalpy is greater than the outside air enthalpy, otherwise the mixing box damper will be set fully closed. The outdoor-air and the return-air enthalpies are compared; this information is used to enable/disable the economizer operation.

3.1.3 AHU-2 Temperature Control

The AHU-2 uses a separate temperature control loop for each of three outputs which control the: heating coil, cooling coil, and mixing-box dampers. The heating coil and cooling coil outputs are controlled to maintain supply-air temperature at its set point. The mixing box dampers are controlled by comparing the outside-air and the return-air enthalpies. If the return-air enthalpy is greater than the outdoor-air enthalpy conditions are favorable for economizing, the mixing-box damper control loop maintains supply-air temperature at its set point. Interlocks, dead bands, and time delays are incorporated to prevent undesirable simultaneous heating, cooling, and economizing.

3.1.4 AHU-3 Fan Control

AHU-3 is a constant volume system, and the supply-air fan and return-air fan both run at constant speed at all times the AHU is operating.

3.1.5 AHU-3 Temperature Control

AHU-3 uses a single control loop to generate a temperature control signal to maintain the supply-air temperature at its set point. Depending on the magnitude of the signal, it is mapped to one of three outputs which control the: heating coil, cooling coil, or mixing box dampers. Additional logic sets the position of the other two outputs appropriately depending on which one is active. For example, if the cooling coil valve is active, the heating coil valve will be fully closed and the mixing box damper will be set fully open if the outside air temperature is less than the changeover temperature (a constant set point), otherwise the mixing box damper will be set fully closed. If the outdoor-air dry-bulb temperature is less the predetermined set point (high limit) the economizer is enabled.

4 Whole Building Diagnostician

The WBD is a modular diagnostic software system (Figure 1) that provides detection and diagnosis of common problems associated with air-handling units (AHUs) and the major energy end-uses in buildings. The OAE, which is one of the two modules, monitors, detects, and diagnoses problems with outdoor-air ventilation and economizer operation. The WBE, which is the other module, tracks energy end-uses at the whole building level, such as whole-building total electricity use, whole-building total thermal energy (cooling or heating) use, chiller or packaged unit energy consumption, or other HVAC electric consumptions other than the chiller.

The WBD is implemented on a personal computer operating on all flavors of the Microsoft Windows operating systems. The two diagnostic modules share a database and a common graphical user interface. Typically, the user interacts with the WBD to start analysis or to view results of diagnoses. Data are stored in the database by an external process as shown in Figure 1. The data may originate directly from a building automation system (BAS) or other data acquisition systems, or they may already be stored in another database. The two diagnostic modules access the database to obtain configuration data and measured data for analysis, and to store the diagnostic results. The two diagnostic modules can process the data, as soon as it is stored (in near real-time), batch-process time-series data, or process entire databases. The user may schedule processing at regular intervals (e.g., hourly or daily) or may manually initiate processing. Once a diagnostic module completes its processing, results are stored in the database. The user can retrieve the results at any time through the WBD, which retrieves the diagnostic results and displays them graphically for the user.

A run-time library of database utility functions is available to all diagnostic modules for database creation, message logging, and other data base operations. In addition, a data base audit module is available to check the consistency and completeness of a database before any processing task is undertaken. All WBD modules are implemented in Visual C++, and the database is implemented using ODBC (Object Data Base Connectivity).

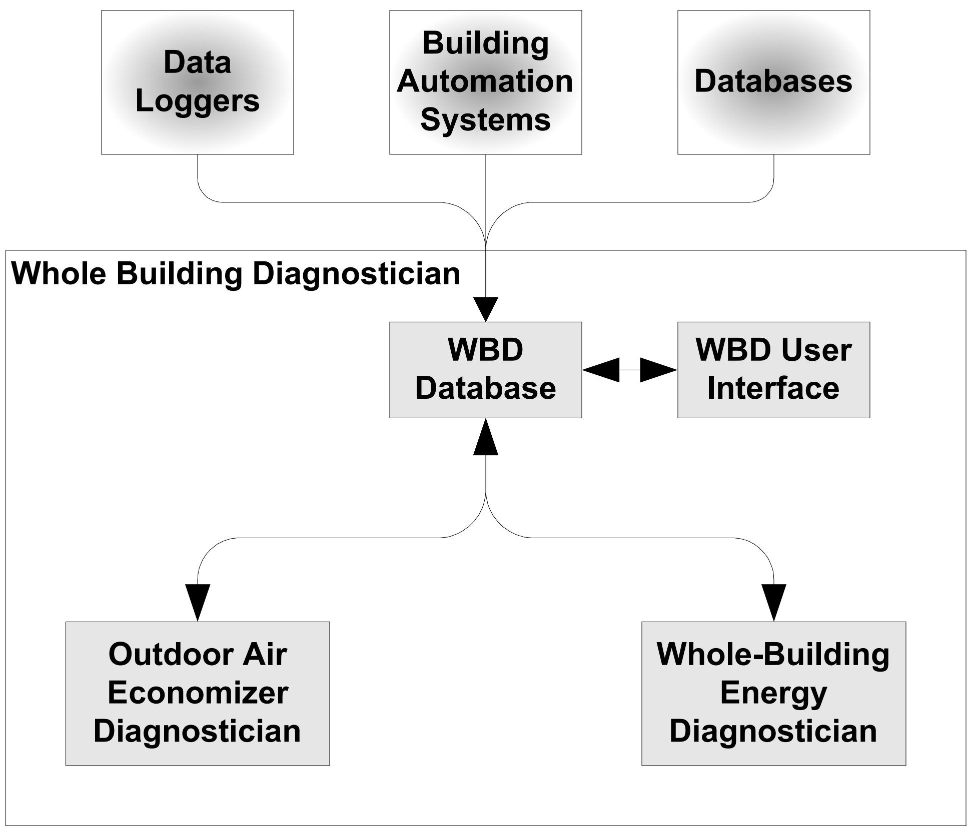

Figure 1 – Overview of the Whole-Building Diagnostician Software Tool

4.1 Data Management

The project database is central to the operation of the WBD. Both modules interact through the database using the Structured Query Language (SQL) for database transactions. The project database contains several data tables implemented using a relational model. Each data table represents a building component and contains data specific to: (1) configuration, (2) schedules, (3) metered data, and (4) intermediate calculations. Two other sets of data tables are used to control analysis and store the diagnostic results.

4.2 Automation of Data Collection and Processing

The system architecture makes possible development of automated monitoring systems that can run diagnostics of specified equipment on a regular basis by a specific diagnostic module. To automate the diagnostics, a separate monitoring program module is run to bypass the graphical user interface. This program allows automated collection and processing of data. As a result, the open architecture and modularized nature of the WBD provides abundant opportunities for implementing automated monitoring and diagnosis.

5 Outdoor-Air Economizer (OAE) Diagnostic Module

This section provides a brief overview of the Outdoor-Air Economizer (OAE) diagnostic module. The OAE monitors the performance of air-handling units and can detect over 20 different basic operation problems (i.e., faults) with outside-air control and economizer operation (Brambley et al. 1998 and Katipamula et al. 1999). The current version of the OAE module does not detect problems with the water side or the refrigerant side of the air-handling unit; it only detects air side problems. The OAE supports many common types of economizers and air-handling units used in today's buildings. The OAE requires some basic setup data to characterize the air-handling unit, and then uses periodically metered data to diagnose air-handler operation.

5.1 OAE Diagnostic Methodology

The OAE uses a logic tree to discern the operational "state" of outdoor-air ventilation and economizer systems at each point in time for which measured data are available. The logic is based on engineering principles that drive the basic operating sequence of the AHU as described below.

5.1.1 Basic Operating Sequence of AHU

An AHU typically has two main controllers: 1) to control the outdoor-air intake and 2 to control the supply-air temperature (in some cases mixed-air temperature is controlled rather than supply-air temperature). The basic operation of the AHU is to draw in outdoor air and mix it with return-air from the zones and, if necessary, condition it before supplying the air back to the zones as shown in Figure 2.

An AHU typically has four primary modes of operation during occupied periods for maintaining ventilation (fresh-air intake) and comfort (the supply-air temperature at the set point) as shown in Figure 3. The operating sequence determines the mode of operation and is based on the ventilation requirements, the internal and external thermal loads, and indoor and outdoor conditions.

When indoor conditions call for heating, the heating-coil valve is modulated (i.e., controlled) to maintain the supply-air set point (Heating mode in Figure 3). When the AHU is in the heating mode, the cooling-coil valve is fully closed, and the outdoor-air damper is positioned to provide the minimum outdoor air required to satisfy the ventilation requirements. As heat gains increase on the zone and the zone calls for cooling, the AHU transitions from heating to cooling. Before mechanical cooling is provided, the outdoor-air dampers are opened fully to use the favorable outdoor conditions to provide 100% cooling (Economizer mode in Figure 3). In this mode, the heating- and the cooling-coil valves are fully closed and the outdoor-air dampers are modulated to meet all the cooling requirements.

As the heat gains in the zone continue to increase, the outdoor air alone cannot provide all the cooling necessary, and the AHU changes modes by initiating mechanical cooling (Cooling and Economizing mode in Figure 3) to supplement the economizer. In this mode, the outdoor damper is fully open, the heating-coil valve is fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature. As the outdoor conditions become unfavorable (i.e., too hot and humid) for economizing, the AHU changes mode again. This time the outdoor-air dampers are modulated to the minimum position to provide the minimum outdoor air required to satisfy the outdoor-air ventilation needs, the heating-coil valve continues to be fully closed, and the cooling-coil valve is modulated to maintain the supply-air-temperature set point.

If an AHU does not have an economizer, then there are two basic modes of operation (Heating and Mechanical Cooling). If the economizer is not integrated with mechanical cooling (i.e., it cannot economize and provide mechanical cooling simultaneously), then there are three basic modes of operation (Heating, Economizing, and Mechanical Cooling).

5.2 Supported Economizer Controls

The economizer control strategies supported by the OAE module include: differential dry-bulb temperature-based, differential enthalpy-based, high-limit dry-bulb temperature-based and high-limit enthalpy-based.

With differential control strategies, the outside-air condition is compared with the return-air condition. As long as the outside-air condition is more favorable (for example, with dry-bulb temperature control, the outside-air dry-bulb temperature is less than the return-air temperature), outside air is used to meet all or part of the cooling demand. If the outside air alone cannot satisfy the cooling demand, mechanical cooling is used to provide the remainder of the cooling load.

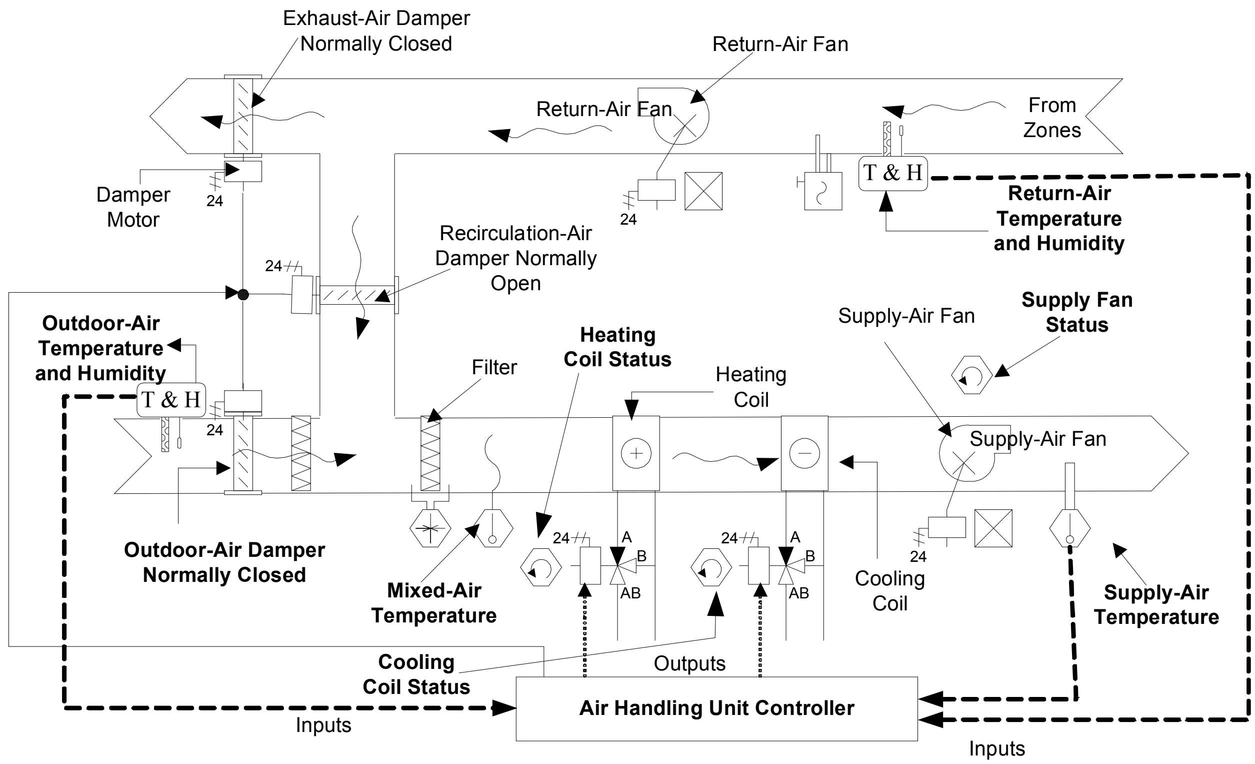

Figure 2 – Schematic diagram of an AHU with Sensor Locations

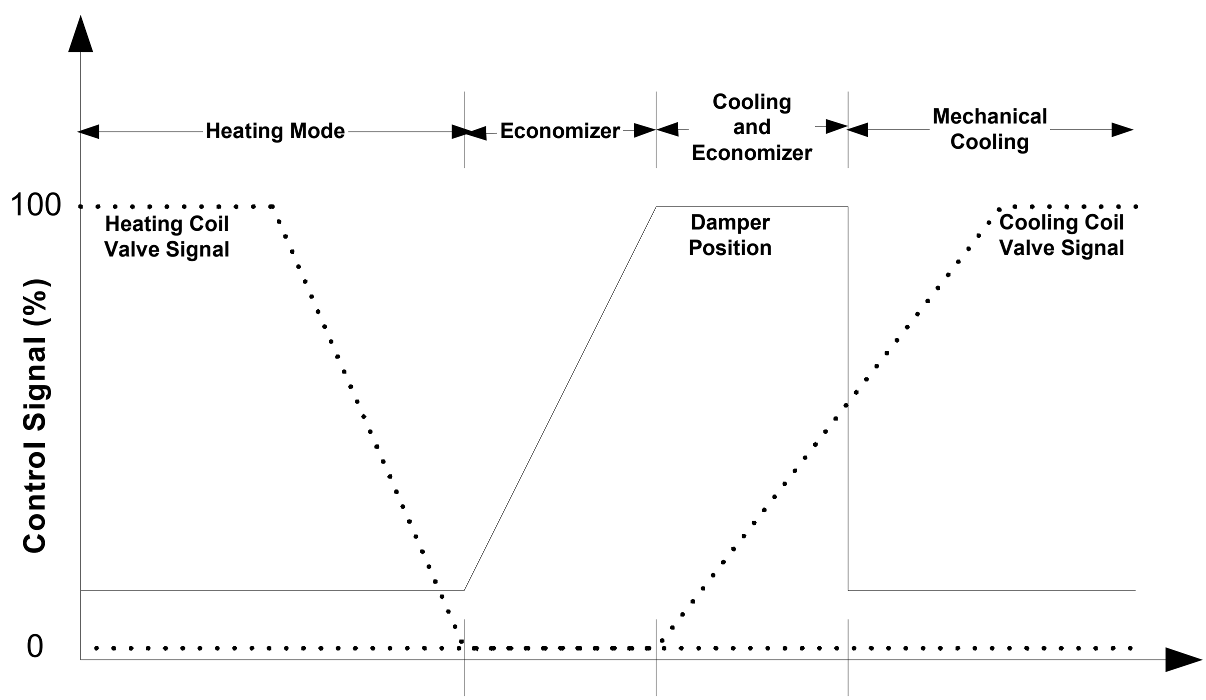

Figure 3 - Basic Operating Sequence of an Air-Handling Unit

With high-limit control strategies, the outside-air condition is compared to a single or fixed set point (usually referred to as a high limit). If the outside-air condition is below the set point, then outside air is used to meet all or part of the cooling demand; any remaining cooling load is provided by mechanical cooling.

In addition to these economizer control strategies, the OAE diagnostic module supports diagnosis of the following types of systems:

1. Integrated economizer operation with simultaneous operation of the economizer and mechanical cooling.
2. Packaged units with multiple stages or central units.

Although the two enthalpy-based economizer controls are supported, they have not been widely field tested.

5.3 Supported Air-Handling Systems

The OAE module supports the following types of air handlers:

1. Constant-air-volume systems.
2. Variable-air-volume (VAV) system with no volume compensation (i.e., outside-air intake is a constant fraction of the supply-air flow rate).[2]

The OAE module will not be able to detect problems reliably with VAV systems that meter outdoor-airflow rate.

5.4 Problems Identifiable by the OAE Module

At a high level, the faults that can be identified by the OAE module can be grouped into four categories: 1) no or inadequate ventilation, 2) energy waste, 3) temperature sensor and other miscellaneous problems, and 4) missing or out of range inputs. These four categories can be further expanded as follows:

1. Outdoor-air ventilation problems (identified by blue cells on the OAE interface)
    a. no ventilation is being supplied
    b. inadequate ventilation being supplied

2. Energy high (identified by red cells on the OAE interface)

    a. too much ventilation during cooling mode
    b. too much ventilation during heating mode
    c. economizer should not be operating
    d. economizer should not be at full flow
    e. economizer operation may be detrimental
    f. economizer should not be off
    g. economizer should not be at part flow
    h. economizer is not throttling to maintain supply-air temperature

[2] This is not the most desirable use of VAV, but it is commonly found in the field as an intended operation mode.

i. mechanical cooling should not be off
j. simultaneous heating and cooling

3. Temperature Sensor and Other problems (identified by yellow cells on the OAE interface)

   a. mechanical cooling should not be on
   b. ventilation air flow is less than the minimum
   c. ventilation air flow is greater than maximum
   d. temperature sensor problem

4. Missing Inputs (identified by gray cells on the OAE interface)

   a. missing/invalid or indeterminate condition, such as when outdoor- and return-air temperatures are equal
   b. return-air and outside-air temperatures are equal
   c. bad WBD setup (configuration error)
   d. missing supply fan on/off data
   e. mixed-air temperature is outside the expected range
   f. outside-air temperature is outside the expected range
   g. return-air temperature is outside the expected range
   h. missing mixed-air temperature
   i. missing outside-air temperature
   j. missing return-air temperature

5.5 Data Requirements

The OAE module requires several one-time (setup or configuration) data inputs to characterize the systems present and how they are controlled. In addition to the setup data, the OAE also requires at least seven metered data points. The engineering units for all inputs (both setup and measured) are assumed to be in IP units unless otherwise specified.

5.5.1 Set-up Data Requirements for the OAE Module

The OAE is capable of detecting and diagnosing faults with most commonly found AHUs using almost all economizer control strategies. In addition, the OAE is designed to be flexible in accepting status inputs; therefore, the setup list is rather long, as shown in Table 1. For example, any one of four signals can be used to indicate whether the supply fan is ON. The related groups of inputs are shaded for convenience (either gray or white) (in Table 1). Once the OAE module is configured, the detection and diagnosis is fully automated.

The set-up data are required for all AHU systems with economizers. These data describe:

1. the basic air-handling system
2. the minimum, maximum, and required (building fully-occupied) outdoor-air fractions
3. the occupancy schedule, defining when the required outdoor air must be supplied
4. data needed to estimate energy and cost impacts of problems.

There are 17 items of user-supplied setup data that must be supplied for every AHU system. In addition, there are a large number of additional setup data inputs along with the types of AHU and economizer controls to which they are applied. As few as three to as many as fifteen additional inputs may be required to describe any given system type. For a typical system with an outdoor-air-fraction-based differential temperature economizer with low-limit control, nine of these setup items are required. Almost all of these inputs are provided with defaults that enable the OAE module to be initialized without the user providing them; however, it will not operate correctly if the default values are incorrect. Some of these set up problems will be identified by the OAE. Generally, these then need to be reconciled by the building operator and setup data changed to correct the differences between the actual and default values.

Table 1 - Setup Data Requirements for the OAE Diagnostic Module (all units are assumed to be in IP units unless otherwise specified)

Parameter	Comments	Expected Range
Outdoor Air Control Basis	Specify whether the damper position or the outdoor air fraction is controlled to maintain the ventilation	Damper or OAF
Minimum Oaf	Minimum possible outdoor air fraction. For example, "0," if the dampers can be shut completely	0 - 1
Maximum Oaf	Maximum possible outdoor air fraction. For example, "1," if 100% of supply air can be drawn through the outdoor air dampers when they are wide open	0 - 1
Occupied Oaf	Specify the minimum required outdoor air fraction to maintain adequate ventilation when the building is fully occupied	0 - 1
Outdoor Air Fraction Sensitivity	Dead band on the outdoor air fraction	0.025
Occupied Damper Position	If damper position is controlled to maintain ventilation, specify the damper position that meets the ventilation requirement when the building is fully occupied	0 – 1%
Minimum Damper Position	Minimum possible damper position. For example, "0," if the dampers can be shut completely	0 – 1
Maximum Damper Position	Maximum possible damper position. For example, "1," if 100% of supply air can be drawn through the outdoor air dampers when they are wide open	0 - 1
Outdoor Air Damper Position Sensitivity	Dead band on the damper position	0.01
Economizer Control Point	Specify whether the supply-air or the mixed-air temperature is used to controlled the dampers or the outdoor air fraction	Supply air Or mixed air
Supply Set Point	If supply air is controlled, and the set point is not reset, then provide the set point	45 - 65
Mixed Set Point	If mixed air is controlled, and the set point is not reset, then provide the set point	45 - 90
AHU Type	Specify whether the AHU is a CAV or a VAV	CAV or VAV

Parameter	Comments	Expected Range
Economizer Type	Specify whether economizer and mechanical cooling can be ON simultaneously	Integrated or not Integrated
Economizer Control	Does the economizer use high-limit or differential type of controls	High limit or Differential
Economizer Control Basis	Does the economizer use dry-bulb temperature or enthalpy	Dry-Bulb or Enthalpy
Economizer Start Differential Temperature	Dead band on the high-limit or the differential, so that the outdoor-air dampers don't hunt or cycle	2
Economizer High-Limit Temperature	Temperature limit below which the economizer is used, if the economizer is based on dry-bulb temperature	< Zone Temperature Set point
Economizer High Limit Enthalpy	Enthalpy limit below which the economizer is used, if the economizer is based on enthalpy	< Zone Enthalpy
Return Air Humidity Sensor Type	Specify whether the return-air relative humidity or dew-point is measured, if differential enthalpy type economizer is used	Relative Humidity or Dew Point
Is Economizer Control Set Point Reset	Is supply- or mixed-air temperature reset	Reset not Reset
Is Mixed Air Sensor After Fan	Is the mixed air sensor before or after the fan motor	Before or after
Is Supply Fan Motor In Air stream	Is the supply fan motor in the air stream	Yes or no
Supply Fan RPM	Specify the supply fan RPM	?
Supply Fan kW	Specify the supply fan's rated kW, to calculate the heat gain	?
Supply Fan Efficiency	Specify the fan's motor efficiency, to calculate the heat gain	0.7
Supply Fan Delta T	If the supply fan rated kW and efficiency are not specified, then specify the approximate temperature rise across the fan	2
Fan On/Off Signal	What sensor value is used as a status flag - supply fan rpm or supply fan kW consumption	RPM, kW, Delta T
Supply Fan Rpm Threshold	If supply fan speed is used as a status flag, specify the threshold when the fan is considered ON	100
Supply Fan kW Threshold	If supply fan kW is used as a status flag, specify the threshold when the fan is ? considered ON	1
Heating On/Off Signal	What sensor value is used as a status flag - heating fraction on time, or heating thermal load, or HW valve position	Heating fraction ON time, Heating thermal Load, or Hot water valve position
Heat On Fraction	If fraction on time is used as a status flag, specify the threshold when the heating is ON	0-1
Heating kW Threshold	If electric re-heat is used as a status flag, specify the threshold when the heating is ON	1

Parameter	Comments	Expected Range
Heating Thermal Threshold	If heating thermal load is used as a status flag, specify the threshold when the heating is ON	1
HW Valve Position Threshold	If heating valve is used as a status flag, specify the threshold when the heating is ON	0-100
Mechanical Cooling On Off Signal	What sensor value is used as a status flag - cooling fraction on time, or cooling thermal load, or CW valve position	Cooling fraction ON time, Cooling thermal Load, or Chilled water valve position
Cool On Fraction	If fraction on time is used as a status flag, specify the threshold when the cooling is ON	0-1
Cooling kW Threshold	If electric consumption to compressor or chiller is used as a status flag, specify the threshold when the cooling is ON	1
Cooling Thermal Threshold	If cooling thermal load is used as a status flag, specify the threshold when the cooling is ON	1
CW Valve Position Threshold	If cooling valve is used as a status flag, specify the threshold when the cooling is ON	0-100
Electric Rate kWh	Specify the electric energy cost	0.1$/kWh
Gas Rate MMBtu	Specify the cost of gas	5 $/MMBtu
Supply CFM	Specify the supply air flow rate to estimate the energy impacts	1000-5000
Heating Energy	Specify whether the heating is energy is from a thermal or electric source	Thermal or Electric
Cooling Energy	Specify whether the cooling is energy is from a thermal or electric source	Thermal or Electric
Heating System Efficiency	Heating system efficiency	0-100
Cooling System COP	Coefficient of performance	0-5
Occupancy Schedule	Specify the fraction of full load occupancy by hour-of-day, and day-of-week and month-of-day	0-1
Outdoor Air Humidity Sensor Type	Specify what type of humidity sensor is used to measure outdoor air relative humidity; relative humidity or dew point?	Relative Humidity Or Dew Point

5.5.2 Metered Data Requirements for the OAE Module

The OAE requires seven periodically measured/collected (currently at hourly increments) data as shown in Figure 2 and Table 2. In addition to the seven variables, the damper- position signal is also required for AHUs with damper-position-signal control, i.e. if the damper-position signal is controlled directly to maintain the ventilation or to control the supply- or mixed-air temperatures when the AHU is economizing. For economizers with enthalpy-based control, outside- and return-air (only for differential enthalpy control) relative humidities or dew-point temperatures are required. If the supply- or mixed-air temperature set point is reset, then the reset value at each hour is also needed.

6 Whole-Building Energy (WBE) Module

The Whole-Building Energy (WBE) module tracks end uses at the whole-building level, such as whole-building total electricity use , whole-building total thermal energy (cooling or heating) use, chiller or packaged unit energy consumption, or other HVAC electric consumptions other than the chiller. Internally, the WBE modeling engine uses time of day, day of the year, day of the week, outdoor-air dry-bulb temperature, and relative humidity (or dew point) as independent variables. The WBE module is currently being extended (as part of another Project) to support the use of up to five independent variables selected by an expert user, such as plug loads, occupancy loads, meals served, etc, to model the end-uses.

Table 2 – Measured Data Requirements for the OAE Diagnostic Module

Measured Parameters[3]	Comments	Range
T_{out}	Outdoor air dry-bulb temperature	0 – 120
Rh_{out} or DP_{out}	Outdoor air relative humidity or dew point, if enthalpy based economizer is used	5 – 100
T_{ret}	Return air dry-bulb temperature	55 – 85
R_{ret} or DP_{ret}	Return air relative humidity or dew point, if differential enthalpy economizer is being used	40 – 70
T_{mix}	Mixed air dry-bulb temperature	55 – 90
T_{supply}	Supply air dry-bulb temperature	45 – 120
Damper Position Signal	Damper position signal, if damper position signal is being controlled to maintain ventilation and control economizer operation	0 –100%
CW Valve Position or Cooling Thermal Flow or Cooling kWh, or Cool On Fraction	One of the four quantities to indicate whether mechanical cooling is being provided	0 –100%
HW Valve Position or Heating kWh or Heating kW, or Heat On Fraction	One of the four quantities to indicate whether heating is being provided	0 –100%
Supply Set Point or Mixed Set Point	If set point is reset, one of the two are required	50 – 60
Fan Speed or Fan kW or Fan On Fraction	One of the three quantities to indicate whether supply fan is ON	

The WBE module uses a daily energy consumption index (ECI) to show deviations in the actual energy consumption from the expected energy consumption. The expected energy consumption is estimated based on the baseline model that is automatically developed with historical energy consumption. The daily energy consumption index (ECI) for one day is calculated as follows:

$$ECI = \frac{\sum_{h=0}^{23} Actual_h}{\sum_{h=0}^{23} Predicted_h}$$

where ECI is the energy consumption index, $Actual_k$ is the actual consumption at the k^{th} hour, and $Predicted_k$ is the predicted consumption at the k^{th} hour.

If the actual energy consumption and the estimated expected energy consumption are the same, by definition, the ECI equals 1.0. As the actual energy consumption deviates from the expected,

[3] All measured data are expected to be hourly and the units are IP unless otherwise mentioned.

the ECI values also deviate from 1.0. In general, ECI values between 0.9 and 1.0 are considered good. However, because of measurement errors and the inability to measure all the independent variables that strongly influence the energy consumption, ECI values between 0.8 and 1.2 are thought to be reasonable.[4] The sensitivity of fault detection (or abnormal operation) can be adjusted to provide more or fewer faults depending on the user preference.

6.1 Supported End-Uses

As mentioned earlier, the current version of the WBE uses hour-of-day, day-of-week and outdoor temperature and humidity as independent variables to model the energy end-uses. These independent variables work reasonable well for an office building. Possible end-uses include:

1. whole-building total electricity use,
2. whole-building total thermal energy (cooling or heating) use,
3. chiller or packaged unit energy consumption, or
4. other HVAC electric consumptions other than the chiller.

6.2 Supported Systems

The WBE is not directly dependent on the building systems.

6.3 Problems Identifiable by the WBE Module

Unlike the OAE module, the WBE module cannot identify the causes of faults; it only detects deviation from normal operation. The operator or the user must diagnose the cause of the abnormal or faulty operation or use another automated FDD tool to identify causes. The WBE can, however, help isolate the major system(s) responsible for whole-building energy anomalies. The faults or abnormal operations that WBE can detect fall into three categories: 1) significant increase or decrease in energy consumption because of scheduling errors, 2) unusually high or low energy consumption (unrelated to a scheduling problem), and 3) values of the sensors outside the expected ranges.

6.4 Data Requirements for the WBE Module

Like the OAE, the WBE also requires setup data and metered data.

6.4.1 Set-up Data Requirements for the WBE Module

The setup data requirements for the WBE include the prices for electricity and thermal energy. The electric price is a blended rate or marginal cost of demand and energy cost and can be provided for each hour-of-day, day-of-week and by month.

Table 3 - Setup Data Requirements for the WBE Diagnostic Module

Measured Parameters	Comments	Range
Blended Electric Rate	Specify the electric energy cost	0.1 $/kWh
Gas Rate	Specify the cost of gas	5 $/MMBtu

[4] The WBE actually uses a statistical measure that depends on the size of the deviation as well as how well that energy consumption is known for those conditions (related to the variance of the historical data) and only alerts the user when the deviations about 1.0 are statistically significant.

6.4.2 Metered Data Requirements for the WBE Module

Table 4 lists the metered data requirements for the WBE module. The current version of WBE can only handle the four independent end-uses listed in Table 4. Although four end-uses are listed, the WBE will process any one or all of the end-uses listed. Currently, the WBE can only handle one thermal end-use, either heating or cooling. However, there are ways to handle both thermal end-uses by setting up separate databases to model heating and cooling energy. In the revised version under development, each energy use may use a different set of independent variables, enabling the modeling of both heating and cooling.

Table 4 – Measured Data Requirements for the WBE Diagnostic Module

Measured Parameters	Comments	Range
T_{out}	Outdoor air dry-bulb temperature	0 – 120
Rh_{out} or DP_{out}	Outdoor air relative humidity or dew point	5 –100
Electric kWh	Whole building electricity consumption	?
HVAC kWh	Electric consumption other than that of the chiller (AHUs, pumps, motors, etc …); this channel is the difference between whole building electricity consumption and the chiller consumption	?
Chiller kWh	Chiller kWh consumption	?
Thermal MMBtu	Heating or cooling energy consumption of the building	5 $/MMBtu

7 Data Gathering Process

This section is described in more detail in a companion report.

8 Potential Faults for Testing the WBD

The basic algorithms used by both the OAE and the WBE modules are independent of the frequency of the measured data, but the graphical user interface and the data base support functions can only handle data at an hourly frequency. Therefore, the OAE processes the hourly data and generates diagnoses on an hourly basis, while the WBE processes hourly data, but generates the ECI indices at daily intervals. Faults or deviations in the energy consumption must occur over several hours within a day for the WBE to detect them; short-term excursions will not be detected by the WBE because they have a negligible effect on energy use for the day.

For the OAE module, the fault should at least span one hour for it to be detected, while fault diagnosis (i.e. identifying the actual cause) typically requires several hours of faulty operation. Some faults, such as inadequate ventilation or scheduling problems (e.g., mechanical cooling being ON when it is not scheduled to be ON), will manifest themselves quickly and, therefore, can be detected with one or two hours of faulty operation. Other faults, such as stuck dampers, may not manifest even after several hours of faulty operation. For example, a damper stuck at the minimum required ventilation position may not be a fault when the air handler is in the heating mode; however, it is a fault when the air handler is in the (mechanical) cooling mode and the outdoor conditions are favorable for economizing. In this case, the fault may not manifest itself for several months depending on the season (i.e., it may manifest itself only during certain seasons).

The diagnostic process of the OAE module is divided into two sub-processes. The single-state or instantaneous diagnosis is performed by analyzing the operating state of the system using measured data from a single time period. The single-state diagnosis uses diagnostic reasoning to determine the state of the ventilation air and economizer system, identify possible failures that could have caused the state if it is a problem, identify impossible failures given the state, provide a list of conditions that led to the diagnosis, and estimate the energy and cost impacts of any problems detected.

Following the single-state detection, the multi-state diagnostic process is exercised to reduce the list of possible causes over some retroactive time span (i.e. historical fault detection results). It uses the outputs of the single-state diagnoses for every measured data interval in a time span to try to reduce the list of possible failures.

Therefore, the length of "faulty" operation (i.e. how long a fault persists) before detection depends on the type of fault and whether conditions (and operating modes) occurring while the fault is present allow the fault manifest itself. Lists of potential faults that both the OAE and the WBE can detect are provided in the following sections.

8.1 Potential Faults for Testing the OAE Module

To help configure the VCBT/FDD Test Shell and to design the simulation test bed, the potential faults the OAE module can detected are outlined Table 5. Using Table 5 as a guide, the team from NIST will configure the VCBT/FDD Test Shell to generate both clean (fault free) and" data representing faulty behavior. The column labeled "How to Instigate the Fault" in Table 5 provides a brief description of how the fault can be instigated. Later in the section, there are more detailed descriptions of how the faults are instigated in the VCBT. The column labeled "Length of the Faulty Operation" in Table 5 provides some guidance on how long the faulty operation should persists in order for it to manifest as a detectable fault. The last column in Table 5 provides the corresponding VCBT fault IDs, which are described in Table 6. In addition to the fault IDs, Table 6 provides descriptions of the component affected, the type of fault being simulated, and the respective fault condition.

Table 5 - List of Potential Faults for Testing the OAE Diagnostic Module

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Simultaneous Heating and Cooling	Operate the AHU in the normal cooling mode, then override the heating-valve signal to an open position (say 40%). At the same time, make sure that the supply-air temperature still meets the supply-air set point requirement for the cooling mode. Maintain the new heating-valve position for the duration of the test.	When the AHU is providing both heating and cooling at the same time, energy is being wasted. The OAE module will detect such occurrences and flag them.	The length of the fault can be an hour or more	19-22 23-26
Inadequate ventilation with outdoor-air damper stuck in the fully-closed position	Operate the AHU in the normal cooling or heating mode and then override the outdoor-air damper to a fully-closed position. Maintain the new outdoor-air-damper position for the duration of the test.	When the actual outdoor-air intake is zero, which indicates no ventilation is being provided; this condition is a fault, as long as the minimum ventilation requirement is greater than zero.	The length of the fault can be an hour or more	10a

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Inadequate ventilation with the outdoor-air damper stuck between fully closed and its minimum position)	Operate the AHU in the normal cooling/heating mode and then override the outdoor-air damper to a position between fully closed and the minimum position that meets the ventilation requirements. Maintain the new outdoor-air-damper position for the duration of the test.	When the actual ventilation is less than the level required to maintain minimum levels of ventilation, this is a fault. OAE will detect such a fault.	The length of the fault can be an hour or more	10b
Excess ventilation/ with the outdoor-air damper stuck open at greater than its minimum position.	Operate the AHU in the normal heating mode or cooling mode. If cooling mode is selected, the conditions should be favorable for economizing. Then, override the outdoor-air damper to a position greater than the minimum position that meets the ventilation requirements. Maintain the new outdoor-air-damper position for the duration of the test.	When the actual ventilation level is greater than the minimum level required to maintain adequate ventilation during the heating mode or during conditions when it is not favorable for economizing, this is a fault and the OAE will detect this fault	This type of fault can always be detected in heating mode. In cooling mode, it can only be detected when the conditions are **not** favorable for economizing. Therefore, the duration of this fault depends on the season – in heating season the fault will manifest itself within an hour or more, while in cooling mode several hours or even days of AHU operation may be required for the fault to manifest.	15

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Economizer at full flow with the damper stuck in the fully-open position	Operate the AHU in the normal heating mode or cooling mode. If the cooling mode is selected, the conditions should be favorable for economizing. Then, override the outdoor-air damper to a fully open position. Maintain the new outdoor-air-damper position for the duration of the test.	The economizer is operating when it is not favorable to economize because the damper is stuck in a fully-open position.	This type of a fault can be detected in heating mode, when the outdoor-air conditions are below the supply- or mixed-air set-point temperature or when the outdoor-air conditions are not favorable for economizing. Depending on the AHU operating mode, the fault can manifest within hours or may take several days.	9
Economizer should not be operating	Operate the AHU in the normal heating mode or cooling mode. If the cooling mode is selected, the conditions should be favorable for economizing. Then, override the outdoor-air damper to a position greater than the minimum position that meets the ventilation requirements.	Economizer is operating when it is not favorable of economizing.	In heating mode, this type of fault can be detected quickly, but in cooling mode this fault may not manifest itself for several days or weeks, depending on the outdoor conditions.	3, 7

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Economizer should be operating	Operate the AHU in the normal cooling mode. The conditions should be favorable for economizing. Then, override the outdoor-air damper to the minimum position that meets the ventilation requirements. Maintain the new outdoor-air-damper position for the duration of the test.	Economizer is not operating when it is favorable of economizing	In heating mode this condition is not a fault and cannot be detected, but in cooling mode this is a fault depending on the outdoor conditions; therefore, it may require several hours or days or weeks depending on the outdoor conditions for the fault to manifest.	4,8
Economizer should not be at part flow	Operate the AHU in the normal cooling mode with the outdoor-air dry-bulb temperature less than or equal to the supply-air set-point temperature, then override the outdoor-air damper to a position less than the fully-open position.	The economizer should be at full flow because the conditions are favorable for economizing. This fault could occur if the outdoor air damper cannot fully open.	In heating mode, this condition is not a fault and cannot be detected, but in cooling mode this is a fault depending on the outdoor conditions. It may take several hours or days or weeks depending on the outdoor conditions for the fault to manifest itself.	5, 10

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Mechanical Cooling should not be ON	Operate the AHU in the normal cooling mode with the outdoor-air dry-bulb temperature less than or equal to the supply-air set point temperature, then override the outdoor-air damper to a position less than a fully-open position. Also, override the chilled-water-valve signal to be open (such as 30%).	When the outdoor air conditions are below the supply or mixed-air temperature set point, mechanical cooling should not be ON.	In heating mode, this condition is not a fault and cannot be detected, but in cooling mode this is a fault depending on the outdoor conditions. It may take several hours or days or weeks depending on the outdoor conditions for the fault to manifest itself.	10, 15, 24-26
Biased sensor	Operate the AHU in the normal heating or cooling mode with a biased outdoor-air, return-air, or mixed-air temperature. The bias should be greater than the combined tolerance of the outdoor-air and mixed-air temperatures (for example, if the tolerance of the temperature sensors is 1°F the bias should at least be 3°F or greater).	Either outdoor-, mixed- or return-air temperature sensor is biased.	These problems manifest quickly, if the bias is significant. The bias should be greater than the tolerance of the sensors.	1-8

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Economizer control fault	Operate the AHU in the normal cooling mode with outdoor temperatures below the supply-air set-point temperature, then override the outdoor-air damper to a fully-open position. This will make the supply-air temperature fall below the supply-air set-point temperature and create the necessary fault. Maintain the outdoor-air dry-bulb temperature below supply-air set-point temperature and the outdoor-air damper in a fully-open position for the duration of the test.	The economizer is failing to properly control the supply- or mixed-air temperature. If the supply- or mixed-air temperature is below set point, outdoor-air fraction less than maximum, cooling is off, and controller not signaling the ventilation damper system to close.	The detection of this problem depends on the outdoor conditions; therefore it may take several hours and may be days to get detected.	31, 32
Supply-air-temperature control fault - I	Operate the AHU in the normal cooling mode and then override the chilled-water valve to a fully-open position to create a situation where the supply-air temperature is below the supply-air set-point temperature.	The supply-air-temperature control failed to close the chilled-water valve or decrease (throttle) cooling.	This problem can only be detected in cooling mode (spring or summer conditions).	20-22

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Supply-air temperature control fault - II	Operate the AHU in the normal cooling mode and then override the chilled-water valve to a fully-closed position to create a situation where the supply-air temperature is above the supply-air set-point temperature.	The supply-air-temperature control failed to open the chilled-water valve or activate mechanical cooling	This problem can only be detected in cooling mode (spring or summer conditions).	19
Failed sensor	Operate the AHU in the normal heating or cooling mode with a failed outdoor-air, return-air, or mixed-air sensor (total failure providing no signal).	Either outdoor-, mixed- or return-air temperature sensor fails.	These problems manifest quickly if the values are significantly different from expected, so they may require only a few hours at faulty conditions to be detected.	33-36
Biased supply air temperature	Operate the AHU in the Normal heating or cooling mode with biased supply-air temperature.	Biased supply-air temperature	This type of fault will manifest itself as other problems. Depending on the conditions, it may require more than a few hours.	1 and 2
Missing or out of range data		If any of the measured data variables is missing or out of range, the fault will be detected and diagnosed.	This type of a fault can be easily detected, usually with one or more hours of faulty operation.	33-36

Type of Fault/Problem	How to Instigate the Fault	Description of the Fault/Problem	Required Duration of the Faulty Operation	Corresponding VCBT Fault #
Scheduling fault	Operate the supply fan or mechanical cooling during unoccupied hours.	The AHU is configured to be OFF during night time or during unoccupied periods, but is actually operating.	This fault can be easily detected with one or more hours of operation.	37

Table 6 – A List of Faults that the VCBT can Generate Including the Fault IDs Numbers.

Fault ID	Component	Fault Type	Fault Condition
0	Fault free	None	None
1	Supply-air-temperature sensor	Drift/Biased sensor	0 to -4 C
2	Supply-air-temperature sensor	Drift/Biased sensor	0 to +4 C
3	Return-air-temperature sensor	Drift/Biased sensor	0 to -4 C
4	Return-air-temperature sensor	Drift/Biased sensor	0 to +4 C
5	Mixed-air-temperature sensor	Drift/Biased sensor	0 to -4 C
6	Mixed-air-temperature sensor	Drift/Biased sensor	0 to +4 C
7	Outdoor-air-temperature sensor	Drift/Biased sensor	0 to -4 C
8	Outdoor-air-temperature sensor	Drift/Biased sensor	0 to +4 C
9	Outdoor-air damper	Stuck	Open
10	Outdoor-air damper	Stuck	15%
10a	Outdoor-air damper	Stuck	0%
10b	Outdoor-air damper	Stuck	10%
15	Recalculating-air damper	Stuck	Closed
16	Recalculating-air damper	Leakage	10%
18	Recalculating-air damper	Leakage	40%
19	Cooling-coil valve	Stuck	Closed
20	Cooling-coil valve	Leakage	10%
21	Cooling-coil valve	Leakage	25%
22	Cooling-coil valve	Leakage	40%
23	Heating-coil valve	Stuck	Closed
24	Heating-coil valve	Leakage	10%
25	Heating-coil valve	Leakage	25%
26	Heating-coil valve	Leakage	40%
31	Economizer-control fault	On/Off	N/A
32	Supply-Air temperature sensor failure	Open circuit	N/A
33	Return-Air temperature sensor failure	Open circuit	N/A
34	Mixed-Air temperature sensor failure	Open circuit	N/A
35	Outdoor-Air temperature sensor failure	Open circuit	N/A
36	Scheduling fault	On/Off	N/A

8.2 VCBT Fault Descriptions for OAE Fault Generation

A selected number of faults will be emulated using the VCBT. The faults will correspond to those typically occurring in AHUs and include sensor drifts, stuck or leaking dampers, and stuck or leaking valves.

The VCBT can emulate AHU operation using real weather data for an entire year or a specified season. Depending on the fault, specific periods for data will be used for emulation. The Descriptions of the faults that can be emulated in the VCBT environment (Table 6) are provided in the following sections.

8.2.1 Normal Operation (Fault 0)

For normal operation, the AHU will follow the basic sequence of operations described earlier in the report (Section 5.1.1). For emulating specific seasons, the data from the months of July, October, and February will be used to represent the cooling, heating, and swing seasons, respectively.

8.2.2 Simultaneous Heating and Cooling (Faults 19 - 26)

Operating the AHU in the normal cooling or heating mode, then overriding the heating- (or cooling-) valve signal to open simultaneous to the one already open will create this fault. Maintain the new heating- and cooling-) valve positions for the duration of the test. The supply-air temperature will follow normal operations, i.e., it will be at the cooling (or heating) set point. The dampers and the economizers will also follow normal operations.

8.2.3 Supply-Air Temperature Sensor Drift or Bias (Faults 1 and 2)

The occurrence of sensor drift for the supply-air-temperature sensor will be introduced as a sensor offset for a range of 0 to ±4 ºC, applied linearly over a one-week emulation period. The drift can either be positive, i.e., +4 ºC, or negative, i.e., -4 ºC. If a controller maintains the measured supply-air temperature at the set point, a negative sensor offset would result in a decreased actual supply-air temperature. A positive sensor offset would then result in an increased actual supply-air temperature. In addition to drift, a constant bias can also be introduced.

While introducing faults related to sensor drifts and bias, the rest of the AHU system will be operated normally, i.e., the AHU operation will follow the basic AHU operating sequence. However, the faulty temperature-sensor value will be used for controls. At any given time, only one sensor fault will be emulated in the AHU system.

8.2.4 Return-Air Temperature Sensor Drift/Bias (Faults 3 and 4)

Return-air temperature-sensor drift will be introduced as a sensor offset for a range of 0 to ±4 ºC, also applied linearly over a one-week emulation period. The return-air temperature sensor is an input to the economizer control, and it is used to calculate the return-air enthalpy, which is used to control the economizer operation. The effect of negative sensor drift for the return-air temperature with no change to the humidity reading would result in an increased return-air enthalpy. A positive sensor drift for the return-air temperature with no change to the humidity reading would result in a decreased return-air enthalpy. Depending on weather conditions, this fault may cause inappropriate economizer control. In addition to drift, a constant bias can also be introduced.

8.2.5 Mixed-Air Temperature Sensor Drift/Bias (Faults 5 and 6)

The occurrence of sensor drift for the mixed-air-temperature sensor will be introduced as a sensor offset for a range of 0 to ±4 ºC, applied linearly over a one-week emulation period. A negative sensor offset would result in a decreased actual mixed-air temperature and a positive sensor offset would then result in an increased actual mixed-air temperature. In addition to drift, a constant bias can also be introduced.

8.2.6 Outdoor-Air Temperature Sensor Drift/Bias (Faults 7 and 8)

The outdoor-air-temperature sensor drift will be introduced as a sensor offset for a range of 0 to ±4 ºC, also applied linearly over a one-week emulation period. Like return-air, the outdoor-air temperature sensor is an input to the economizer control and is used to calculate the outdoor-air enthalpy, which is used to control the economizer operation. The effect of negative sensor drift for the outdoor-air temperature with no change to the humidity reading would result in an increased outdoor-air enthalpy. A positive sensor drift for the outdoor-air temperature with no change to the humidity reading would result in a decreased outdoor-air enthalpy. Depending on weather conditions, this fault may cause inappropriate economizer control. In addition to drift, a constant bias can also be introduced.

8.2.7 Outdoor-Air Damper Fault (Faults 9, 10, 10a, 10b)

The faults associated with the outdoor-air-damper systems will be introduced by overriding the normal control signal to the dampers with a control signal that would force the motor-driven actuator to the specified position, causing the damper to stay at that position throughout the emulation period.

While emulating the outdoor-air-damper fault, the return-air and the exhaust-air dampers will follow normal operation. The economizer may not be operating correctly because of the fault, the behavior depending on the outdoor-air and indoor-air conditions. The supply-air temperature will also follow normal operations.

8.2.8 Recirculation Air Damper Fault (Faults 15, 16, 18)

The faults associated with recirculation-air (return-air) dampers will be introduced by overriding the normal control signal to the dampers with a control signal that would force the motor-driven actuator to the specified position, causing the damper to stay at that position throughout the emulation period. Three different fault levels can be emulated: stuck closed, 10% leakage, and 40% leakage.

While emulating the recirculation-air-damper fault, the outdoor-air and the exhaust-air dampers will follow normal operation. The economizer may not be operating correctly because of the fault, the behavior depending on the outdoor-air and indoor-air conditions. The supply-air temperature will also follow normal operations.

8.2.9 Cooling Coil Valve Faults (Faults 19, 20, 21, 22)

Cooling-coil-valve faults will be introduced by overriding normal cooling-coil -valve operations with a control signal that would force the motor-driven valve actuator to any of the four different levels: stuck closed, 10% leakage, 25% leakage, and 40% leakage. If the AHU is in the heating mode, the heating-coil-valve signal will be based on normal operation. The damper-control signals and the supply-air-temperature control will also follow normal operations.

8.2.10Heating Coil Valve Faults (Faults 23, 24, 25, 26)

Heating-coil valve faults will be introduced by overriding the normal heating-coil-valve operations with a control signal that will force the motor-driven valve actuator to any of four different levels: stuck closed, 10% leakage, 25% leakage, and 40% leakage. If the AHU is in the cooling mode, the cooling–coil-valve signal will be based on normal operation. The damper-control signals and the supply-air-temperature control will also follow normal operations.

8.2.11 Economizer Control Fault (Fault 31)

This fault will be introduced by reversing the logic used to decide whether the economizer or the minimum ventilation operation should become active. The supply-air-temperature controller will follow normal operations during this test.

8.2.12 Supply-Air Temperature Sensor Failure (Fault 32)

The supply-air-temperature-sensor fault will be introduced by disconnecting the leads to the appropriate sensor terminals on the AHU controller. The damper and economizer operations will follow normal operations.

8.2.13 Return-Air Temperature Sensor Failure (Fault 33)

The return-air-temperature-sensor fault will be introduced by disconnecting the leads to the appropriate sensor terminals on the AHU controller. The damper and economizer operations will follow normal operations.

8.2.14 Mixed-Air Temperature Sensor Failure (Fault 34)

The mixed-air-temperature-sensor fault will be introduced by disconnecting the leads to the appropriate sensor terminals on the AHU controller. The damper and economizer operations will follow normal operations.

8.2.15 Outdoor-Air Temperature Sensor Failure (Fault 35)

The outdoor-air-temperature-sensor fault will be introduced by disconnecting the leads to the appropriate sensor terminals on the AHU controller. The damper and economizer operations will follow normal operations.

8.2.16 Scheduling Fault (Fault 36)

This fault was introduced by changing the normal occupancy schedules and calendars used by the supervisory controllers in the VCBT. The dampers, economizer, and supply-air temperature controller will follow normal operations during the test.

8.3 Potential Faults for Testing the WBE Module

To help configure the simulation models and to design the simulation test bed, the potential faults the WBE module can detected are outlined Table 7. The faults listed in Table 7 can be for any of the end-uses that are being tracked. Using Table 7 as a guide, the team from NIST will configure VCBT/FDD Test Shell to generate faulty data.

Table 7 - List of Potential Faults for Testing the WBE Diagnostic Module

Type of Fault/Problem	Description of the Fault/Problem	Length of the Faulty Operation
Scheduling Problems	When the building is being conditioned when it should not be, the overall energy consumption increases. The WBE module will detect this fault. For example, a fault would be detected if during the training period the building was not conditioned on weekends, but during the test period the building is being conditioned during the weekends.	Depends on the magnitude of the load. Usually, it takes several hours of faulty operation per day to detect this type of a fault.
Excessive use of energy by 5%	Increase or decrease the energy consumption by 5% compared to the consumption during the training period.	Usually several hours of faulty operation each day
Excessive use of energy by 15%	Increase or decrease the energy consumption by 15% compared to the consumption during the training period.	Usually several hours of faulty operation each day
Excessive use of energy by 20%	Increase or decrease the energy consumption by 20% compared to the consumption during the training period.	Usually several hours of faulty operation each day
Excessive use of energy by 25%	Increase or decrease the energy consumption by 25% compared to the consumption during the training period.	Usually several hours of faulty operation each day
Sensor values out of range	If the expected values of any measured quantities both dependent and independent go out of range, the WBE will detect the fault.	Usually several hours of faulty operation each day
Progressively developing a fault during the test period	If the fault develops over a period of time, for example, a gradual deterioration in chiller efficiency that translates to higher electricity consumption over time	Usually requires several days of faulty operation

9 WBD Test Plan

This section specifies how the team plans to verify the data from VCBT/FDD Test Shell and describes the general requirements for the test data and limitations of the two diagnostic modules.

9.1 VCBT/FDD Test Shell Validation Plan

One of the primary objectives of this work is to verify the capability of VCBT/FDD Test Shell to generate both fault-free data and data from faulty operations. Therefore, before the OAE and the WBE modules process the simulated data from faulty operations, the data from the VCBT/FDD Test Shell and the simulation models (for WBE) must be verified and validated. To a large extent, the validation can be accomplished by using graphical tools to view the raw data from the VCBT/FDD Test Shell and the simulation models.

9.1.1 VCBT/FDD Test Shell Validation Process

The process to test the ability of VCBT/FDD Test Shell to generate fault-free data and data corresponding to faulty operations will be accomplished as follows.

1. Specify system, controls and data requirements for the OAE (Battelle).
2. List the potential faults the OAE can detect and diagnose (Battelle).
3. Design VCBT/FDD Test Shell to provide the measured data required for the OAE module (listed in Table 2) (NIST).
4. Design/Modify the VCBT/FDD Test Shell to simulate at least one AHU with a constant air-volume system (NIST).
5. Pick one or more economizer-control strategies (NIST).
6. Generate "clean" fault free data for the selected AHUs and economizer-control strategies. Preferably, the data should span all operating modes of the AHU (heating, cooling, economizer only, economizer and cooling) (NIST).
7. Validate the "clean" data using the WBD and the OAE module (Battelle).
8. Pick a list of faults that will be used in the blind test (list of potential faults are provided in Table 5) (NIST).
9. Modify VCBT/FDD Test Shell to provide the faulty data (NIST).
10. Generate data with faulty operations for the selected systems (NIST).
11. Validate the raw data from faulty operations through the use of graphical tools (NIST and Battelle).

9.2 OAE Plan

In order to detect and diagnose the faults with the ventilation and economizer operations of an AHU, all data listed in the data requirements section (Section 5.5) are needed. In addition, the OAE must be properly configured to identify the type of AHU and the type of economizer controls being employed.

9.2.1 Selection of Systems

As mentioned earlier, the OAE module is capable of detecting and diagnosing faults with CAV systems and VAV systems that do not meter the outdoor-air-flow rate (intake). Therefore, for the blind tests, one to three air-handling systems will be selected with at least one being a CAV system, and the other two either CAV or VAV systems. The OAE has been primarily designed to detect and diagnose faults with constant- volume built-up systems and constant-volume packaged roof-top units. If a VAV system is selected, the outdoor airflow must be ensured to float with the supply-air flow rate (i.e. the outdoor-air flow is not metered).

9.2.2 Selection of Economizer Controls

Again, as mentioned earlier, the OAE module can detect faults with almost all commonly found economizer-control strategies, such as, high-limit (dry-bulb temperature or enthalpy), or differential (dry-bulb temperature or enthalpy). For the test, NIST will pick at least one air handler with high-limit dry-bulb-temperature control, and the other two systems can be any one of the four control strategies mentioned (high-limit dry-bulb temperature, high-limit enthalpy, differential dry-bulb temperature, or differential enthalpy).

9.2.3 Generation of Fault Free Data for the OAE Module

First, NIST will generate "clean" faultless data for all AHUs selected. The data should preferably span all operating modes (Heating, Cooling, Economizing only, Economizing and Cooling). The "clean" data without faults will be processed using the OAE; this will enable verification of the configuration parameters, the dead bands, the sensitivities, and will enable ensuring that the data from the VCBT/FDD Test Shell is as expected. Once the "clean" data from the AHUs are validated using the OAE, it will be ready to accept the faulty data from blind tests.

9.2.4 Generation of Faulty Data for the OAE Module

The OAE module can detect and diagnose a number of faults with ventilation and economizer operations of an AHU as listed in Table 5. Since a number of blind tests with different faults will be created for testing the OAE's detection and diagnostic capabilities, the data from the blind tests should be stored in separate databases, each database representing a single blind test, while each blind test can be for faulty or fault-free operation. As mentioned earlier, some faults take several hours, days and sometimes even months to manifest themselves. Therefore, the faulty operation should persist for the entire period of data collection for a blind test. The length of the faulty operation should be sufficiently long for the fault to manifest.

If the AHU has simultaneous multiple faults (i.e. more than one fault at a time), the OAE module will detect a problem, but may not be able to diagnose the causes of more than one fault simultaneously. Therefore, it is preferable not to have simultaneous multiple faults for the majority of the blind tests. To test the OAE's capabilities when there are multiple simultaneous faults, a blind test with multiple simultaneous faults should be generated. In this case, a different testing process should be used because a multi-step process is employed when the OAE encounters multiple, simultaneous faults. For multiple faults, the OAE is used to detect one fault at a time. That fault is corrected, and the OAE is then run on new data collected after the system was repaired. If other faults remain, the OAE will detect them based on the new data.

9.2.5 OAE Testing Process

The ability of the OAE to detect and diagnose faults will be accomplished as follows:

1. Specify system, controls and data requirements for the OAE (Battelle).
2. List the potential faults the OAE can detect and diagnose (Battelle).
3. Design the VCBT/FDD Test Shell to provide the measured data required for the OAE module (listed in Table 2) (NIST).
4. Design/Modify the VCBT/FDD Test Shell to simulate at least one AHU with a CAV system (NIST).

5. Pick one or more economizer control strategies (preferably one of them will be based on high-limit dry-bulb temperature) (NIST).
6. Configure the WBD to the systems and controls selected (Battelle).
7. Generate "clean" fault-free data for the selected AHUs and economizer-control strategies. Preferably, the data should span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling) (NIST).
8. Validate the "clean" data using the WBD and the OAE module (Battelle).
9. Pick a list of faults that will be used in the blind test (list of potential faults from which to select are provided in Table 5) (NIST).
10. Modify VCBT/FDD Test Shell to provide the faulty data (NIST).
11. Generate fault data for the selected systems (NIST).
12. Process the fault data with the OAE (Battelle).
13. For the dataset with multiple simultaneous faults, it is likely that the OAE will only diagnose one fault (Battelle). After the OAE diagnoses the first fault correctly, another blind test dataset will be created. The new dataset will not contain the fault that was identified; it will only have the other remaining fault (NIST). The new dataset will then be processed with the OAE (Battelle).
14. Evaluate the results (Battelle/NIST).

9.3 WBE Test Plan

Unlike the OAE module, the WBE is independent of the details of the systems and control strategies. The WBE can detect abnormal energy end-use consumption due to improper or faulty operations, and more than one fault can be the cause of the abnormal energy consumption. The current version of the WBE is limited to four end-uses as listed in Table 4. The VCBT can only generate the test data in real time. Given this limitation, it would take a significant amount of time for VCBT to generate necessary training data (6 to 9 months) for the WBE. Therefore, it was decided that the test data (both training and "faulty" data) would be generated using simulation models used by VCBT, but without emulation.

9.3.1 Generation of Fault Free Data for the WBE Module

First, NIST will generate "clean" fault-free data for all energy end-uses selected. The data should preferably cover 6 to 9 months, so that it spans all operating modes (Heating, Cooling, Economizing only, Economizing with Cooling). The "clean" data without faults will be processed using the WBE; this will enable the verification of the configuration parameters, the sensitivities, and also ensure that the data from the simulation models are as expected. In addition, the "clean" data will also serve as the baseline reference model for the WBE. Once the "clean" or fault-free data from the end-uses are validated and baseline models developed using the WBE, the WBE will be ready to accept the faulty data from blind tests.

9.3.2 Generation of Faulty Data for the WBE Module

The WBE module can detect a number of faults with energy end-uses as listed in Table 7. Unlike the blind test data for the OAE module, all data from the blind tests for the WBE should be stored in a single database, because the reference model for detection is common to all faults.

As mentioned earlier, the WBE processes hourly data, but generates the ECI indexes at daily intervals. Therefore, unless the faults or deviations in the energy consumption occur over several hours within a day, the WBE may not be able to detect the deviations (depending on the magnitude of the energy impacts of those faults and the sensitivity setting of the WBE). To test the WBE's capabilities, the blind test data should be created to produce a varying degree of deviation. For example, blind tests should be created that produce 2% deviation is daily energy consumption compared to similar operating conditions in the reference period. Then increase the deviation to 10%, 20%, and 30% for subsequent blind tests. In addition, a fault with gradual degradation in performance or gradual increase or decrease in energy end-use will be created as well.

9.3.3 WBE Testing Process

The process to test the ability of the simulation models to generate fault-free and faulty data and the ability of the WBE to detect faults will be accomplished as follows:

1. Specify data requirements for the WBE (Battelle).
2. List the potential faults the WBE can detect (Battelle).
3. Design the VCBT/FDD Test Shell to provide the measured data required for the WBE module (listed in Table 4) (NIST).
4. Configure the WBD to the systems selected (Battelle).
5. Generate three to six months of "clean" fault-free data for the selected end-uses. Preferably, the data should span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling).
6. Validate the "clean" data using the WBD and also build baseline models for the selected end-uses (Battelle).
7. Pick a list of faults that will be used in the blind test (list of potential faults are provided in Table 7) (NIST).
8. Modify the simulation models to provide the data corresponding to faulty behavior (NIST).
9. Generate data with faulty operation for the selected end-uses (NIST).
10. Process the data for faulty operation with the WBE (Battelle).
11. Evaluate the results (Battelle/NIST).

10 Schedule for Generating Fault-Free and Faulty Data

After reviewing the data requirements for the two WBD modules, NIST will make the necessary modifications to the VCBT/FDD Test Shell and the simulation models.

10.0.1Fault Free

Once the VCBT/FDD Test Shell and the simulation models are tuned, NIST will generate one week of fault-free data for each AHU selected for testing for training, setting thresholds, and verifying the OAE parameters.

10.0.2Fault Data

After the fault-free data has been analyzed, NIST will start generating data for faulty cases. NIST can instigate three different data sets simultaneously. Each data set will be based on operating the VCBT AHUs for three weeks, with a different fault instigated for each AHU. NIST will conduct five runs like this to create a total of 15 data sets.

11 Evaluation Process

An outline of the evaluation process is provided in this section. The following items will be evaluated: 1) the ability to exchange data (initially one way) between BACnet® devices/controllers and the WBD through the VCBT/FDD Test Shell, 2) the ability of the VCBT/FDD Test Shell to simulate data both for both fault-free and faulty operation and 3) the automated diagnostic capabilities of the two WBD diagnostic modules.

For the OAE module, data for faulty operation generated from the blind tests from the VCBT/FDD Test shell will be evaluated two different ways. First, the data will be processed in an automated fashion using the two WBD diagnostic modules. This evaluation process is how a building operator or a building manager would use the tool. The various steps of the evaluation process for items 2 and 3 above will be accomplished as follows:

1. Generate data for faulty operation (NIST).
2. Automatically process the faulty data using the WBE and OAE modules (Battelle).
3. Summarize the results from WBE and the OAE (Battelle).
4. Use semi-automated graphically routines to process the data for faulty operation of air handling units and generate the results (only for OAE) (Battelle).
5. Compare the results from the automatic FDD process and the semi-automated graphically process (Battelle).
6. Report the results from the tests to NIST (Battelle).
7. Compare the faults identified by the WBE and the OAE to the list of faults actually introduced (NIST).
8. If the identified faults do not match the actual, then identify the cause of the difference (NIST/Battelle).
9. Identify the sources of differences between the instigated faults and those detected blindly (e.g., problems with the VCBT/FDD Test Shell or the OAE) (NIST/Battelle).
10. Summarize the findings (NIST/Battelle).

12 References

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