Evaluation of an AHU Fault Detection Scheme Based on Finite State Machine Sequencing Control

Final Report

John E. Seem
Johnson Controls, Inc.
507 East Michigan Street
P.O. Box 423
Milwaukee, WI 53201-0423
Phone: 414-524-4677
E-mail: john.e.seem@jci.com

John M. House
Iowa Energy Center
Energy Resource Station
DMACC, 2006 S. Ankeny Blvd.
Ankeny, IA 50021
Phone: 515-965-7345
E-mail: jhouse@energy.iastate.edu

January, 2007
This page intentionally left blank.
ABSTRACT

Numerous studies in the literature cite the successful application of fault detection and diagnostic methods to simulation and laboratory data from central air-handling units; however, unstable control, a lack of standard control sequences, and data handling challenges have limited their application in the field. This paper describes a new method for integrated control and fault detection of central air-handling units that addresses these challenges found in the field. The method is based on finite state machine sequencing logic and utilizes thirteen residuals that compare measured conditions to model-based expected conditions. The residuals are derived from mass and energy balances applied at specific operating conditions where steady-state conditions are imposed on the air-handling unit by the sequencing logic. For faulty operation, one or more of the residuals is expected to have a value that is significantly different from zero, the expected value for normal operation.

The simulations were of a one-year period and utilized a 2.5 second time step to enable local loop control of the various AHU processes. The faults simulated consisted of the following: 1) Positive and negative offset faults of the supply air temperature, return air temperature, mixed air temperature, and outdoor air temperature; 2) Recirculation air damper stuck open, stuck closed, stuck half-way open; 3) Leakage of the recirculation air damper; 4) Cooling and heating coil valves stuck partially open (faults were simulated individually, not simultaneously); and 6) Leakage of the cooling and heating coil valves (faults were simulated individually, not simultaneously). In all, 16 fault cases were simulated.

With the exception of the return temperature sensor offset faults, at least two of the 13 residuals are noticeably affected by each fault and could be used as the basis for fault detection. In addition, the results indicate that residuals $r_1$ and $r_2$, which require only measurements of the supply air and outdoor air temperatures, may be adequate for detecting all of the damper and valve faults considered, with the exception of the stuck closed recirculation air damper fault. With the addition of return air temperature measurement, residuals $r_3$ and $r_4$ can be calculated and used to detect the stuck closed recirculation air damper fault. The results indicate the residuals enable these common air-handling unit faults to be clearly differentiated from normal operation, although the degree of differentiation will clearly depend on the severity of the fault.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1 Air-Handling Unit System Description</td>
<td>1</td>
</tr>
<tr>
<td>1.1.2 Finite State Machine</td>
<td>2</td>
</tr>
<tr>
<td>1.1.3 Air-Handling Unit Faults</td>
<td>5</td>
</tr>
<tr>
<td>1.1.4 Control Performance Monitor</td>
<td>5</td>
</tr>
<tr>
<td>1.1.5 Fault Detection and Diagnostic Methods</td>
<td>6</td>
</tr>
<tr>
<td>1.1.6 Steady-State Fault Detection System for HVAC Systems</td>
<td>6</td>
</tr>
<tr>
<td>1.1.7 Challenges to Developing a Fault Detection System for HVAC Systems</td>
<td>7</td>
</tr>
<tr>
<td>1.2 Objective</td>
<td>7</td>
</tr>
<tr>
<td>1.3 Report Outline</td>
<td>7</td>
</tr>
<tr>
<td>2 DESCRIPTION OF INTEGRATED CONTROL AND FAULT DETECTION METHOD</td>
<td>8</td>
</tr>
<tr>
<td>2.1 System 1: Supply and Outdoor Air Temperature Sensors</td>
<td>9</td>
</tr>
<tr>
<td>2.1.1 State 1 for System 1</td>
<td>10</td>
</tr>
<tr>
<td>2.1.2 State 2 for System 1</td>
<td>10</td>
</tr>
<tr>
<td>2.1.3 State 3 for System 1</td>
<td>10</td>
</tr>
<tr>
<td>2.1.4 State 4 for System 1</td>
<td>10</td>
</tr>
<tr>
<td>2.1.5 Transition from State 2 to State 3 for System 1</td>
<td>10</td>
</tr>
<tr>
<td>2.1.6 Transition from State 3 to State 2 for System 1</td>
<td>12</td>
</tr>
<tr>
<td>2.2 System 2: Supply, Return and Outdoor Air Temperature Sensors</td>
<td>13</td>
</tr>
<tr>
<td>2.2.1 Transition from State 1 to State 2 for System 2</td>
<td>14</td>
</tr>
<tr>
<td>2.2.2 Transition from State 2 to State 1 for System 2</td>
<td>15</td>
</tr>
<tr>
<td>2.2.3 Transitions from State 2 to State 3 for System 2</td>
<td>16</td>
</tr>
<tr>
<td>2.2.4 Transition from State 3 to State 2 for System 2</td>
<td>16</td>
</tr>
<tr>
<td>2.3 System 3: Supply, Return, Outdoor and Mixed Air Temperature Sensors</td>
<td>16</td>
</tr>
<tr>
<td>2.3.1 State 1 for System 3</td>
<td>17</td>
</tr>
<tr>
<td>2.3.2 State 2 for System 3</td>
<td>18</td>
</tr>
<tr>
<td>2.3.3 State 3 for System 3</td>
<td>19</td>
</tr>
<tr>
<td>2.3.4 State 4 for System 3</td>
<td>20</td>
</tr>
<tr>
<td>2.3.5 Transition from State 1 to State 2 for System 3</td>
<td>21</td>
</tr>
<tr>
<td>2.3.6 Transition from State 2 to State 1 for System 3</td>
<td>21</td>
</tr>
<tr>
<td>2.3.7 Transition from State 2 to State 3 for System 3</td>
<td>21</td>
</tr>
<tr>
<td>2.3.8 Transition from State 3 to State 2 for System 3</td>
<td>21</td>
</tr>
<tr>
<td>2.4 Residual Summary</td>
<td>21</td>
</tr>
<tr>
<td>3 DESCRIPTION OF THE SIMULATION TESTBED</td>
<td>23</td>
</tr>
<tr>
<td>3.1 Supply Air Temperature Control</td>
<td>23</td>
</tr>
<tr>
<td>3.2 Mixing Box Configuration and Control</td>
<td>24</td>
</tr>
<tr>
<td>3.3 Heating Coil</td>
<td>25</td>
</tr>
<tr>
<td>3.4 Design Conditions and Thermophysical Parameters</td>
<td>25</td>
</tr>
<tr>
<td>3.5 Implementation of Faults in Code</td>
<td>25</td>
</tr>
<tr>
<td>3.5.1 Supply Air Temperature Sensor Offset</td>
<td>26</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Single-duct central air-handling unit.</td>
<td>2</td>
</tr>
<tr>
<td>Figure 2</td>
<td>State transition diagram for sequencing the AHU heating coil valve,</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>cooling coil valve, and mixing box dampers.</td>
<td></td>
</tr>
<tr>
<td>Figure 3</td>
<td>Controller output saturated in the no heating position.</td>
<td>4</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Block diagram for steady-state fault detection system.</td>
<td>6</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Overall structure of the integrated control and fault detection system.</td>
<td>8</td>
</tr>
<tr>
<td>Figure 6</td>
<td>State diagram illustrating an action based on a transition.</td>
<td>9</td>
</tr>
<tr>
<td>Figure 7</td>
<td>State transition diagram for integrated control and diagnosis of a single</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>AHU with supply and outdoor air temperature sensors (System 1).</td>
<td></td>
</tr>
<tr>
<td>Figure 8</td>
<td>Control volume used to perform mass and energy balances during the</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>transition between States 2 and 3 (System 1).</td>
<td></td>
</tr>
<tr>
<td>Figure 9</td>
<td>State transition diagram for integrated control and fault detection of a</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>single duct AHU with supply, return and outdoor air temperature sensors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(System 2).</td>
<td></td>
</tr>
<tr>
<td>Figure 10</td>
<td>Control volume used to perform mass and energy balances during the</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>transitions between States 1 and 2 (System 2).</td>
<td></td>
</tr>
<tr>
<td>Figure 11</td>
<td>State transition diagram for integrated control and fault detection of a</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>single duct AHU with supply, return, outdoor and mixed air temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sensors (System 3).</td>
<td></td>
</tr>
<tr>
<td>Figure 12</td>
<td>Control volume used to perform mass and energy balance in States 1, 2</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>and 3 (System 3).</td>
<td></td>
</tr>
<tr>
<td>Figure 13</td>
<td>Control volume used to perform mass and energy balances in State 2 and</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>during transitions between States 2 and 3. (System 3).</td>
<td></td>
</tr>
<tr>
<td>Figure 14</td>
<td>Control volume used to perform mass and energy balances in State 3 and</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>during the transitions between States 2 and 3 (System 3).</td>
<td></td>
</tr>
<tr>
<td>Figure 15</td>
<td>Supply air temperature setpoint profile.</td>
<td>24</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Illustration of sensor offset faults evolving over a three-month period.</td>
<td>26</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Comparison of residuals for normal operation and a supply air temperature</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of -2°C.</td>
<td></td>
</tr>
<tr>
<td>Figure 18</td>
<td>Comparison of residuals for normal operation and a supply air temperature</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of +2°C.</td>
<td></td>
</tr>
<tr>
<td>Figure 19</td>
<td>Comparison of residuals for normal operation and a return air temperature</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of -2°C.</td>
<td></td>
</tr>
<tr>
<td>Figure 20</td>
<td>Comparison of residuals for normal operation and a return air temperature</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of +2°C.</td>
<td></td>
</tr>
<tr>
<td>Figure 21</td>
<td>Comparison of residuals for normal operation and a mixed air temperature</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of -2°C.</td>
<td></td>
</tr>
<tr>
<td>Figure 22</td>
<td>Comparison of residuals for normal operation and a mixed air temperature</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of +2°C.</td>
<td></td>
</tr>
<tr>
<td>Figure 23</td>
<td>Comparison of residuals for normal operation and an outdoor air temperature</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of -2°C.</td>
<td></td>
</tr>
<tr>
<td>Figure 24</td>
<td>Comparison of residuals for normal operation and an outdoor air temperature</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>sensor offset fault of +2°C.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 25  Comparison of residuals for normal operation and operation with the recirculation air damper stuck open
Figure 26  Comparison of residuals for normal operation and operation with the recirculation air damper stuck closed.
Figure 27  Comparison of residuals for normal operation and operation with the recirculation air damper stuck half-way open.
Figure 28  Comparison of residuals for normal operation and operation with the recirculation air damper leakage of 10%.
Figure 29  Comparison of residuals for normal operation and operation with the cooling coil valve stuck 20% open.
Figure 30  Comparison of residuals for normal operation and operation with a cooling coil valve leakage of 3%.
Figure 31  Comparison of residuals for normal operation and operation with the heating coil valve stuck 10% open.
Figure 32  Comparison of residuals for normal operation and operation with a heating coil valve leakage of 3%.
LIST OF TABLES

Table 1  Common faults in AHUs from Yoshida (1996). ................................................................. 5
Table 2  Summary of residuals and conditions for applying residuals. .................................. 22
Table 3  Design conditions and thermophysical parameters. ..................................................... 26
Table 4  Information written to the output file. ........................................................................... 32
Table 5  Summary of achievable outdoor air fraction residual ranges for \( f_{\text{design}} = 0.3 \). .... 35
Table 6  Flow rates for recirculation air damper faults at minimum and 100% outdoor air. ......................................................................................................................... 49
Table 7  Qualitative assessment of residuals impacted by each fault based on median values. ........................................................................................................................................... 59
Table 8  Summary statistics for normal operation and supply air temperature sensor offset faults of -2°C and +2°C. ........................................................................................................... 64
Table 9  Summary statistics for normal operation and return air temperature sensor offset faults of -2°C and +2°C. ........................................................................................................... 65
Table 10 Summary statistics for normal operation and mixed air temperature sensor offset faults of -2°C and +2°C. ......................................................................................................... 66
Table 11 Summary statistics for normal operation and outdoor air temperature sensor offset faults of -2°C and +2°C. ......................................................................................................... 67
Table 12 Summary statistics for normal operation and two faults associated with the recirculation air damper: damper stuck open and damper stuck closed. ....... 68
Table 13 Summary statistics for normal operation and two additional faults associated with the recirculation air damper: damper stuck half-way open and damper leakage of 10%. ......................................................................................................................... 69
Table 14 Summary statistics for normal operation and two cooling coil valve faults: valve stuck at 20% open, and valve leakage of 3%. ................................................................. 70
Table 15 Summary statistics for normal operation and two heating coil valve faults: valve stuck at 10% open, and valve leakage of 3%. ................................................................. 71
1 INTRODUCTION

Over the past decade a significant effort has been made to develop fault detection and diagnostic (FDD) methods and tools for heating, ventilating, and air-conditioning (HVAC) applications. Numerous studies in the literature report methods that have been developed for central air-handling units (e.g., Glass et al. 1994; Haves et al. 1996; Salsbury 1996; Dexter and Benouarets 1996; Lee et al. 1996a, 1996b, 1997; House et al. 1999, 2001; Katipamula et al. 1999; Carling 2002; Norford et al. 2002). In general the methods have been implemented in software applications that process data collected through passive monitoring (i.e., without disrupting the control of the system). Early studies utilized data from simulations or laboratory test rigs. More recently the focus has shifted to testing using data collected in the field. Methods tend to be based on steady-state operating conditions because steady-state behavior is easier to predict and deviations from expected behavior are easier to identify.

While significant progress has been made toward making the methods robust and effective, there are still challenges to be addressed. Requiring that steady-state conditions prevail prior to invoking an FDD method can be problematic because poor control frequently leads to unsteady behavior, thereby limiting the usefulness of the FDD method. Another challenge stems from the lack of standard control sequences for central air-handling units (AHUs), which results in the need to customize FDD methods to accommodate the nuances of individual units. Data handling and storage problems are a frequent challenge as well. Data collected for off-line processing can be difficult to obtain and cumbersome to store.

This report describes a new method for integrated control and fault detection of AHUs that addresses these challenges. The method collects much of the key diagnostic information at times when steady-state conditions are imposed on the AHU by the sequencing logic. This eliminates the need to filter data to identify steady-state conditions. Furthermore, integrating the fault detection method with the control logic eliminates the difficulty associated with understanding an existing control sequence and tailoring an FDD method to that sequence. Finally, by converting raw data into meaningful information within the controller, data handling and storage requirements are minimized.

The remainder of this chapter describes background material developed as part of the Johnson Controls invention disclosure for this method. The background provides an overview of AHUs, the finite state machine sequencing control strategy upon which the integrated control and fault detection method is based, and fault detection and diagnostic methods.

1.1 Background

1.1.1 Air-Handling Unit System Description

Central air-handling units provide conditioned air to rooms. A wide variety of air-handling system designs exist. Sun (1994) describes a variety of constant volume and variable-air-volume air-handling units.
Figure 1 shows a schematic diagram of an AHU. The description of the AHU will be restricted to the components used to maintain the supply air temperature at the setpoint value. Air returns from the conditioned rooms through the return air duct. Depending on the damper settings, the return air may be exhausted or directed from the return air plenum to the mixed air plenum. Air passing from the return air plenum to the mixed air plenum is called recirculated air. In the mixed air plenum, outside air is mixed with recirculated air. The air then passes through the filter, heating coil, cooling coil, and supply fan. The temperatures and flow rates of the outdoor and recirculation air streams determine the conditions at the exit of the mixed air plenum. At most only one of the two coils will be active at any given time assuming the sequencing control strategy is implemented properly and there are no valve leaks or other faults in the system. After being conditioned by the coils, the air is distributed to the zones through the supply air ductwork.

![Figure 1 Single-duct central air-handling unit.](image)

### 1.1.2 Finite State Machine

The air-handling controller in Figure 1 includes a feedback controller (or controllers) to control the heating coil valve, cooling coil valve, and mixing box dampers. The air-handling controller also has control logic to determine the proper component(s) (heating coil, cooling coil, dampers, cooling coil and dampers) to use to maintain the supply air temperature at the setpoint value at any given time. Seem et al. (1999) and ASHRAE (1999) described a new sequencing strategy that saves energy and reduces wear on actuators.
Figure 2 shows a state transition diagram for the new sequencing strategy. The states identified in Figure 2 are described below.

**State 1**

In State 1, feedback control is used to modulate the amount of energy transferred from the heating coil to the air. Common methods for heating air are to use steam, hot water, or electricity. The mixing box dampers are positioned to provide the minimum outdoor airflow rate required for ventilation and the cooling coil valve is closed. The transition to State 2 occurs after the control signal has saturated in the no heating position.

The control signal is considered saturated in the no heating position when it has been continuously at this position for a time period equal to the state transition delay. Figure 3 shows the control signal for the heating coil. At time $t_1$ the control signal goes to the no heating position. The control signal remains at the no heating position until time $t_2$. If $t_2 - t_1$ is less than the state transition delay, then the control signal is not considered saturated in the no heating position. At time $t_3$, the control signal again goes to the no heating position and remains there. The control signal is considered saturated in the no heating position when the current time ($t$) – $t_3$ equals the state transition delay.

**State 2**

**State 2**

**State 3**

**State 4**

Figure 2  State transition diagram for sequencing the AHU heating coil valve, cooling coil valve, and mixing box dampers.
State 2

In State 2, feedback control is used to adjust the position of the mixing box dampers in order to maintain the supply air temperature at the setpoint value. Adjusting the positions of the dampers varies the relative amounts of outdoor air and return air in the supply air stream. In State 2, the heating and cooling coil valves are closed. Transition to State 1 occurs after the control signal for the dampers has been at the minimum outdoor air position for a time period equal to the state transition delay. Transition to State 3 occurs after the control signal for the dampers has been at the 100% outdoor air position for a time period equal to the state transition delay.

State 3

In State 3, feedback control is used to modulate the flow of cold water to the cooling coil, thereby controlling the amount of energy extracted from the air. The mixing box dampers are positioned for 100% outdoor air and the heating coil valve is closed. Transition to State 2 occurs after the control signal for mechanical cooling has been saturated at the no cooling position for a time period equal to the state transition delay. Economizer logic is used to determine the transition to State 4. Either enthalpy-based, temperature-based or combined enthalpy and temperature economizer logic can be used. In the state transition diagram shown in Figure 2, logic based on outdoor air temperature is used to determine the transition point. Transition to State 4 occurs when the outdoor air temperature is greater than the switchover temperature plus the deadband temperature. Typically, the switchover temperature is equal the return air temperature, and the deadband is about 0.56°C. The purpose of the deadband temperature is to prevent cycling from State 3 to State 4 due to noise in the return and outdoor air temperature sensor readings.
State 4

State 4 also uses feedback control to modulate the flow of cold water to the cooling coil, thereby controlling the amount of energy extracted from the air. However, in this case, the mixing box dampers are set at the minimum outdoor air position. Economizer logic is used to determine the transition to State 3. In the state transition diagram shown in Figure 4, transition to State 3 occurs when the outdoor air temperature is less than the switchover temperature.

1.1.3 Air-Handling Unit Faults

Yoshida (1996) lists a number of faults for variable-air-volume (VAV) AHUs. A partial list of those faults is provided in Table 1.

Table 1 Common faults in AHUs from Yoshida (1996).

<table>
<thead>
<tr>
<th>Fault</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td>1. Complete failure</td>
</tr>
<tr>
<td></td>
<td>2. Incorrect reading due to offset, wrong scale or drifting</td>
</tr>
<tr>
<td></td>
<td>3. Excessive noise</td>
</tr>
<tr>
<td>Heating and chilled water valve and actuator</td>
<td>1. Stuck due to mechanical failure or actuator failure or motor failure</td>
</tr>
<tr>
<td></td>
<td>2. Water leakage past a closed valve</td>
</tr>
<tr>
<td>Damper and actuator</td>
<td>1. Stuck open, closed, or in an intermediate position</td>
</tr>
<tr>
<td></td>
<td>2. Incorrect positioning for minimum outdoor air</td>
</tr>
<tr>
<td></td>
<td>3. Air leakage past a closed damper</td>
</tr>
</tbody>
</table>

1.1.4 Control Performance Monitor

Seem et al. (1996) used performance indices based on exponentially weighted moving averages (EWMAs) to detect faults in air-handling units and VAV boxes. The following faults were detected for air-handling units:

- Complete failure of the supply fan;
- Complete failure of the return fan;
- Stuck cooling coil valve;
- Complete failure of the supply air thermocouple;
- Complete failure of the supply airflow station; and
- Complete failure of the return airflow station.

For VAV boxes, performance indices based on EWMAs have been used to detect the
following faults:

- Unstable supply fan control;
- Stuck damper;
- Electric actuator failure; and
- Improperly installed actuator.

### 1.1.5 Fault Detection and Diagnostic Methods

Gertler (1998) breaks the methods of fault detection and diagnosis into two main groups: model-free methods and model-based methods. The model-free methods include approaches based on: 1) physical redundancy where multiple sensors are installed to measure the same physical quantity; 2) special sensors installed for directly detecting and diagnosing faults; 3) limit checking in which process variables are compared to thresholds; 4) spectrum analysis for diagnosing problems; and 5) logic reasoning approaches. There are two main steps involved in model-based fault detection and diagnosis. First, residuals are generated by comparing the process output to observations. Second, the residuals are evaluated to determine if a fault exists and, if so, the cause of the fault.

Sprecher (1993) investigated two approaches for model-based fault detection and diagnostics of HVAC systems. One of the approaches used Kalman filters, and the other approach used a robust observer. Both of these approaches have quite restrictive assumptions about the plant and also about the noise characteristics. Sprecher concluded that these approaches are very powerful if the stringent assumptions can be satisfied.

### 1.1.6 Steady-State Fault Detection System for HVAC Systems

The IEA Annex 25 source book (Hyvärinen and Kärki, 1996) describes a number of fault detection and diagnostic methods for HVAC systems. The majority of the methods are based on analyzing the system after it has reached a steady-state condition. Figure 4 is a block diagram of a steady-state fault detection system. The schematic depicts process data being

![Block diagram for steady-state fault detection system.](image)
input to a filtering algorithm, often referred to as a steady-state detector, where it is analyzed to determine if the system is operating in steady state. If it is, the fault detection system will perform additional analyses to determine if the data represent fault-free or faulty operation. Otherwise the fault detection system issues a command that the system is not in steady state. Non-steady-state operation can be caused by poorly tuned control systems, oversized control valves, or control valves with poor authority. Glass and Gruber (1996) describe a number of methods for detecting steady state operating conditions.

1.1.7 Challenges to Developing a Fault Detection System for HVAC Systems

The HVAC industry is very cost sensitive. Consequently, there are very few sensors installed on HVAC systems. This makes it difficult to detect faults. Adding to the challenge are the nonlinear characteristics of HVAC equipment and time-varying nature of loads. These characteristics make it difficult to determine robust alarm limits that identify real problems and avoid false alarms.

1.2 Objective

This report describes an integrated control and fault detection system for HVAC equipment and presents results obtained through simulation testing of the integrated system applied to a central air-handling system. The method can detect faults in AHUs using the sensors commonly installed in the field today. In addition, faults can also be detected at state transitions when steady-state conditions are imposed on a system that may otherwise be unstable (i.e., control loops may be oscillating due to poor tuning or inadequate valve authority). The method described is capable of detecting a number of common faults in air-handling systems. Following is a partial list of the faults that this method can detect:

- Stuck damper and actuator;
- Ventilation flow too high or low;
- Setting for minimum ventilation position is incorrect;
- Air leakage past closed recirculating damper;
- Water leakage past closed chilled water valve;
- Water (or steam) leakage past closed hot water (or steam) valve;
- Failure of the system to reach setpoint;
- Fouled heat exchanger; and
- Equipment malfunctioning.

1.3 Report Outline

Chapter 2 describes the integrated control and fault detection method and its application to an AHU system with various sensing capabilities. Chapter 3 describes the simulation model used to test the method and Chapter 4 presents results from applying to method to data representing normal operation and a variety of fault conditions. Conclusions and future work are outlined in Chapter 5.
2 DESCRIPTION OF INTEGRATED CONTROL AND FAULT DETECTION METHOD

This report describes a new fault detection system applied to central AHUs with a single duct. Fault detection systems are presented for the following combinations of sensors:

- **System 1.** Supply and outdoor air temperature sensors
- **System 2.** Supply, return and outdoor air temperature sensors
- **System 3.** Supply, return, outdoor and mixed air temperature sensors

Figure 5 shows a block diagram for the overall structure of the integrated control and fault detection system. A finite state machine is used to provide sequential control of the devices. Based on the current state or transition, observations are passed from the finite state machine to the model-based residual generation block. At the same time, control loops are analyzed to identify saturated loops and to calculate values of performance indices. This block determines residuals based on an energy balance of the system. The residuals, saturation status, and performance indices are passed in to the fault analysis block. This block determines if a fault is present. Also, if a fault is present, then the finite state machine may switch the mode of operation to maintain control.

The performance indices described by Seem et al. (1997) should be computed in each state. The fault analysis block in Figure 5 should analyze the residuals, saturation status and performance indices. If the residuals have gone through a significant change, then a fault...
condition exists. Outlier detection methods, such as those described by Rousseeuw and Leroy (1988) or Barnett et al. (1994), can be used to determine if a residual has experienced a significant change. The methods described by Basseville and Nikiforov (1993) can be used to detect abrupt changes in the residuals. Also, upper and lower threshold values for each of the performance indices can be determined from an uncertainty analysis, or laboratory and field tests. A fault exists when a performance index is greater than an upper threshold value or is lower than a lower threshold value. Another alternative for analyzing the residuals is to use statistical quality control methods, such as those described in Grant and Leavenworth (1996) or Montgomery (1996).

The new integrated control and fault detection system uses state machines with actions based on transitions. Figure 6 shows a state diagram with two states. The transition from State 1 to State 2 occurs after the event \( \alpha \), and the transition from State 2 to State 1 occurs after the event \( \beta \). The transition from State 2 to State 1 triggers the action \( S \). The notation “\( \beta/S \)” is from Harel’s (1987) extension of state machines and state charts and indicates that action \( S \) is taken after event \( \beta \).

Details of the integrated control and fault detection system will be presented in the ensuing sections of this chapter for the four systems listed previously; however, the use of control loop saturation status will not be described. Furthermore, the fault tolerant control aspect of the integrated control and fault detection system is not covered in this report.

Figure 6  State diagram illustrating an action based on a transition.

2.1 System 1: Supply and Outdoor Air Temperature Sensors

Figure 7 shows a state transition diagram for the integrated control and fault detection system that uses only supply air and outdoor air temperature sensors. The state transition diagram is similar to the state transition diagram in Figure 2. The four states are controlled in an identical manner. The fault detection method is described below. The method consists of analysis of observations during the transitions between States 2 and 3.
2.1.1 State 1 for System 1

In State 1, a heating coil is controlled to maintain the supply air temperature at setpoint. The dampers are positioned for minimum outdoor air and there is no mechanical cooling.

2.1.2 State 2 for System 1

In State 2, the dampers are used to control the supply air temperature. There is no heating or mechanical cooling.

2.1.3 State 3 for System 1

In State 3, a cooling coil is controlled to maintain the supply air temperature at setpoint. The dampers are positioned for 100% outdoor air and there is no heating.

2.1.4 State 4 for System 1

In State 4, a cooling coil is controlled to maintain the supply air temperature at setpoint. The dampers are positioned for minimum outdoor air and there is no heating.

2.1.5 Transition from State 2 to State 3 for System 1

The outdoor and supply air temperatures are recorded after the damper control signal is saturated in minimum outdoor air position. Compare outdoor & supply air temperatures. If the outdoor air temperature is greater than switchover temperature plus deadband, then the system transitions to State 3 where the cooling coil is used to maintain the supply air temperature.
saturated in the 100% outdoor air position. After the temperatures are recorded, the control switches to State 3. The system should be at nearly steady-state conditions when the damper control signal is saturated in the 100% outdoor air position. Assuming the system is at steady state and performing a mass balance for the dry air entering and leaving the control volume in Figure 8 gives

\[ \dot{m}_o = \dot{m}_s \quad \text{Eq. 1} \]

where \( \dot{m}_o \) is the mass of dry air entering the control volume from the outside and \( \dot{m}_s \) is the mass of dry air leaving the control volume through the supply air duct. Performing a mass balance on the water vapor results in

\[ \dot{m}_o \omega_o = \dot{m}_s \omega_s \quad \text{Eq. 2} \]

where \( \omega_o \) and \( \omega_s \) are the humidity ratios of the outside air and supply air, respectively. Substituting Equation 1 into Equation 2 gives

\[ \omega_o = \omega_s \quad \text{Eq. 3} \]

Performing an energy balance on the control volume with the assumption that the kinetic and potential energy of the air entering and leaving the control volume are the same gives

\[ \dot{m}_o h_o + \dot{W}_{\text{fan}} = \dot{m}_s h_s \quad \text{Eq. 4} \]

Air can be modeled as an ideal gas at the temperatures found in HVAC systems (Kuehn et al., 1998). Using the ideal-gas assumption, the enthalpy of air is

\[ h = c_p T + \omega h_{g0} \quad \text{Eq. 5} \]

where \( c_p \) is the specific heat of the mixture and \( h_{g0} \) is the enthalpy of the water vapor at the

**Figure 8**  Control volume used to perform mass and energy balances during the transition between States 2 and 3 (System 1).
reference state. The specific heat of the mixture is determined from
\[ c_p = c_{pa} + \omega c_{pw} \]  
Eq. 6
where \( c_{pa} \) is the specific heat at constant pressure of dry air and \( c_{pw} \) is the specific heat at constant pressure of water vapor. Substituting Equation 5 into Equation 4 gives
\[ \dot{m}_s \left( c_p T_s + \omega_s h_{g0} \right) + \dot{W}_{fan} = \dot{m}_s \left( c_p T_s + \omega_s h_{g0} \right) \]  
Eq. 7
Substituting Equation 1 and Equation 3 into Equation 7 and solving for the temperature difference between the supply and outdoor air temperatures gives
\[ T_s - T_o = \frac{\dot{W}_{fan}}{\dot{m}_s c_p} \]  
Eq. 8
The temperature difference is due to the energy gained from the fan.

The variables on the right hand side of Equation 8 can be estimated from design data or, in the case of \( c_p \), typical operating conditions. Using the recorded temperatures, after the controller output is saturated in the 100% outdoor air position, a residual is computed using
\[ r_1 = T_{s,2\rightarrow3} - T_{o,2\rightarrow3} = \frac{\dot{W}_{fan}}{\dot{m}_s c_p} \]  
Eq. 9
where \( T_{s,2\rightarrow3} \) and \( T_{o,2\rightarrow3} \) are the recorded supply and outdoor air temperatures at the transition from State 2 to State 3, and the symbol \( \hat{\ } \) over the variables on the right hand side of Equation 8 indicates an estimated value. For normal operating conditions, the residual \( r_1 \) will be nearly equal to zero. The residual may be non-zero for a number of reasons: sensor errors, errors in the estimated values, modeling errors, or faults.

Various methods can be applied to detect faults using the residual \( r_1 \). Two methods are described briefly here. The first method uses upper and lower threshold values. A fault occurs when the residual is greater than an upper threshold value, or is less than a lower threshold value. Further work is required to determine robust threshold values for AHUs that will not cause false alarms. In the second method, the residuals are stored and statistical quality control methods are used to determine when the time series of residuals goes through a significant change. A number of different methods can be used to detect when the residuals have gone through a significant change. For example, outlier detection methods (Rousseeuw and Leroy, 1987; Barnett et al., 1994), methods for detecting abrupt changes (Basseville and Nikiforov, 1993), and methods for statistical quality control (Montgomery, 1996 or Grant and Leavenworth, 1996) could be used.

### 2.1.6 Transition from State 3 to State 2 for System 1

The transition from State 3 to State 2 occurs after the control signal is saturated in the no cooling position. The supply and outdoor air temperatures are recorded and a residual is
determined from

\[ r_2 = T_{r,3-2} - T_{o,3-2} - \frac{\hat{W}_{\text{fan}}}{m_r \bar{c}_p} \]  \hspace{1cm} \text{Eq. 10} \]

Equation 10 was developed in a similar manner to Equation 9.

### 2.2 System 2: Supply, Return and Outdoor Air Temperature Sensors

Figure 9 shows the state transition diagram for the integrated control and fault detection of a single duct AHU with supply, return and outdoor air temperature sensors. The fault detection system for System 2 is identical to System 1, except for the transitions between States 1 and 2.

Between States 1 and 2 the minimum fraction of outdoor air is estimated. The estimated minimum fraction of outdoor air is compared with the design value for the minimum fraction of outdoor air. The equations for estimating the minimum fraction of outdoor air are presented next.

**Figure 9** State transition diagram for integrated control and fault detection of a single duct AHU with supply, return and outdoor air temperature sensors (System 2).
2.2.1 Transition from State 1 to State 2 for System 2

Figure 10 shows a control volume used to perform mass and energy balances during transitions between State 1 and State 2. Performing a mass balance for the dry air entering and leaving the control volume gives

\[ \dot{m}_o + \dot{m}_r = \dot{m}_s \]  

Eq. 11

A mass balance on the water vapor entering and leaving the control volume gives

\[ \dot{m}_o \omega_o + \dot{m}_r \omega_r = \dot{m}_s \omega_s \]  

Eq. 12

Solving Equation 11 for \( \dot{m}_r \) and substituting into Equation Error! Reference source not found. and rearranging yields

\[ \dot{m}_o (\omega_o - \omega_r) = \dot{m}_s (\omega_s - \omega_r) \]  

Eq. 13

Performing a steady-state energy balance on the control volume in Figure 10 gives

\[ \dot{m}_o h_o + \dot{m}_r h_r + \dot{W}_{\text{fan}} = \dot{m}_s h_s \]  

Eq. 14

Substituting Equation 5 into Equation 14 and simplifying using the result in Equation 13 yields

\[ \dot{m}_o c_p (T_o - T_r) = \dot{m}_s c_p (T_s - T_r) - \dot{W}_{\text{fan}} \]  

Eq. 15

Finally, rearranging Equation 15 yields an equation for the fraction of outdoor air (\( f \)) entering the AHU

![Figure 10](control_volume_diagram.png)
between States 1 and 2 (System 2).

\[
f = \frac{\dot{m}_o - T_s - T_r - \left( \frac{\dot{W}_{\text{fan}}}{\dot{m}_s c_p} \right)}{T_o - T_r}
\]

Eq. 12

where the final term in the numerator is the temperature rise across the supply fan. The following equation can be used to estimate the fraction of the outdoor air \( f \) during the transition from State 1 to State 2:

\[
\hat{f}_{1\to2} = \frac{T_{s,1\to2} - T_{r,1\to2} - \left( \frac{\dot{W}_{\text{fan}}}{\dot{m}_s c_p} \right)}{T_{o,1\to2} - T_{r,1\to2}}
\]

Eq. 13

where \( T_{s,1\to2} \), \( T_{r,1\to2} \), \( T_{o,1\to2} \) are the supply, return, and outdoor air temperatures during the transition from State 1 to State 2.

The desired minimum fraction of outdoor air necessary to meet ventilation requirements should be known for design conditions. The actual fraction of outdoor air will be different than the estimated value. Laboratory and field tests or analysis needs to be performed to determine the modeling and sensor errors associated with using Equations 12 and 13. If the desired minimum fraction of outdoor air is significantly different from the estimated fraction of outdoor air after taking sensor and modeling errors into consideration, then the fault analysis should issue a fault indication. The following residual is determined from the desired minimum fraction of outdoor air:

\[
r_3 = f_{\text{design}} - \hat{f}_{1\to2}
\]

Eq. 14

### 2.2.2 Transition from State 2 to State 1 for System 2

The fraction of outdoor air during the transition from State 2 to State 1 can be estimated using

\[
\hat{f}_{2\to1} = \frac{T_{s,2\to1} - T_{r,2\to1} - \left( \frac{\dot{W}_{\text{fan}}}{\dot{m}_s c_p} \right)}{T_{o,2\to1} - T_{r,2\to1}}
\]

Eq. 15

where \( T_{s,2\to1} \), \( T_{r,2\to1} \), \( T_{o,2\to1} \) are the supply, return, and outdoor air temperatures during the transition from State 2 to State 1. Following is a residual based on the estimated minimum fraction outdoor air and the design minimum fraction outdoor air:

\[
r_4 = f_{\text{design}} - \hat{f}_{2\to1}
\]

Eq. 16
Equations 15 and 16 were developed in a similar manner as Equations 13 and 14.

2.2.3 Transitions from State 2 to State 3 for System 2

During transitions from State 2 to State 3, residual $r_i$ is determined using Equation 9.

2.2.4 Transition from State 3 to State 2 for System 2

During transitions from State 3 to State 2, residual $r_2$ is determined using Equation 10.

2.3 System 3: Supply, Return, Outdoor and Mixed Air Temperature Sensors

Figure 11 shows the state transition diagram for the integrated control and fault detection of a single duct AHU with supply, return, outdoor and mixed air temperature sensors. The

Figure 11 State transition diagram for integrated control and fault detection of a single duct AHU with supply, return, outdoor and mixed air temperature sensors (System 3).
following sections describe each state and transition and define additional residuals appropriate for this system.

### 2.3.1 State 1 for System 3

In State 1, the supply air temperature is maintained by controlling the heating coil. An estimate of the fraction of outdoor air entering the AHU is determined from the return, outdoor, and mixed air temperature readings. To estimate the outdoor air fraction, mass and energy balances are performed on the control volume shown in Figure 12. Performing a mass balance on the dry air and water vapor yield

\[ \dot{m}_o + \dot{m}_r = \dot{m}_m \]  
\[ \text{Eq. 17} \]

\[ \dot{m}_o \omega_o + \dot{m}_r \omega_r = \dot{m}_m \omega_m \]  
\[ \text{Eq. 22} \]

Solving Equation 21 for \( \dot{m}_r \) and substituting the result into Equation 22 and rearranging yield

\[ \dot{m}_o (\omega_o - \omega_r) = \dot{m}_m (\omega_m - \omega_r) \]  
\[ \text{Eq. 23} \]

Performing an energy balance on the control volume in Figure 12 yields

\[ \dot{m}_o h_o + \dot{m}_r h_r = \dot{m}_m h_m \]  
\[ \text{Eq. 24} \]

Substituting Equation 5 into Equation 24 and simplifying using the result in Equation 23 yield

\[ \dot{m}_o c_p (T_o - T_r) = \dot{m}_m c_p (T_m - T_r) \]  
\[ \text{Eq. 25} \]

![Figure 12](image-url)  
**Figure 12** Control volume used to perform mass and energy balances in States 1, 2 and 3 (System 3).
Solving for the fraction of outdoor air to mixed air gives

\[
f = \frac{\dot{m}_o}{\dot{m}_m} = \frac{T_m - T_r}{T_o - T_r}
\]

Eq. 26

In State 1, the dampers are positioned to allow the minimum amount of outdoor air required for ventilation. The HVAC engineer should know the desired minimum fraction of outdoor air in the supply air duct. Using this minimum fraction of outdoor air and the measured temperatures in the return air duct, outdoor air duct, and mixed air duct, the following residual is computed:

\[
r_5 = f_{\text{design}} - \frac{T_{m,1} - T_{r,1}}{T_{o,1} - T_{r,1}}
\]

Eq. 27

### 2.3.2 State 2 for System 3

In State 2 the supply air temperature is controlled by modulating the mixing box dampers. No additional energy from the cooling or heating coil is needed to control the supply air temperature at setpoint. A residual is determined in this state by performing a mass and energy balance on the control volume shown in Figure 13. Performing a mass balance on the dry air and water vapor gives

\[
\dot{m}_m = \dot{m}_s
\]

Eq. 28

\[
\dot{m}_m \phi_m = \dot{m}_s \phi_s
\]

Eq. 29

Substituting Equation 28 into Equation 29 gives

\[
\dot{m}_m, \phi_m, \dot{m}_m, \phi_s, \dot{m}_s
\]

\[
T_m, \phi_m, \dot{m}_m, \phi_s, \dot{m}_s
\]

\[
W_{\text{fan}}
\]

\[
T_s, \phi_s, \dot{m}_s
\]

**Figure 13** Control volume used to perform mass and energy balances in State 2 and during transitions between States 2 and 3. (System 3).
Performing an energy balance on the control volume in Figure 13 gives

\[ \dot{m}_m h_m + \dot{W}_{\text{fan}} = \dot{m}_s h_s \]  

Eq. 31

Equation 31 assumes the potential and kinetic energy of the air entering and leaving the control volume are the same. Substituting Equations 5, 28, and 30 into Equation 31 and rearranging results in

\[ T_s - T_m = \frac{\dot{W}_{\text{fan}}}{\dot{m}_r c_p} \]  

Eq. 32

Equation 32 states that the temperature rise between the supply air temperature sensor and the mixed air temperature sensor is due to the energy input from the fan.

While in State 2, the supply and mixed air temperatures are measured and a residual is computed using

\[ r_6 = T_{s,2} - T_{m,2} - \frac{\dot{W}_{\text{fan}}}{\dot{m}_r c_p} \]  

Eq. 33

where \( T_{s,2} \) and \( T_{m,2} \) are the supply air and mixed air temperatures while in State 2.

2.3.3 State 3 for System 3

In State 3, the cooling coil is controlled to maintain the supply air temperature at setpoint. The mixing box dampers are positioned to allow 100% outdoor air into the AHU. Although there should be no recirculation air for this state, the analysis for the control volume in Figure 12 can be used and Equation 27 adapted to the following residual:

\[ r_7 = 1 - \frac{T_{m,3} - T_{r,3}}{T_{r,3} - T_{s,3}} \]  

Eq. 34

where an outdoor air fraction equal to unity is assumed in State 3.

A second residual in State 3 is determined by performing mass and energy balances on the control volume shown in Figure 14. Performing a mass balance for the dry air entering and leaving the control volume in Figure 14 gives

\[ \dot{m}_p = \dot{m}_m \]  

Eq. 35

and performing a mass balance on the water vapor gives

\[ \dot{m}_w \omega_w = \dot{m}_m \omega_m \]  

Eq. 36

Finally, performing an energy balance on the control volume in Figure 14 results in
Figure 14  Control volume used to perform mass and energy balances in State 3 and during the transitions between States 2 and 3 (System 3).

\[ \dot{m}_o h_o = \dot{m}_m h_m \]  

Eq. 37

Equation 37 assumes the kinetic and potential energy of the air entering and leaving the control volume are the same. Substituting Equations 5, 35, and 36 into Equation 37 gives

\[ T_o = T_m \]  

Eq. 38

Equation 38 states that the outdoor air temperature should equal the mixed air temperature while in State 3. Because of sensor errors, modeling errors, or faults the outdoor air temperature may not be equal to the mixed air temperature. A residual for use in fault analysis is computed from

\[ r_8 = T_{o,3} - T_{m,3} \]  

Eq. 39

where \( T_{o,3} \) and \( T_{m,3} \) are the outdoor air and mixed air temperatures while in State 3.

2.3.4 State 4 for System 3

In State 4, the dampers are positioned to allow the minimum amount of outdoor air required for ventilation, and the cooling coil is used to maintain the supply air temperature at setpoint. For this situation, Equation 27 can be adapted to

\[ r_9 = f_{design} \frac{T_{m,4} - T_{r,4}}{T_{o,4} - T_{r,4}} \]  

Eq. 40

Although residuals \( r_5, r_7, \) and \( r_9 \) are based on the same equation, the variances of the residuals will likely be different because the denominator of the term on the right-hand side of the equations for determining the residuals will vary.
2.3.5 Transition from State 1 to State 2 for System 3

During transitions from State 1 to State 2, residual \( r_3 \) is determined using Equation 14.

2.3.6 Transition from State 2 to State 1 for System 3

During transitions from State 1 to State 2, residual \( r_4 \) is determined using Equation 16.

2.3.7 Transition from State 2 to State 3 for System 3

During transitions from State 2 to State 3, residual \( r_1 \) is determined using Equation 9. In addition, mass and energy balances applied to the control volumes in Figure 13 and Figure 14 yield the following residuals:

\[
\begin{align*}
ps_{fan} & = \frac{\hat{W}_{fan}}{m \cdot c_p} \\
ms_{cm} & = \frac{\hat{W}_{fan}}{m \cdot c_p} \\
WT_{Tr} & = \frac{\hat{W}_{fan}}{m \cdot c_p} \\
\end{align*}
\]

Equation 41 was developed in a manner similar to Equation 33, and Equation 42 was developed in a manner similar to Equation 39. Residual \( r_{10} \) could be eliminated since it can be derived by combining residual \( r_1 \) and residual \( r_{11} \), however, it will be retained so that a fault with any of the three temperature sensors (supply air, outdoor air, and mixed air temperature) will affect at least two residuals.

2.3.8 Transition from State 3 to State 2 for System 3

During transitions from State 3 to State 2, residual \( r_2 \) is determined using Equation 10. In addition, the following residuals are defined:

\[
\begin{align*}
ps_{fan} & = \frac{\hat{W}_{fan}}{m \cdot c_p} \\
ms_{cm} & = \frac{\hat{W}_{fan}}{m \cdot c_p} \\
WT_{Tr} & = \frac{\hat{W}_{fan}}{m \cdot c_p} \\
\end{align*}
\]

Residual \( r_{12} \) could be eliminated since it can be derived by combining residual \( r_2 \) and residual \( r_{13} \), however, as in the case of residual \( r_{10} \), it will be retained so that a fault with any of the three temperature sensors (supply air, outdoor air, and mixed air temperature) will affect at least two residuals.

2.4 Residual Summary

Table 2 lists the residuals, the sensor requirements to compute the residuals, and the mode of operation or mode transition for which each residual is applicable.
Table 2  Summary of residuals and conditions for applying residuals.

<table>
<thead>
<tr>
<th>Residual</th>
<th>Sensor Requirements</th>
<th>Conditions When Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1 = T_{s,2} - T_{o,2} - \frac{\hat{W}_{\text{fan}}}{m_s \hat{C}_p}$</td>
<td>$T_s, T_o$</td>
<td>Mode transitions from State 2 to State 3 – valves closed, 100% OA</td>
</tr>
<tr>
<td>$r_2 = T_{s,3} - T_{o,3} - \frac{\hat{W}_{\text{fan}}}{m_s \hat{C}_p}$</td>
<td>$T_s, T_o$</td>
<td>Mode transitions from State 3 to State 2 – valves closed, 100% OA</td>
</tr>
<tr>
<td>$r_3 = f_{\text{design}} - \frac{T_{s,1} - T_{o,1}}{T_{o,1} - T_{s,1}}$</td>
<td>$T_s, T_r, T_o$</td>
<td>Mode transitions from State 1 to State 2 – valves closed, min. OA</td>
</tr>
<tr>
<td>$r_4 = f_{\text{design}} - \frac{T_{s,2} - T_{o,2}}{T_{o,2} - T_{s,2}}$</td>
<td>$T_s, T_r, T_o$</td>
<td>Mode transitions from State 2 to State 1 – valves closed, min. OA</td>
</tr>
<tr>
<td>$r_5 = f_{\text{design}} - \frac{T_{s,3} - T_{o,3}}{T_{o,3} - T_{s,3}}$</td>
<td>$T_s, T_r, T_m$</td>
<td>State 1 – min. OA</td>
</tr>
<tr>
<td>$r_6 = T_{s,2} - T_{o,2} - \frac{\hat{W}_{\text{fan}}}{m_s \hat{C}_p}$</td>
<td>$T_s, T_m$</td>
<td>State 2 – valves closed</td>
</tr>
<tr>
<td>$r_7 = 1 - \frac{T_{s,3} - T_{o,3}}{T_{o,3} - T_{s,3}}$</td>
<td>$T_s, T_o, T_m$</td>
<td>State 3 – 100% OA</td>
</tr>
<tr>
<td>$r_8 = T_{o,3} - T_{s,3}$</td>
<td>$T_o, T_m$</td>
<td>State 3 – 100% OA</td>
</tr>
<tr>
<td>$r_9 = f_{\text{design}} - \frac{T_{o,4} - T_{s,4}}{T_{o,4} - T_{s,4}}$</td>
<td>$T_s, T_o, T_m$</td>
<td>State 4 – min. OA</td>
</tr>
<tr>
<td>$r_{10} = T_{s,2\rightarrow3} - T_{o,2\rightarrow3} - \frac{\hat{W}_{\text{fan}}}{m_s \hat{C}_p}$</td>
<td>$T_s, T_m$</td>
<td>Mode transitions from State 2 to State 3 – valves closed, 100% OA</td>
</tr>
<tr>
<td>$r_{11} = T_{o,2\rightarrow3} - T_{s,2\rightarrow3}$</td>
<td>$T_o, T_m$</td>
<td>Mode transitions from State 2 to State 3 – valves closed, 100% OA</td>
</tr>
<tr>
<td>$r_{12} = T_{s,3\rightarrow2} - T_{o,3\rightarrow2} - \frac{\hat{W}_{\text{fan}}}{m_s \hat{C}_p}$</td>
<td>$T_s, T_m$</td>
<td>Mode transitions from State 3 to State 2 – valves closed, 100% OA</td>
</tr>
<tr>
<td>$r_{13} = T_{o,3\rightarrow2} - T_{s,3\rightarrow2}$</td>
<td>$T_o, T_m$</td>
<td>Mode transitions from State 3 to State 2 – valves closed, 100% OA</td>
</tr>
</tbody>
</table>
3 DESCRIPTION OF THE SIMULATION TESTBED

The simulation testbed developed to test the JCI integrated control and fault detection system is based on component and system models developed in ASHRAE 825-RP A Standard Simulation Testbed for the Evaluation of Control Algorithms and Strategies (Norford and Haves, 1997). Specifically, an HVACSIM+ (Clark, 1977) implementation of models based on idealized flow relationships of a single-duct VAV AHU and the zones it serves was used in this study.

The building and mechanical equipment are described in detail by Norford and Haves (1997) and DeSimone (1995), as are the loads and models developed to simulate the building and equipment. Hence, only significant changes to the simulation model are described here. These changes include replacing the sequencing logic for controlling the supply air temperature, modifying the mixing box configuration and control, and adding a heating coil in the central AHU.

3.1 Supply Air Temperature Control

Supply air temperature control is achieved using the finite state machine sequencing logic implemented in Unit 4 Type 580 (“Types” represent a generic model implementation whereas “Units” represent specific components in the model and are used because the same Type could be implemented multiple times in a system model.). The finite state machine logic is shown in Figure 2. Type 580 replaces the supply air temperature control logic implemented in Type 486 that was used in the ASHRAE 825-RP system models.

The source code in Type 580 was adapted from a previous study that compared the finite state machine sequencing logic to a traditional split-range sequencing control strategy (Seem et al., 1999). Modifications to the model used in Seem et al. (1999) include the following:

1) Calculations necessary for computing the residuals defined in Table 2 were added. This includes logic for monitoring the running time spent in various modes of operation to ensure that residuals are calculated at the appropriate times.

2) Two inputs were added corresponding to the return and outdoor air temperatures. These inputs are necessary to calculate some of the residuals.

3) Three outputs were added corresponding to the absolute value of the change in the controller output to the AHU heating coil valve actuator, the AHU cooling coil valve actuator, and the AHU damper actuator. These values were not used in this study, but can be used in future studies to identify unstable control loops.

4) An output was added for the current mode of operation (heating = 1; cooling with outdoor air = 2; mechanical cooling with 100% outdoor air = 3; and mechanical cooling with minimum outdoor air = 4).
5) Flags were added to signal transitions between modes of operation. These flags are written to the output file and identify the residuals that are applicable at any given time.

The set point for the supply air temperature control strategy is determined by a reset strategy implemented in Unit 7 Type 489 in the ASHRAE 825-RP system model. This strategy was altered to produce a fixed supply air temperature set point of 12.78°C from April 1 through October 31, and a fixed set point of 15.55°C for the remainder of the year. The set point profile is shown graphically in Figure 15.

![Supply Air Temperature Setpoint Profile](image)

**Figure 15** Supply air temperature setpoint profile.

### 3.2 Mixing Box Configuration and Control

The mixing box model consisting of a single modulating damper for outdoor air is implemented in Unit 25 Type 324. Type 324 replaces the mixing box with minimum outdoor air damper model implemented in Type 326 that was used in the ASHRAE 825-RP system models. The control strategy (Unit 2 Type 484) and motor-driven actuator (Unit 14 Type 321) for the minimum damper were also removed from the model.

The other significant change to the mixing box relates to its control, which is implemented in Unit 3 Type 585. In the ASHRAE 825-RP model, Unit 3 Type 485 implemented the control strategy for the modulating outdoor air damper. That model was altered to maintain the outdoor air damper 100% open at all times when the supply fan is running (Seem et al., 2000). In this study, the supply fan ran continuously throughout all simulations. The recirculation air damper modulated between 0 and 65% open and the exhaust air dampers modulated between 35 and 100% open. The recirculation and exhaust air damper positions correspond to how the dampers would be modulated in a traditional mixing box control system with an outdoor air damper minimum position of 35% open.
3.3 Heating Coil

The ASHRAE 825-RP system model does not include a heating coil in the AHU. For this study it was necessary to add a heating coil, heating coil valve, and actuator to the model so that heating coil valve faults could be simulated. The heating coil and three-way heating coil valve are combined into a single component model designated Unit 82 Type 524. The model is identical to the cooling coil and three-way cooling coil valve (implemented as Unit 36 Type 524), although some of the model parameters differ to reflect the fact that the heating coil generally has a smaller capacity than the cooling coil. The model for the motor-driven actuator for the heating coil valve is designated as Unit 83 Type 321 and is identical to the actuator model used for the cooling coil valve.

3.4 Design Conditions and Thermophysical Parameters

Design conditions and thermophysical parameter values are necessary to compute residuals $r_1$, $r_2$, $r_3$, $r_4$, $r_5$, $r_6$, $r_9$, $r_{10}$, and $r_{12}$. The design power and mass flow rate of the supply fan were determined through a numerical experiment in which all zone heating set points were set to 14°C, all cooling set points were set to 16°C, and summertime weather conditions were used. This combination of conditions forced the AHU to provide the maximum airflow rate to all zones. This flow rate and the associated power used by the supply fan were established as two of the design conditions needed for the calculation of the residuals.

The design value of the outdoor air fraction was established under the same operating conditions just described. The dampers were initially controlled such that while the outdoor and exhaust air dampers modulated from 35% open to fully open, the recirculation air damper modulated from 65% open to fully closed. The design outdoor air fraction $f_{\text{design}}$ was determined with the outdoor air damper 35% open and the recirculation air damper 65% open. Later the outdoor air damper control was modified such that it was 100% open during all occupied times; however, the design outdoor air fraction was not recomputed.

The constant pressure specific heat of moist air is given by Equation 6 as $c_p = c_{pa} + \omega c_{pw}$, where $c_{pa}$ is the constant pressure specific heat of dry air, $c_{pw}$ is the constant pressure specific heat of water vapor, and $\omega$ is the humidity ratio of the moist air mixture. For temperatures common in HVAC applications (e.g., 0 to 25°C), $c_{pa} = 1.00$ kJ/kg-K and $c_{pw} = 1.86$ kJ/kg-K are good approximations. Assuming a value of 0.01 kg$_w$/kg$_a$ for the humidity ratio, $c_p = 1.02$ kJ/kg-K. Design conditions and thermophysical parameter values used in this study are listed in Table 3.

3.5 Implementation of Faults in Code

The faults that have been implemented in the HVACSIM code have a thermal impact on the AHU. The faults considered are 1) supply air temperature sensor offset, 2) return air temperature sensor offset, 3) mixed air temperature sensor offset, 4) outdoor air temperature sensor offset, 5) stuck/leaking recirculation air damper, 6) stuck/leaking cooling coil valve,
Table 3  Design conditions and thermophysical parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow Rate of Supply Air</td>
<td>$\dot{m}$</td>
<td>10.53 kg/s</td>
</tr>
<tr>
<td>Supply Fan Power</td>
<td>$\dot{W}_{\text{fan}}$</td>
<td>7.14 kW</td>
</tr>
<tr>
<td>Outdoor Air Fraction</td>
<td>$f_{\text{design}}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Constant Pressure Specific Heat of Moist Air</td>
<td>$\hat{c}_p$</td>
<td>1.02 kJ/kg-K</td>
</tr>
</tbody>
</table>

and 7) stuck/leaking heating coil valve. These faults are representative of the AHU faults identified by Yoshida (1996) and listed in Table 1. The fault implementations are described in terms of changes that were made to HVACSIM$^+$ TYPE routines.

### 3.5.1 Supply Air Temperature Sensor Offset

- Fault Condition: 0°C to +2°C
  - 0°C to -2°C
- HVACSIM$^+$ TYPE 301: Temperature sensor
- HVACSIM$^+$ Unit 55: Supply air temperature sensor
- HVACSIM$^+$ Variable: Parameter 1; offset (input for zero output)

The fault (and all other temperature sensor faults) is introduced by linearly increasing or decreasing the temperature sensor model offset parameter (parameter 1) as time increases. The initial offset is 0°C, increasing to ±2°C over a three month period. The fault conditions corresponding to positive and negative offsets are illustrated in Figure 16.

A positive offset will produce an artificially low sensor reading. That is, if the actual supply air temperature is 15°C and a +2°C offset is imposed via parameter 1 of the model, the sensed temperature will be 13°C. A negative offset will produce an artificially high sensor reading and will lead to cooler supply air temperatures than anticipated.

![Figure 16 Illustration of sensor offset faults evolving over a three-month period.](image_url)
3.5.2 Return Air Temperature Sensor Offset

- Fault Condition: 0ºC to +2ºC
  0ºC to -2ºC
- HVACSIM+ TYPE 301: Temperature sensor
- HVACSIM+ Unit 56: Return air temperature sensor
- HVACSIM+ Variable: Parameter 1; offset (input for zero output)

The fault is introduced as described for the supply air temperature sensor fault.

3.5.3 Mixed Air Temperature Sensor Offset

- Fault Condition: 0ºC to +2ºC
  0ºC to -2ºC
- HVACSIM+ TYPE 301: Temperature sensor
- HVACSIM+ Unit 57: Mixed air temperature sensor
- HVACSIM+ Variable: Parameter 1; offset (input for zero output)

The fault is introduced as described for the supply air temperature sensor fault.

3.5.4 Outdoor Air Temperature Sensor Offset

- Fault Condition: 0ºC to +2ºC
  0ºC to -2ºC
- HVACSIM+ TYPE 301: Temperature sensor
- HVACSIM+ Unit 54: Outdoor air temperature sensor
- HVACSIM+ Variable: Parameter 1; offset (input for zero output)

The fault is introduced as described for the supply air temperature sensor fault.

3.5.5 Stuck Recirculation Air Damper

- Fault Condition: Stuck open, stuck closed, stuck midway
- HVACSIM+ TYPE 321: Motor-driven actuator
- HVACSIM+ Unit 16: Recirculation air damper actuator
- HVACSIM+ Variable: Output 1; position of final control element (0 for stuck closed, 0.65 for stuck open, 0.325 for stuck midway)

As described in Section 3.2, the recirculation damper modulates between fully closed and 65% open. Therefore, the stuck open fault corresponds to the damper fixed at 65% open and the stuck midway fault corresponds to the damper fixed at 32.5% open.
3.5.6 Leaking Recirculation Air Damper

- Fault Condition: 10% of full flow
- HVACSIM\(^+\) TYPE 324: AHU mixing box
- HVACSIM\(^+\) Unit 25: AHU mixing box
- HVACSIM\(^+\) Variable: Parameter 11; leakage for recirculation air damper (0.1 for 10% of full flow)

This fault was implemented by changing the leakage parameter for the recirculation air damper from its normal value of 0.01 to 0.1.

3.5.7 Stuck Cooling Coil Valve

- Fault Condition: Stuck 20% open
- HVACSIM\(^+\) TYPE 321: Motor-driven actuator
- HVACSIM\(^+\) Unit 18: Cooling coil valve actuator
- HVACSIM\(^+\) Variable: Output 1; position of final control element (0.2 for 20% open)

A stuck cooling coil valve fault is implemented by setting the first output variable for the valve actuator equal to 0.2 corresponding to 20% open.

3.5.8 Leaking Cooling Coil Valve

- Fault Condition: 3% of full flow
- HVACSIM\(^+\) TYPE 524: Coil plus three port valve
- HVACSIM\(^+\) Unit 36: Cooling coil plus three port valve
- HVACSIM\(^+\) Variable: Parameter 23; valve leakage (0.03 for 3% of full flow)

A leaking cooling coil valve fault is implemented by changing the leakage parameter for the valve from its normal value of 0.1e-3 to 0.03.

3.5.9 Stuck Heating Coil Valve

- Fault Condition: Stuck 10% open
- HVACSIM\(^+\) TYPE 321: Motor-driven actuator
- HVACSIM\(^+\) Unit 83: Heating coil valve actuator
- HVACSIM\(^+\) Variable: Output 1; position of final control element (0.1 for stuck 10% open)

A stuck heating coil valve fault is implemented by setting the first output variable for the valve actuator equal to 0.1 corresponding to 10% open.
3.5.10 Leaking Heating Coil Valve

- Fault Condition: 3% of full flow
- HVACSIM+ TYPE: 524: Coil plus three port valve
- HVACSIM+ Unit 82: Heating coil plus three port valve
- HVACSIM+ Variable: Parameter 23; valve leakage (0.03 for 3% of full flow)

A leaking heating coil valve fault is implemented by changing the leakage parameter for the valve from its normal value of 0.1e-3 to 0.03 corresponding to 3% of full flow.

3.6 Restrictions on Residual Calculations

One of the key benefits of the integrated control and fault detection method is the fact that residuals are calculated under well controlled conditions. For instance, at state transitions, valves and dampers that would ordinarily be modulating to maintain the supply air temperature at setpoint are maintained in a fixed position. This promotes steady-state operation, minimizing the modeling error associated with using steady-state mass and energy balances in the residuals. It is important to realize, however, that steady-state conditions may not be achieved at the beginning of a transition between states. If the heating valve was open prior to the transition and has just closed (i.e., transition from State 1 to State 2), the water in the heating coil may contain some residual heat that will be transferred to the air passing over the coil. Thus, to further minimize errors in the residual calculations, all residuals associated with state transitions are evaluated just prior to a transition to a new state. Continuing with the example involving a transition from State 1 to State 2, $r_3$ would be computed at the end of the transition period, just prior to the transition to State 2.

Five residuals are calculated while the AHU operates in one of the four states (i.e., heating, cooling with outdoor air, mechanical cooling with 100% outdoor air, and mechanical cooling with minimum outdoor air). In these states, one device is modulating to maintain the supply air temperature at setpoint. In State 1 it is the heating valve, in State 2 it is the mixing box dampers, and in States 3 and 4 it is the cooling valve. This might seem to contradict the assumption that steady-state conditions exist when the residuals are calculated; however, closer inspection of the residuals reveals that all the measurements are either upstream or downstream of the process being used to control the supply temperature in a particular state. For instance, $r_5$ calculates the fraction of outdoor air in State 1 while the heating valve modulates to maintain the supply air temperature at setpoint and the mixing box dampers are positioned for minimum outdoor air. The measurements used in the calculation of $r_5$ are the outdoor air temperature, the return air temperature, and the mixed air temperature, all of which are upstream of the heating coil. Thus, this residual should be unaffected by dynamics associated with the heating coil and should hold whenever the AHU operates fault free in State 1.

The situation is slightly different for residual $r_6$. Residual $r_6$ is calculated in State 2 and uses the supply air temperature. Typically, because no control is provided during state transitions, the supply air temperature will not be at the setpoint value immediately after transitioning to
State 2 from either State 1 or State 3. Thus, as soon as the transition to State 2 is made, the mixing box dampers begin to modulate to try to bring the supply air temperature back to setpoint. The transients associated with this response have been observed to occasionally produce an outlier in the residual \( r_6 \). Therefore, it is recommended to delay the calculation of residual \( r_6 \) for approximately five minutes after the transition to State 2 has been made to allow the mixing box dampers to bring the supply air temperature under control. This five minute delay after a transition to State 2 was not implemented in this study.

Residuals \( r_7 \) and \( r_8 \) are calculated in State 3. When the AHU transitions from State 4 to State 3, the transition in operating mode within the controller is immediate; however, the mixing box dampers may require as much as a minute or more to stroke from minimum outdoor air (State 4) to 100% outdoor air (State 3). Thus, residuals \( r_7 \) and \( r_8 \), which apply to operation with 100% outdoor air (State 3), may not hold immediately after a transition from State 4. Therefore, it is recommended to delay the calculation of residuals \( r_7 \) and \( r_8 \) for approximately five minutes after the transition to State 3 from State 4 to allow the mixing box dampers to move from the minimum outdoor air position to wide open for 100% outdoor air. A similar delay is not necessary after transitions from State 2 to State 3 because the mixing box dampers are positioned for 100% outdoor air in both cases. This five minute delay after the transition to State 3 from State 4 was implemented in this study.

Residual \( r_9 \) is calculated in State 4. For the same reason described in the previous paragraph, it is recommended to delay the calculation of residual \( r_9 \) for approximately five minutes after the transition to State 4 from State 3. This five minute delay after the transition to State 4 from State 3 was implemented in this study.

Residuals \( r_5, r_6, r_7, r_8 \) and \( r_9 \) can be calculated as frequently as desired once the recommended delays corresponding to transitions to a new state have been satisfied. In this study, five minute delays were used. As described above, the delays should be imposed after transitions to State 2 from either State 1 or State 3 (residual \( r_6 \)), after transitions to State 3 from State 4 (residuals \( r_7 \) and \( r_8 \)), and after transitions to State 4 from State 3 (residual \( r_9 \)). After satisfying any applicable delay, the residuals corresponding to a specific operating state were calculated at thirty minute intervals. That is, residual \( r_5 \) was calculated at thirty minute intervals in State 1, residual \( r_6 \) was calculated at thirty minute intervals in State 2, residuals \( r_7 \) and \( r_8 \) were calculated at thirty minute intervals in State 3, and residual \( r_9 \) was calculated at thirty minute intervals in State 4.

### 3.7 Execution of Simulations

The following items describe details concerning the simulations:

1. The heating set point for all zones is 21.11°C and the cooling set point for all zones is 22.22°C.

2. Chicago Typical Meteorological Year (TMY) weather data were used. The ASHRAE 825-RP model uses sol-air temperatures to represent external heat gains by the zones
due to ambient air temperature and insolation. Sol-air temperatures are computed using the analysis, zone descriptions and orientations described by DeSimone (1995). Separate sol-air temperatures are calculated at one-hour intervals for each zone and each zone ceiling plenum. Three FORTRAN programs were used to convert the TMY weather data into sol-air temperatures. Brief descriptions of the programs and a summary of the user input to the programs are provided in Appendix B. A listing of the FORTRAN program SOLAIR.FOR for computing the sol-air temperatures is also provided in Appendix B. The calculations to determine the sol-air temperatures were validated against data tabulated on pages 476-490 of DeSimone (1995). The output of SOLAIR.EXE is the boundary variable file used by HVACSIM+.

3. Initial conditions for all simulations were established from the final conditions obtained by simulating a complete year of operation under normal operating conditions. All simulations correspond to one complete year of operation under either normal conditions or with a fault condition implemented.

4. A 2.5 s time step was used in the simulations.

5. All simulation results presented in this report were obtained with the HVACSIM+ state variable freezing option disabled. Initially, this option, designed to speed the solution of the differential equations in the simulation model, was enabled. Variable freezing was disabled when it was determined that this was producing erroneous values of the residuals.

6. All residuals are written to a file at the following times:

   • Immediately before a mode transition from State 1 to State 2;
   • Immediately before a mode transition from State 2 to State 1;
   • Immediately before a mode transition from State 2 to State 3;
   • Immediately before a mode transition from State 3 to State 2; and
   • At regular intervals of 30 minutes, except in States 3 and 4, where it is also required that the AHU has operated in the current mode for at least 5 minutes. This requirement prevents a situation where residuals are collected at a time when the mixing box dampers are transitioning from 100% outdoor air to minimum outdoor air, or vice versa.

   Flags are also written to the file to indicate which residuals are applicable at any given time. A summary of the information presented in the output file is provided in Table 4.
Table 4  Information written to the output file.

<table>
<thead>
<tr>
<th>Output Column</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>Time in seconds since the beginning of the simulation</td>
</tr>
<tr>
<td>Column 2</td>
<td>Mode of operation (State 1, 2, 3 or 4)</td>
</tr>
<tr>
<td>Columns 3-15</td>
<td>Residuals 1 through 13</td>
</tr>
<tr>
<td>Columns 16-19</td>
<td>Supply, return, outdoor and mixed air temperatures</td>
</tr>
<tr>
<td>Column 20</td>
<td>Flag indicating a transition from State 1 to State 2 (1 = true and 0 = false)</td>
</tr>
<tr>
<td>Column 21</td>
<td>Flag indicating a transition from State 2 to State 1 (1 = true and 0 = false)</td>
</tr>
<tr>
<td>Column 22</td>
<td>Flag indicating a transition from State 2 to State 3 (1 = true and 0 = false)</td>
</tr>
<tr>
<td>Column 23</td>
<td>Flag indicating a transition from State 3 to State 2 (1 = true and 0 = false)</td>
</tr>
<tr>
<td>Columns 24-27</td>
<td>Cumulative time spent in States 1, 2, 3 and 4 since the last mode transition</td>
</tr>
<tr>
<td>Column 28</td>
<td>Parameter representing the delay time used to ensure that sufficient time has been allowed for the mixing dampers to open or close when calculating residuals in States 3 and 4.</td>
</tr>
</tbody>
</table>
4 RESULTS AND DISCUSSION

Results of the simulations described in Chapter 3 are presented below. All 13 residuals from Table 2 were calculated during the simulations to identify the dominant residuals for a system having supply, return, outdoor and mixed air temperature sensors. If one or more of these sensors is not installed, a smaller number of residuals would be available. Recall that the temperature sensor offset faults were introduced gradually, with the offset increasing linearly from zero to the maximum offset after three months of the year. The residuals presented for sensor offset faults were computed only for the final nine months of the year (i.e., after the sensor offset had achieved its maximum value).

4.1 Normal Operation

The residuals for normal operation and a supply air temperature sensor offset fault of -2°C are shown in Figure 17. The upper plot in Figure 17 includes all residuals that compare the calculated outdoor air fraction to an expected value. The residuals are grouped along the y-axis according to the sensors they require. The dimensionless magnitudes of the residuals are shown on the x-axis. The lower plot in Figure 17 consists of the remaining residuals, which are again grouped along the y-axis according to the sensors they require. All the residuals in the lower plot have units of temperature.

Before discussing the results corresponding to faulty operation, residual ranges for normal operation will be considered. The outdoor air fraction in an AHU can vary from 0 to 1. This realization makes it possible to define a range of values for each outdoor air fraction residual that is physically achievable. These ranges are shown in Table 5. Note, however, that the outdoor air fractions in the residuals are computed using temperature measurements and are subject to sensing errors that could produce inaccurate measurements, and modeling errors. Modeling errors could result, for example, from improper placement of the sensors (i.e., accurate measurement, but of the wrong condition), use of a single point measurement device instead of an averaging sensor, and/or failure to account for the possibility of leakage. Thus, residual values outside the ranges defined in Table 5 are possible, even for normal operation. Take, for instance, residual $r_7$, which computes the outdoor air fraction in State 3 when the AHU operates at 100% outdoor air and subtracts this value from unity, the expected value for this operating condition. Note in Figure 17 that $r_7$ has values for normal operation as low as -0.07. This implies that the outdoor air fraction is greater than unity, which is physically impossible. This is a direct result of the fact that the time constant of the outdoor air temperature sensor is an order of magnitude larger than the time constant of the other AHU temperature sensors (supply, return and mixed air). As the outdoor air temperature decreases, the mixed air temperature sensor responds and decreases more quickly than the outdoor air temperature sensor, which is sensing the temperature in the same air stream when the AHU operates with 100% outdoor air. The result is a measured mixed air temperature that is lower

1 Tables of summary statistics for normal operation and all faults are contained in Appendix A. The summary includes the minimum, maximum, median, mean, and standard deviation for each residual.
Figure 17 Comparison of residuals for normal operation and a supply air temperature sensor offset fault of -2°C.
Table 5  Summary of achievable outdoor air fraction residual ranges for $f_{design} = 0.3$.

<table>
<thead>
<tr>
<th>Residual Definition</th>
<th>Normal Residual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% Outdoor Air</td>
</tr>
<tr>
<td>$r_3 = f_{design} - \hat{f}_{1\rightarrow 2}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$r_4 = f_{design} - \hat{f}_{2\rightarrow 1}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$r_5 = f_{design} - \frac{T_{m,1} - T_{r,1}}{T_{o,1} - T_{r,1}}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$r_7 = 1 - \frac{T_{m,3} - T_{r,3}}{T_{o,3} - T_{r,3}}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$r_9 = f_{design} - \frac{T_{m,4} - T_{r,4}}{T_{o,4} - T_{r,4}}$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

than the measured temperature of either the outdoor or the return air streams. Since the model does not account for the different time constants of the temperature sensors, residuals slightly outside the range of physically achievable values can occur.

The difference in the time constants for the outdoor and mixed air temperature sensors also affects the temperature residuals $r_8$, $r_{11}$, and $r_{13}$. Each of these residuals compares the outdoor air temperature to the mixed air temperature at operating conditions corresponding to 100% outdoor air. If there were no leakage through the recirculation air damper and no measurement error, the simulated outdoor and mixed air temperatures would be the same for this condition. Since there is a small amount of leakage for normal operation and the outdoor air temperature is less than the recirculation air temperature when the AHU operates with 100% outdoor air, the mixed air temperature is expected to be slightly greater than the outdoor air temperature. Figure 17 shows that this is the case some of the time, resulting in values for residuals $r_8$ and $r_{11}$ that reach as low as -0.5 and -0.54, respectively, for normal operation. Note that residual $r_{13}$ only reaches -0.23 for normal operation. This residual is calculated during transitions from State 3 to State 2, which are associated with decreasing outdoor air temperatures. As noted in the discussion in the preceding paragraph, in this operating state where both the mixed and outdoor air temperature measurements are of the same air stream, the measured mixed air temperature decreases faster than the measured outdoor air temperature due to the difference in the time constants of the sensors. Thus, the leakage of return air that tends to cause the mixed air temperature to be higher than the outdoor air temperature is countered by this opposite effect, causing the range of residual $r_{13}$ to be shifted to the right in Figure 17 in comparison to residual $r_{11}$. Residual $r_8$ shows the largest variability of the three residuals and ranges from -0.50 to 0.49.
4.2 Supply Air Temperature Sensor Offset

Residual values for a supply air temperature sensor offset fault of -2°C are shown in Figure 17 with the residual values for normal operation. Figure 17 shows that the dominant temperature residuals for a supply air temperature sensor offset fault of -2°C are \( r_5, r_2, r_6, r_{10}, \) and \( r_{12} \). The absolute value of the difference between the median values of these residuals for normal and faulty operation ranges from 2.00 to 2.06°C. The dominant outdoor air fraction residuals are \( r_3 \), and \( r_4 \), for which the median values of the data clusters corresponding to normal and faulty operation differ by 0.12. The magnitudes of all the residuals impacted by the fault are a function of the severity of the fault. Note that all of the dominant residuals correspond to operation when the heating and cooling coil valves are closed. In this operating state, the temperature rise or drop across the two coils should be zero when steady-state conditions prevail, as happens at the end of the state transition delay. Thus, the expected value of the supply air temperature can be easily related to the mixed air temperature and, if the outdoor air dampers are 100% open, to the outdoor air temperature. Residuals \( r_{11} \) and \( r_{13} \) are also computed when the heating and cooling coil valves are closed, however, they utilize sensors that are not affected by this particular fault. If either the heating or cooling coil valve is open (partially or fully), the temperature rise or drop becomes difficult to predict in the absence of a fairly sophisticated model.

The residuals for normal operation and a supply air temperature sensor offset fault of +2°C are shown in Figure 18. The dominant residuals, \( r_1, r_2, r_3, r_4, r_6, r_{10}, \) and \( r_5 \) are the same as those identified for a supply air temperature sensor offset fault of -2°C, although the signs are all reversed. The median values of the dominant outdoor air fraction residuals, \( r_3 \) and \( r_4 \), differ by only 0.08 from normal operation. For an offset of -2°C this difference was 0.12. In addition, \( r_3 \) and \( r_4 \) have tighter data clusters for this case than the case with an offset fault of -2°C. The tighter data clusters result because the denominator in the second term of residuals \( r_3 \) and \( r_4 \) is larger for an offset fault of +2°C compared to an offset fault of -2°C, primarily because of the lower outdoor air temperatures associated with the offset fault of +2°C. The larger denominator makes the residual less sensitive to variations in the numerator of the second term. This same explanation applies to the smaller difference in the median values for normal and faulty operation for the offset fault of +2°C compared to an offset fault of -2°C.

4.3 Return Air Temperature Sensor Offset

The residuals for normal operation and a return air temperature sensor offset fault of -2°C are shown in Figure 19. The dominant residual is \( r_9 \), which ranges in value from -0.014 to 0.057 for normal operation, and from -0.3 to -0.051 for faulty operation. The median values of \( r_9 \) for normal and faulty operation differ by 0.19. The largest differences between the normal and faulty values of \( r_9 \) occur when the outdoor air temperature is closest to the return air temperature; however, it is important to keep in mind that as the difference between the outdoor and return air temperatures decreases, the uncertainty of the outdoor air fraction calculation increases. For this reason, the outdoor air fraction residuals (\( r_1, r_4, r_5, r_7, \), and \( r_9 \) ) are not calculated if the outdoor and return air temperatures differ by less than 5°C. Further consideration of Figure 19 reveals that residuals \( r_3, r_4, \) and \( r_5 \) also vary slightly
Figure 18 Comparison of residuals for normal operation and a supply air temperature sensor offset fault of +2°C.
Figure 19 Comparison of residuals for normal operation and a return air temperature sensor offset fault of -2°C.
from their values for normal operation. The median values for normal and faulty operation for the three residuals differ by 0.06 to 0.07. Finally, the temperature residuals are unaffected by this fault because the return air temperature is not used in their calculation.

The residuals for normal operation and a return air temperature sensor offset fault of +2°C are shown in Figure 20. Once again the dominant residual for this fault is \( r_9 \), which ranges in value from -0.017 to 0.05 for normal operation, and from 0.148 to 0.324 for faulty operation. Residuals \( r_3 \), \( r_4 \), and \( r_5 \) also vary slightly from their values for normal operation. The median values for normal and faulty operation for the three residuals differ by 0.05 to 0.06. The temperature residuals are independent of the return air temperature and, therefore, unaffected by this fault.

4.4 Mixed Air Temperature Sensor Offset

The residuals for normal operation and mixed air temperature sensor offset faults of -2°C and +2°C are shown in Figure 21 and Figure 22, respectively. For these faults, eight of the 13 residuals \( (r_6, r_7, r_8, r_9, r_{10}, r_{11}, r_{12}, \text{ and } r_{13}) \) demonstrate a significant departure from their values for normal operation. The median values of the data clusters for normal and faulty operation differ by 2°C for the temperature residuals \( (r_6, r_8, r_{10}, r_{11}, r_{12}, r_{13}) \) and by approximately 0.28 for the outdoor air fraction residuals \( (r_7 \text{ and } r_9) \). Residual \( r_5 \) is also impacted by the faults. For both faults, its median value for faulty operation differs by approximately 0.08 from its median value for normal operation. These findings reveal that a mixed air temperature sensor offset fault demonstrates symptoms under many operating conditions including State 2, State 3, State 4 and the transitions between States 2 and 3.

4.5 Outdoor Air Temperature Sensor Offset

The residuals for normal operation and outdoor air temperature sensor offset faults of -2°C and +2°C are shown in Figure 23 and Figure 24, respectively. For these faults, residuals \( r_1 \), \( r_2 \), \( r_7 \), \( r_8 \), \( r_9 \), and \( r_{13} \) show a significant departure from their values for normal operation. Each of these residuals is computed when the AHU operates with 100% outdoor air (i.e., either in State 3 or at transitions between States 2 and 3). The median values of the data clusters for normal and faulty operation differ by approximately 2°C for the temperature residuals \( (r_1, r_2, r_7, r_8, r_{13}) \) for both the negative and positive offset faults. The median values of the data clusters for normal and faulty operation for the outdoor air fraction residual \( r_7 \) differ by 0.24 for the -2°C offset fault, and by 0.31 for the +2°C offset fault. The outdoor air fraction residuals \( r_3 \), \( r_4 \), \( r_5 \), and \( r_6 \) are also impacted by the fault; however, the difference in the median values for normal and faulty operation is only 0.07 to 0.08 for residual \( r_5 \) and 0.02 to 0.03 for the other residuals. Furthermore, the data clusters for normal and faulty operation for \( r_5 \) overlap, so the residual will not always be a reliable indicator of the presence of this particular fault.
Figure 20 Comparison of residuals for normal operation and a return air temperature sensor offset fault of $+2^\circ$C.
Figure 21 Comparison of residuals for normal operation and a mixed air temperature sensor offset fault of -2°C.
Figure 22 Comparison of residuals for normal operation and a mixed air temperature sensor offset fault of +2°C.
Figure 23 Comparison of residuals for normal operation and an outdoor air temperature sensor offset fault of -2°C.
Figure 24 Comparison of residuals for normal operation and an outdoor air temperature sensor offset fault of +2°C.
4.6 Stuck Recirculation Air Damper

The residuals for normal operation and three cases with stuck recirculation air damper faults are shown in Figure 25 through Figure 27. To help understand the results for the recirculation air damper faults, simulated air flow rates corresponding to 100% outdoor air and minimum outdoor air are provided in Table 6 for normal operation, three cases with stuck recirculation air damper faults, and a leaking damper fault that will be discussed in Section 4.7. Table 6 also provides values of the control signals and feedback positions for the recirculation and exhaust air dampers, where 0 corresponds to closed and 1 corresponds to fully open. Leakage through the recirculation air dampers can be determined by dividing the recirculation airflow rate by the supply flow rate when the damper position signals indicate the recirculation damper is closed and the exhaust damper is open. All of the results in Table 6 corresponding to 100% outdoor air correspond to the same point in time in the simulation and have supply airflow rates that are essentially the same. In the same way, all the results for minimum outdoor air correspond to the same point in time in the simulation and have supply airflow rates that are essentially the same. Finally, note that the supply airflow rates between the cases with 100% outdoor air and those with minimum outdoor air are different at the selected points in simulation time.

The first set of results is for a stuck open recirculation damper fault and is shown in Figure 25. The residuals affected by the fault are \( r_1, r_2, r_7, r_8, r_{11} \) and \( r_{13} \). All of these residuals are calculated when the control sequence calls for 100% outdoor air and normal operation dictates that the recirculation air damper is closed. For normal operation, Table 6 reveals there is 2% leakage through the recirculation damper when 100% outdoor air is desired and the recirculation damper is closed; however, the stuck open recirculation air damper fault causes mixing of approximately 34% return air and 66% outdoor air when 100% outdoor air is desired. The result is a mixed air temperature that is frequently significantly warmer than expected. With the exception of \( r_7 \), all the residuals affected by the fault are temperature residuals having magnitudes that can exceed 4°C. The two distinct clusters of data points for residuals \( r_1, r_2, r_{11}, \) and \( r_{13} \) result from the two supply air set point temperatures used in the simulation (one set point for the heating season and a second for the cooling season, as shown in Figure 15). Note also that while the magnitude of residual \( r_8 \) frequently exceeds 4°C, this residual, which compares the outdoor and mixed air temperatures during operation in State 3, has a broad range of values and the residual range for normal operation overlaps that for faulty operation. The other dominant residuals have significant gaps between the clusters of data corresponding to normal and faulty operation. The overlap of data clusters for residual \( r_8 \) occurs when the outdoor air temperature approaches the return air temperature, resulting in a mixed air temperature that differs from the outdoor air temperature by a relatively small amount in spite of the presence of the fault. The only outdoor air fraction residual affected by the stuck open recirculation air damper fault is \( r_2 \). Instead of an outdoor air fraction equal to unity, as expected for normal operation, the outdoor air fraction is approximately 0.64. As a result, the median values of the data clusters for normal and faulty operation differ by 0.33.
Figure 25 Comparison of residuals for normal operation and operation with the recirculation air damper stuck open.
Figure 26 Comparison of residuals for normal operation and operation with the recirculation air damper stuck closed.
Figure 27 Comparison of residuals for normal operation and operation with the recirculation air damper stuck half-way open.
Table 6  Flow rates for recirculation air damper faults at minimum and 100% outdoor air.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Control Signal [0,1]</th>
<th>Valve Position [0,1]</th>
<th>Mass Flow Rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Recirc. Damper</td>
<td>Exhaust Damper</td>
<td>Recirc. Damper</td>
</tr>
<tr>
<td>100% OA</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Min. OA</td>
<td>0.65</td>
<td>0.35</td>
<td>0.65</td>
</tr>
<tr>
<td>Recirculation Air Damper Stuck Open</td>
<td>100% OA</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Min. OA</td>
<td>0.65</td>
<td>0.35</td>
<td>0.65</td>
</tr>
<tr>
<td>Recirculation Air Damper Stuck Closed</td>
<td>100% OA</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Min. OA</td>
<td>0.65</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>Recirculation Air Damper Stuck Half-Way Open</td>
<td>100% OA</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Min. OA</td>
<td>0.65</td>
<td>0.35</td>
<td>0.325</td>
</tr>
<tr>
<td>Recirculation Air Damper Leakage (10 %)</td>
<td>100% OA</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Min. OA</td>
<td>0.65</td>
<td>0.35</td>
<td>0.65</td>
</tr>
</tbody>
</table>

The residuals for normal operation and a stuck closed recirculation air damper fault are shown in Figure 26. The dominant residuals are \( r_3 \), \( r_4 \), \( r_5 \), and \( r_6 \). All of these residuals are outdoor air fraction residuals calculated when the control sequence calls for minimum outdoor air, which corresponds to a recirculation air damper positioned fully open for a normally operating system.\(^2\) The stuck closed recirculation air damper results in an outdoor air fraction that is approximately equal to 0.9, instead of the design value of 0.3 (Table 3) that is expected at minimum outdoor air. Thus, as shown in Figure 26, the dominant residuals differ in magnitude by approximately 0.6 from their values for normal operation. The fault cannot be identified using the temperature residuals because, with the exception of \( r_6 \), all of the residuals are calculated when the dampers are positioned for 100% outdoor air (either in State 3, or at a transition from State 2 to State 3 or State 3 to State 2), which corresponds to a closed recirculation damper for normal operation. Residual \( r_6 \) is computed from an energy balance across the coils and supply fan, so the fault does not affect this calculation.

Figure 27 shows the residuals for normal operation and a fault in which the recirculation air damper is stuck half-way open.\(^3\) All of the residuals impacted by the previous two faults (stuck open and stuck closed recirculation air damper faults) are affected by this fault, albeit to a lesser extent. The dominant outdoor air fraction residuals, \( r_3 \), \( r_4 \), \( r_5 \), and \( r_6 \), correspond to operation when the control sequence calls for minimum outdoor air. The fault results in an outdoor air fraction that is approximately equal to 0.59 instead of the design value of 0.3

\(^2\) As described in Section 3.2, the recirculation air damper modulates between 0 and 65% open. Fully open implies the damper was positioned 65% open.

\(^3\) As described in Section 3.2, the recirculation air damper modulates between 0 and 65% open. Half-way open implies the damper was positioned 32.5% open.
(Table 3) that is expected at minimum outdoor air. Residual \( r_7 \), which is calculated when the control sequence calls for 100% outdoor air, also differs noticeably from its value for normal operation; however, there is considerable overlap between the normal and faulty data clusters for this residual and the magnitude of the difference between the median values of the two cluster centers is only 0.1. Thus, the other outdoor air fraction residuals are more reliable indicators of the fault when the damper sticks in this position. As the position at which the recirculation damper sticks gets closer to the full open position, the difference between normal and faulty values of residual \( r_7 \) will increase and those for residuals \( r_3 \), \( r_4 \), \( r_5 \), and \( r_9 \) will decrease.

The dominant temperature residuals in Figure 27 are \( r_1 \), \( r_2 \), \( r_{11} \), and \( r_{13} \). These residuals correspond to operation when the control sequence calls for 100% outdoor air. The median values of the residuals differ from their median values for normal operation by at most 1.03°C. These are relatively small differences compared to the differences observed in Figure 25 corresponding to a stuck open recirculation air damper. The residual magnitudes do not scale linearly with the fault magnitude because the flow rates corresponding to the two faults do not scale linearly. From Table 6 the flow rate through the recirculation damper is approximately 36% of the supply airflow rate when the damper is stuck fully open, but only approximately 12% when the damper is stuck half-way open.

### 4.7 Leaking Recirculation Air Damper

The residuals for normal operation and a leaking recirculation air damper fault are shown in Figure 28. For normal operation, there is 2% leakage through the recirculation damper when it is closed. This leakage fault, produced by setting the damper leakage parameter in the simulation model equal to 10%, causes 16% leakage through the recirculation air damper when it is closed (see Table 5). The fault has symptoms that are similar to the stuck open recirculation air damper fault (see Figure 25). In both cases all of the affected residuals are calculated when the sequencing controller calls for 100% outdoor air (i.e., recirculation air damper should be closed). Air is allowed to recirculate when the control sequence calls for 100% outdoor air, resulting in higher mixed air temperatures than expected and significant deviations of residuals \( r_1 \), \( r_2 \), \( r_7 \), \( r_8 \), \( r_{11} \) and \( r_{13} \) from their values for normal operation. At other operating conditions, the fault is not evident from the residuals.

Although the residuals impacted by the recirculation air damper leakage fault and the stuck open recirculation air damper fault are the same, the magnitudes of the differences in the residuals between normal and faulty operation are less for the leakage fault. The residuals \( r_1 \), \( r_2 \), \( r_{11} \), and \( r_{13} \) have distinct gaps between the normal and faulty data clusters, whereas the clusters almost touch one another for residual \( r_7 \) and they overlap for residual \( r_8 \). Both \( r_7 \) and \( r_8 \) are calculated during operation in State 3. In this operating state, the outdoor air temperature can get as high as 20.5°C, while the return air temperature is approximately 22°C in the simulations. The data points that overlap (or nearly overlap) correspond to situations in which the outdoor and return air temperatures are nearly the same. When this occurs, the mixed air temperature becomes insensitive to the amount of air coming from the two air streams and the faulty data becomes indistinguishable from normal operation.
Figure 28 Comparison of residuals for normal operation and operation with the recirculation air damper leakage of 10%.
4.8 Stuck Cooling Coil Valve

The residuals for normal operation and a stuck cooling coil valve fault are shown in Figure 29. The valve is stuck 20% open, resulting in a constant flow rate of 0.53 kg/s of chilled water through the valve. This is approximately 11% of the flow through the cooling coil when the valve is 100% open. The stuck open valve results in unnecessary and/or excessive mechanical cooling at certain times, and insufficient mechanical cooling at other times. The residuals affected by this fault are \( r_1, r_2, r_3, r_4, r_6, r_{10}, \) and \( r_{12} \). The residuals all correspond to operating conditions for which the cooling coil and heating coil valves are closed (transitions back and forth between State 1 and State 2, State 2, and transitions back and forth between State 2 and State 3). Furthermore, all the residuals affected by the fault are functions of the supply air temperature. Note that the data points for the affected residuals are not clustered in tight groups as they have generally been for the previous faults. This spread in the residuals is due to the variation of the airflow rate across the coil.

Consider, for example, residual \( r_6 \), which is calculated while the AHU operates in State 2. In State 2 the dampers modulate to maintain the supply air temperature at its set point value. As the cooling loads in the zones change, the supply airflow rate adjusts accordingly to modulate the amount of cooling provided by the AHU. For a fixed supply air temperature and constant (or nearly constant) chilled water inlet conditions (temperature and flow rate) to the cooling coil, lower airflow rates lead to larger temperature drops across the cooling coil. Thus, the dampers must modulate to provide mixed air at a temperature that, when coupled with the temperature drop across the cooling coil and temperature rise across the supply fan, will produce the appropriate supply air temperature. For lower airflow rates, higher mixed air temperatures are necessary to produce the appropriate supply air temperature. The final result is that the residual \( r_6 \) becomes more negative as the airflow rate decreases.

The explanation is similar for residuals \( r_3 \) and \( r_4 \), except these residuals are computed using an energy balance that includes the mixing box. In this case, higher outdoor air temperatures are necessary to offset the higher temperature drops across the cooling coil corresponding to lower airflow rates. Note that residuals \( r_3 \) and \( r_4 \) range in magnitude from -0.41 to -1.66. Using a design outdoor air fraction of 0.3, the maximum possible range of the residuals is only 0.3 (corresponding to no outdoor air) to -0.7 (corresponding to 100% outdoor air).

4.9 Leaking Cooling Coil Valve

The residuals for normal operation and a leaking cooling coil valve fault are shown in Figure 30. For this fault, the valve leakage parameter in the simulation model was set to 3%, which produces a leak when the cooling coil valve is commanded closed that is approximately 4.8% of the flow through the cooling coil when the valve is 100% open. By comparison, the normal leakage when the cooling coil valve is commanded closed is essentially zero. The fault produces symptoms that are the same as the stuck cooling coil valve fault considered in Section 4.8. The same seven residuals \( (r_1, r_2, r_3, r_4, r_6, r_{10}, \) and \( r_{12}) \) are impacted by the two faults. All the affected residuals are calculated when the heating
Figure 29 Comparison of residuals for normal operation and operation with the cooling coil valve stuck 20% open.
Figure 30 Comparison of residuals for normal operation and operation with a cooling coil valve leakage of 3%.
coil and cooling coil valves are commanded closed; the fault is not evident under other operating conditions. The primary difference in the results for the two faults is that the magnitudes of the residuals for the leaking cooling coil valve are roughly half the magnitudes of those for the stuck open cooling coil valve. This is a direct consequence of the lower flow rate through the cooling coil associated with the leakage fault (4.8% of maximum flow, compared to 11% for the stuck cooling coil valve fault).

4.10 Stuck Heating Coil Valve

The residuals for normal operation and a stuck heating coil valve fault are shown in Figure 31. The valve is stuck 10% open, resulting in a constant flow rate of 0.09 kg/s of heated water through the valve. This is approximately 47% of the largest flow through the heating coil under normal operating conditions (for normal operation, the control signal to the heating coil never exceeded 30% open). The stuck open valve results in unnecessary and/or excessive heating at certain times, and insufficient heating at other times. The same seven residuals \( r_1, r_2, r_3, r_4, r_5, r_6 \), and \( r_7 \) impacted by the cooling coil valve faults (see Sections 4.8 and 4.9) are affected by the stuck open heating coil valve fault. The residuals all correspond to operating conditions for which the cooling coil and heating coil valves are closed. Furthermore, all the residuals affected are functions of the supply air temperature. The temperature residuals \( r_1, r_2, r_6, r_{10}, \) and \( r_{12} \) range in magnitude from approximately 2 to 4°C, with smaller residuals occurring at higher supply airflow rates. The same phenomenon was observed in Section 4.8 for the stuck cooling coil valve fault; however, for the stuck heating coil valve fault, the temperature rises across the heating coil instead of dropping across the cooling coil. Larger temperature rises occur at lower airflow rates, and the dampers must modulate to provide the appropriate (cooler) inlet conditions to the coils that will compensate for the temperature rise across the heating coil.

The outdoor air fraction residuals impacted by the stuck heating coil valve \( r_1, r_6 \) have magnitudes approximately equal to 0.1 and are computed at transitions between State 1 and State 2 when the AHU operates with minimum outdoor air. As described in the preceding paragraph, lower inlet temperatures to the coils are necessary to compensate for the fault. Since the dampers are fixed in the minimum outdoor air position, the lower inlet conditions are achieved by utilizing colder outdoor air. For normal operation, the outdoor air temperature ranges from approximately -2 to 1.5°C for transitions between State 1 and State 2, whereas it ranges from approximately -6 to -13°C for this fault. Lower outdoor air temperatures cause the magnitude of the denominator of the second term of residuals \( r_1 \) and \( r_6 \) to become larger, so the term becomes smaller and approximately equal to 0.2. Subtracting this value from the design outdoor air fraction yields residual values approximately equal to 0.1. It should also be noted that for this fault there are only 41 data points the entire year corresponding to transitions from State 1 to State 2, and another 41 corresponding to transitions from State 2 to State 1. For normal operation there are 1111 such transitions between State 1 and State 2 and another 1111 between State 2 and State 1.
Figure 31 Comparison of residuals for normal operation and operation with the heating coil valve stuck 10% open.
4.11 Leaking Heating Coil Valve

The residuals for normal operation and a leaking heating coil valve fault are shown in Figure 32. For this fault, the valve leakage parameter in the simulation model was set to 3%, which produces a leak when the heating coil valve is commanded closed that is approximately 35% of the largest flow through the heating coil when the valve operates normally (for normal operation, the control signal to the heating coil never exceeds 30% open). By comparison, the normal leakage when the heating coil valve is commanded closed is essentially zero. The fault produces symptoms that are the same as the stuck heating coil valve fault considered in Section 4.10. The same seven residuals ($r_1$, $r_2$, $r_3$, $r_4$, $r_6$, $r_{10}$, and $r_{12}$) are impacted by the two faults. All the affected residuals are calculated during operating conditions when the heating coil and cooling coil valves are closed. The primary difference in the results for the two faults is that the magnitudes of the residuals for the leaking heating coil valve are approximately 80% of those for the stuck open heating coil valve. This is a direct consequence of the lower flow rate through the heating coil associated with the leakage fault (35% of largest flow for normal operation, compared to 47% of the largest flow for normal operation for the stuck heating coil valve fault).

Residual $r_6$ has one data point with a significantly larger magnitude than the remainder of the data for this fault. As described in Section 3.6, this outlier occurs shortly after a transition to State 2 from State 1 and is due to transients associated with the mixing box dampers responding to a supply air temperature setpoint error. It is recommended that a delay of three to five minutes be implemented prior to calculating residuals in State 2 to avoid these transients.

4.12 Summary of Results

Results for all of the faults considered in this study are summarized in Table 7. The results are summarized in terms of the absolute value of the difference between the median values of residuals for normal and faulty operation. Symbols are used to differentiate residual types (circles represent temperature residuals and squares represent outdoor air fraction residuals) and magnitudes of differences between normal and faulty operation (large symbols indicate large differences). Empty cells in Table 7 indicate that differences in residual values for normal and faulty operation were deemed small relative to other residuals and/or faults. Symbols are defined quantitatively in the legend under Table 7. Table 7 shows that with the exception of the return temperature sensor offset faults, each fault has more than one residual that is impacted and that can be used to detect the fault. In addition, the results indicate that residuals $r_1$ and $r_2$ may be adequate for detecting all of the damper and valve faults considered, except for the stuck closed recirculation air damper fault. Residuals $r_1$ and $r_2$ only require measurements of the supply air and outdoor air temperatures. Finally, with the addition of return air temperature measurement, residuals $r_3$ and $r_4$ can be calculated and used to detect the stuck closed recirculation air damper fault.
Figure 32 Comparison of residuals for normal operation and operation with a heating coil valve leakage of 3%.
Table 7 Qualitative assessment of residuals impacted by each fault based on median values.

<table>
<thead>
<tr>
<th>Valves Closed</th>
<th>Valves Modulating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum Outdoor Air</td>
</tr>
<tr>
<td>$r_1$</td>
<td>$r_2$</td>
</tr>
</tbody>
</table>

- Designates outdoor air fraction residual differences for which $0.1 < \left| \tilde{r}_{i,\text{normal}} - \tilde{r}_{i,\text{fault}} \right| \leq 0.3$, where $i$ is the residual number, $\tilde{r}_{i,\text{normal}}$ is the median value of residual $i$ for normal operation, and $\tilde{r}_{i,\text{fault}}$ is the median value of residual $i$ for faulty operation.
- Designates outdoor air fraction residual differences for which $0.3 < \left| \tilde{r}_{i,\text{normal}} - \tilde{r}_{i,\text{fault}} \right| < 3.0$.
- Designates temperature residual differences for which $1.0 < \left| \tilde{r}_{i,\text{normal}} - \tilde{r}_{i,\text{fault}} \right| \leq 3.0$.
- Designates temperature residual differences for which $3.0 < \left| \tilde{r}_{i,\text{normal}} - \tilde{r}_{i,\text{fault}} \right|$. 


5 CONCLUSIONS AND FUTURE WORK

This report describes a new method for integrated control and fault detection of AHUs. The method utilizes energy balances calculated periodically in each operating state and at transitions between states when steady-state conditions are imposed on the AHU by the finite state machine sequencing logic. The energy balances are used to compute temperature residuals and outdoor air fraction residuals based on AHU temperature sensor measurements available in the field today. For a complete sensor suite that includes the supply, return, outdoor and mixed air temperature sensors, a total of 13 residuals are calculated and are the basis for identifying operational faults.

The utility of the integrated control and fault detection method was assessed through simulations of each of sixteen faults. The simulations were of a one-year period and utilized a 2.5 second time step to enable local loop control of the various AHU processes. Temperature sensor offset faults, stuck and leaking damper faults, and stuck and leaking valve faults were simulated. With the exception of the return temperature sensor offset faults, each fault has more than one of the 13 residuals that is impacted and that can be used as the basis for fault detection. In addition, the results indicate that residuals $r_1$ and $r_2$, which require only measurements of the supply air and outdoor air temperatures, may be adequate for detecting all of the damper and valve faults considered, except for the stuck closed recirculation air damper fault. With the addition of return air temperature measurement, residuals $r_3$ and $r_4$ can be calculated and used to detect the stuck closed recirculation air damper fault.

To avoid calculating residuals during transient periods, it is recommended that a time delay of three to five minutes be implemented after each transition to a new operating state. During this time delay, residuals should not be calculated. For this study, the time delay was only implemented for transitions between State 3 and State 4.

There are several attributes associated with integrating the fault detection method with the finite state machine sequencing logic. This approach eliminates the need for a steady-state detector algorithm and, over time, provides a rich data set collected under very specific operating conditions for which expected operation is well understood. It also eliminates the difficulty associated with understanding an existing control sequence and the engineering necessary to tailor an FDD method to that sequence. Finally, by converting raw data into meaningful information within the controller, data handling and storage requirements are minimized.

The next development step for the integrated control and fault detection method is to enable the automatic detection of faults by establishing thresholds for each residual that separate normal and faulty operation. One way to approach this step is to install the integrated control and fault detection method at a number of field sites that have been commissioned to ensure the proper operation of the AHU. Data can then be collected and used to establish robust statistical ranges for normal operation of each residual.
6 REFERENCES


Haves, P., T. I. Salsbury, and J. A. Wright, “Condition Monitoring in HVAC Subsystems


## A. APPENDIX A: SUMMARY STATISTICS

Table 8 Summary statistics for normal operation and supply air temperature sensor offset faults of -2°C and +2°C.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Normal</strong></td>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
</tr>
</tbody>
</table>

|                  |                 |         |         |        |       |                   |
| **Supply Air Temperature Offset (-2°C)** | 1           | -2.2493 | -2.0018 | -2.1803| -2.1656| 0.0501            |
|                  | 2               | -2.4677 | -2.1459 | -2.2914| -2.3099| 0.0858            |
|                  | 3               | -0.1737 | -0.0999 | -0.1425| -0.1401| 0.0200            |
|                  | 4               | -0.1802 | -0.1051 | -0.1488| -0.1450| 0.0204            |
|                  | 5               | -0.0226 | 0.0224  | -0.0148| -0.0113| 0.0072            |
|                  | 6               | -2.8426 | -2.0503 | -2.2988| -2.2962| 0.0271            |
|                  | 7               | -0.0692 | 0.0770  | 0.0191 | 0.0179 | 0.0137            |
|                  | 8               | -0.4993 | 0.4875  | -0.0878| -0.0950| 0.0856            |
|                  | 9               | -0.0092 | 0.0591  | 0.0349 | 0.0338 | 0.0082            |
|                  | 10              | -2.5269 | -2.1992 | -2.3198| -2.3237| 0.0516            |
|                  | 11              | -0.5040 | 0.0215  | -0.1418| -0.1582| 0.0929            |
|                  | 12              | -2.5636 | -2.0834 | -2.4308| -2.3959| 0.0905            |
|                  | 13              | -0.1678 | 0.3496  | -0.1013| -0.0859| 0.0680            |

|                  |                 |         |         |        |       |                   |
| **Supply Air Temperature Offset (+2°C)** | 1           | 1.7848  | 2.0259  | 1.9272 | 1.9173 | 0.0633            |
|                  | 2               | 1.5510  | 1.9064  | 1.7581 | 1.7684 | 0.0925            |
|                  | 3               | 0.0434  | 0.0569  | 0.0499 | 0.0496 | 0.0027            |
|                  | 4               | 0.0434  | 0.0500  | 0.0478 | 0.0472 | 0.0019            |
|                  | 5               | -0.0169 | -0.0123 | -0.0149| -0.0148| 0.0008            |
|                  | 6               | 1.4176  | 1.9836  | 1.7012 | 1.7012 | 0.0200            |
|                  | 7               | -0.0678 | 0.0787  | 0.0191 | 0.0189 | 0.0120            |
|                  | 8               | -0.5501 | 0.4921  | -0.1157| -0.1215| 0.0968            |
|                  | 9               | -0.0359 | 0.0450  | 0.0157 | 0.0151 | 0.0102            |
|                  | 10              | 1.4176  | 1.7663  | 1.6509 | 1.6558 | 0.0679            |
|                  | 11              | -0.5648 | -0.0479 | -0.2578| -0.2615| 0.1195            |
|                  | 12              | 1.4334  | 1.8760  | 1.6864 | 1.6535 | 0.0994            |
|                  | 13              | -0.1822 | 0.1925  | -0.1358| -0.1148| 0.0711            |
Table 9 Summary statistics for normal operation and return air temperature sensor offset faults of -2°C and +2°C.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normal Return Air Temperature Offset (+2 C)</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normal Return Air Temperature Offset (+2 C)</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.0911</td>
<td>-0.0633</td>
<td>-0.0838</td>
<td>-0.0822</td>
<td>0.0058</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.0915</td>
<td>-0.0709</td>
<td>-0.0868</td>
<td>-0.0853</td>
<td>0.0044</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.0776</td>
<td>-0.0498</td>
<td>-0.0658</td>
<td>-0.0656</td>
<td>0.0070</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-0.0782</td>
<td>0.0822</td>
<td>0.0127</td>
<td>0.0139</td>
<td>0.0115</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.1475</td>
<td>0.3241</td>
<td>0.2506</td>
<td>0.2472</td>
<td>0.0411</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
<td></td>
</tr>
</tbody>
</table>
Table 10  Summary statistics for normal operation and mixed air temperature sensor offset faults of -2°C and +2°C.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
<td></td>
</tr>
<tr>
<td>Mixed Air Temp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset (-2 C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.1145</td>
<td>-0.0693</td>
<td>-0.0953</td>
<td>-0.0952</td>
<td>0.0117</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.4327</td>
<td>1.9875</td>
<td>1.7012</td>
<td>1.7034</td>
<td>0.0232</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-0.4676</td>
<td>-0.1681</td>
<td>-0.2599</td>
<td>-0.2674</td>
<td>0.0555</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.5027</td>
<td>2.4906</td>
<td>1.8978</td>
<td>1.8919</td>
<td>0.0910</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.1683</td>
<td>0.4367</td>
<td>0.3011</td>
<td>0.3042</td>
<td>0.0608</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.4689</td>
<td>1.7835</td>
<td>1.6849</td>
<td>1.6655</td>
<td>0.0666</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.4591</td>
<td>2.0331</td>
<td>1.8240</td>
<td>1.7864</td>
<td>0.1184</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1.4268</td>
<td>1.8868</td>
<td>1.6302</td>
<td>1.6398</td>
<td>0.0912</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1.7709</td>
<td>2.2280</td>
<td>1.8964</td>
<td>1.9091</td>
<td>0.0702</td>
<td></td>
</tr>
<tr>
<td>Mixed Air Temp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset (+2 C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.0397</td>
<td>0.0852</td>
<td>0.0670</td>
<td>0.0661</td>
<td>0.0116</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-2.5673</td>
<td>-2.0125</td>
<td>-2.2988</td>
<td>-2.2966</td>
<td>0.0232</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.1867</td>
<td>0.4613</td>
<td>0.2976</td>
<td>0.3043</td>
<td>0.0571</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-2.4973</td>
<td>-1.5094</td>
<td>-2.1022</td>
<td>-2.1081</td>
<td>0.0910</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-0.4025</td>
<td>-0.0996</td>
<td>-0.2539</td>
<td>-0.2578</td>
<td>0.0693</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-2.5311</td>
<td>-2.2165</td>
<td>-2.3151</td>
<td>-2.3345</td>
<td>0.0666</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-2.5409</td>
<td>-1.9669</td>
<td>-2.1760</td>
<td>-2.2136</td>
<td>0.1184</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-2.5732</td>
<td>-2.1132</td>
<td>-2.3698</td>
<td>-2.3602</td>
<td>0.0912</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-2.2291</td>
<td>-1.7720</td>
<td>-2.1036</td>
<td>-2.0909</td>
<td>0.0702</td>
<td></td>
</tr>
</tbody>
</table>
Table 11  Summary statistics for normal operation and outdoor air temperature sensor offset faults of -2°C and +2°C.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outdoor Air Temperature Offset (-2 C)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7504</td>
<td>2.0235</td>
<td>1.8602</td>
<td>1.8792</td>
<td>0.0569</td>
</tr>
<tr>
<td>2</td>
<td>1.5034</td>
<td>1.8832</td>
<td>1.7264</td>
<td>1.7307</td>
<td>0.0865</td>
</tr>
<tr>
<td>3</td>
<td>-0.0026</td>
<td>0.0158</td>
<td>0.0022</td>
<td>0.0029</td>
<td>0.0035</td>
</tr>
<tr>
<td>4</td>
<td>-0.0023</td>
<td>0.0078</td>
<td>-0.006</td>
<td>0.0000</td>
<td>0.0018</td>
</tr>
<tr>
<td>5</td>
<td>0.0010</td>
<td>0.0196</td>
<td>0.0092</td>
<td>0.0089</td>
<td>0.0034</td>
</tr>
<tr>
<td>6</td>
<td>-0.5678</td>
<td>-0.0305</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0234</td>
</tr>
<tr>
<td>7</td>
<td>0.1527</td>
<td>0.4666</td>
<td>0.2619</td>
<td>0.2728</td>
<td>0.0638</td>
</tr>
<tr>
<td>8</td>
<td>-2.4973</td>
<td>-1.5097</td>
<td>-2.0821</td>
<td>-2.0873</td>
<td>0.0968</td>
</tr>
<tr>
<td>9</td>
<td>-0.1068</td>
<td>-0.0024</td>
<td>-0.0573</td>
<td>-0.0567</td>
<td>0.0206</td>
</tr>
<tr>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td>11</td>
<td>-2.5409</td>
<td>-1.9669</td>
<td>-2.1760</td>
<td>-2.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td>12</td>
<td>-0.5728</td>
<td>-0.1107</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td>13</td>
<td>-2.2291</td>
<td>-1.7721</td>
<td>-2.1036</td>
<td>-2.0909</td>
<td>0.0702</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outdoor Air Temperature Offset (+2 C)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.2495</td>
<td>-1.9765</td>
<td>-2.1404</td>
<td>-2.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td>2</td>
<td>-2.4974</td>
<td>-2.1175</td>
<td>-2.2736</td>
<td>-2.2693</td>
<td>0.0865</td>
</tr>
<tr>
<td>3</td>
<td>-0.0670</td>
<td>-0.0387</td>
<td>-0.0596</td>
<td>-0.0581</td>
<td>0.0060</td>
</tr>
<tr>
<td>4</td>
<td>-0.0678</td>
<td>-0.0476</td>
<td>-0.0631</td>
<td>-0.0618</td>
<td>0.0042</td>
</tr>
<tr>
<td>5</td>
<td>-0.0513</td>
<td>-0.0320</td>
<td>-0.0421</td>
<td>-0.0422</td>
<td>0.0046</td>
</tr>
<tr>
<td>6</td>
<td>-0.5685</td>
<td>-0.0931</td>
<td>-0.2988</td>
<td>-0.2969</td>
<td>0.0223</td>
</tr>
<tr>
<td>7</td>
<td>-0.4245</td>
<td>-0.2113</td>
<td>-0.2886</td>
<td>-0.2957</td>
<td>0.0416</td>
</tr>
<tr>
<td>8</td>
<td>1.5026</td>
<td>2.3801</td>
<td>1.8762</td>
<td>1.8730</td>
<td>0.0891</td>
</tr>
<tr>
<td>9</td>
<td>0.0561</td>
<td>0.1577</td>
<td>0.0905</td>
<td>0.0927</td>
<td>0.0161</td>
</tr>
<tr>
<td>10</td>
<td>-0.5311</td>
<td>-0.2166</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td>11</td>
<td>1.4591</td>
<td>2.0330</td>
<td>1.8236</td>
<td>1.7864</td>
<td>0.1184</td>
</tr>
<tr>
<td>12</td>
<td>-0.5739</td>
<td>-0.1123</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td>13</td>
<td>1.7709</td>
<td>2.2294</td>
<td>1.8964</td>
<td>1.9091</td>
<td>0.0702</td>
</tr>
</tbody>
</table>
Table 12 Summary statistics for normal operation and two faults associated with the recirculation air damper: damper stuck open and damper stuck closed.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
</tr>
<tr>
<td>Recirculation Air Damper Stuck Open</td>
<td>1</td>
<td>2.9853</td>
<td>5.0302</td>
<td>4.5859</td>
<td>4.4140</td>
<td>0.5518</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.7214</td>
<td>4.9483</td>
<td>4.4632</td>
<td>4.2748</td>
<td>0.5725</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0306</td>
<td>-0.0091</td>
<td>-0.0256</td>
<td>-0.0244</td>
<td>0.0042</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0315</td>
<td>-0.0178</td>
<td>-0.0288</td>
<td>-0.0278</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0055</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5062</td>
<td>-0.0150</td>
<td>-0.2988</td>
<td>-0.2962</td>
<td>0.0246</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.2921</td>
<td>0.3898</td>
<td>0.3510</td>
<td>0.3519</td>
<td>0.0075</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-5.3411</td>
<td>-0.4348</td>
<td>-2.5101</td>
<td>-2.6348</td>
<td>1.2261</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0326</td>
<td>0.0500</td>
<td>0.0244</td>
<td>0.0231</td>
<td>0.0092</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5062</td>
<td>-0.2532</td>
<td>-0.3161</td>
<td>-0.3230</td>
<td>0.0436</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-5.4272</td>
<td>-3.3278</td>
<td>-4.8807</td>
<td>-4.7369</td>
<td>0.5566</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5904</td>
<td>-0.2405</td>
<td>-0.3954</td>
<td>-0.3960</td>
<td>0.0922</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-5.3411</td>
<td>-3.2677</td>
<td>-4.8632</td>
<td>-4.6708</td>
<td>0.5464</td>
</tr>
<tr>
<td>Recirculation Air Damper Stuck Closed</td>
<td>1</td>
<td>-0.2426</td>
<td>-0.0056</td>
<td>-0.1361</td>
<td>-0.1258</td>
<td>0.0467</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4999</td>
<td>-0.1130</td>
<td>-0.2770</td>
<td>-0.2701</td>
<td>0.0868</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.6414</td>
<td>-0.5788</td>
<td>-0.6118</td>
<td>-0.6137</td>
<td>0.0113</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.6538</td>
<td>-0.6190</td>
<td>-0.6296</td>
<td>-0.6303</td>
<td>0.0080</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.6302</td>
<td>-0.5527</td>
<td>-0.6004</td>
<td>-0.5998</td>
<td>0.0048</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5508</td>
<td>-0.0552</td>
<td>-0.2975</td>
<td>-0.2974</td>
<td>0.0596</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.697</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0182</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4976</td>
<td>0.4900</td>
<td>-0.0999</td>
<td>-0.1065</td>
<td>0.0897</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.6450</td>
<td>-0.5161</td>
<td>-0.5929</td>
<td>-0.5928</td>
<td>0.0135</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5508</td>
<td>-0.2085</td>
<td>-0.3139</td>
<td>-0.3362</td>
<td>0.0720</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5297</td>
<td>0.0340</td>
<td>-0.1743</td>
<td>-0.2104</td>
<td>0.1125</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5757</td>
<td>-0.1090</td>
<td>-0.3702</td>
<td>-0.3615</td>
<td>0.0913</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2351</td>
<td>0.2275</td>
<td>-0.1044</td>
<td>-0.0914</td>
<td>0.0709</td>
</tr>
</tbody>
</table>
Table 13  Summary statistics for normal operation and two additional faults associated with the recirculation air damper: damper stuck half-way open and damper leakage of 10%.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>-0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
</tr>
<tr>
<td>Recirculation Air Damper Stuck Half-Way</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.4704</td>
<td>1.0363</td>
<td>0.8866</td>
<td>0.8297</td>
<td>0.1691</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.1991</td>
<td>1.0167</td>
<td>0.7043</td>
<td>0.6943</td>
<td>0.1867</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.3153</td>
<td>-0.2767</td>
<td>-0.3055</td>
<td>-0.3032</td>
<td>0.0086</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.3260</td>
<td>-0.2880</td>
<td>-0.3104</td>
<td>-0.3093</td>
<td>0.0059</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.3101</td>
<td>-0.2640</td>
<td>-0.2911</td>
<td>-0.2897</td>
<td>0.0039</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5192</td>
<td>-0.2028</td>
<td>-0.2988</td>
<td>-0.2963</td>
<td>0.0380</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.0381</td>
<td>0.1702</td>
<td>0.1171</td>
<td>0.1170</td>
<td>0.0111</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-1.4379</td>
<td>0.0051</td>
<td>-0.6981</td>
<td>-0.7067</td>
<td>0.2882</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.3109</td>
<td>-0.2068</td>
<td>-0.2656</td>
<td>-0.2650</td>
<td>0.0126</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5102</td>
<td>-0.2223</td>
<td>-0.3111</td>
<td>-0.3311</td>
<td>0.0621</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-1.4997</td>
<td>-0.7079</td>
<td>-1.1759</td>
<td>-1.1608</td>
<td>0.1991</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5905</td>
<td>-0.1311</td>
<td>-0.3611</td>
<td>-0.3692</td>
<td>0.0885</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-1.3358</td>
<td>-0.6118</td>
<td>-1.1358</td>
<td>-1.0634</td>
<td>0.1591</td>
</tr>
<tr>
<td>Recirculation Air Damper Leakage (10%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.7657</td>
<td>1.5587</td>
<td>1.3825</td>
<td>1.3144</td>
<td>0.1962</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.5666</td>
<td>1.5367</td>
<td>1.3119</td>
<td>1.2494</td>
<td>0.2362</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0258</td>
<td>-0.0246</td>
<td>0.0043</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0178</td>
<td>-0.0289</td>
<td>-0.0279</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0045</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.9096</td>
<td>0.1386</td>
<td>-0.2988</td>
<td>-0.2981</td>
<td>0.0390</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.0872</td>
<td>0.2104</td>
<td>0.1600</td>
<td>0.1600</td>
<td>0.0104</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-1.8776</td>
<td>-1.787</td>
<td>-0.9649</td>
<td>-0.9838</td>
<td>0.4066</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0327</td>
<td>0.0501</td>
<td>0.0243</td>
<td>0.0231</td>
<td>0.0092</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5848</td>
<td>-0.2283</td>
<td>-0.3128</td>
<td>-0.3586</td>
<td>0.0976</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-1.9247</td>
<td>-1.0873</td>
<td>-1.7259</td>
<td>-1.6730</td>
<td>0.2128</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5562</td>
<td>-0.1996</td>
<td>-0.3406</td>
<td>-0.3613</td>
<td>0.0866</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-1.8573</td>
<td>-1.0038</td>
<td>-1.6849</td>
<td>-1.6108</td>
<td>0.2178</td>
</tr>
</tbody>
</table>
Table 14  Summary statistics for normal operation and two cooling coil valve faults: valve stuck at 20% open, and valve leakage of 3%.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
</tr>
<tr>
<td>Normal Cooling Coil Valve Stuck Open (20%)</td>
<td>1</td>
<td>-8.9557</td>
<td>-2.1849</td>
<td>-5.7667</td>
<td>-5.7717</td>
<td>1.5698</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-7.7474</td>
<td>-1.9041</td>
<td>-5.3259</td>
<td>-5.1186</td>
<td>1.3973</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-1.6492</td>
<td>-0.4054</td>
<td>-1.0439</td>
<td>-1.0409</td>
<td>0.4247</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-1.6576</td>
<td>-0.4222</td>
<td>-1.0674</td>
<td>-1.0554</td>
<td>0.4291</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0331</td>
<td>0.0356</td>
<td>-0.0149</td>
<td>-0.0121</td>
<td>0.0069</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-9.3343</td>
<td>-2.2545</td>
<td>-6.5291</td>
<td>-6.7142</td>
<td>1.1694</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0616</td>
<td>0.0495</td>
<td>0.0134</td>
<td>0.0134</td>
<td>0.0137</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.3678</td>
<td>0.4840</td>
<td>-0.0639</td>
<td>-0.0658</td>
<td>0.0767</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.0358</td>
<td>0.0759</td>
<td>0.0563</td>
<td>0.0563</td>
<td>0.0038</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-9.3343</td>
<td>-2.4469</td>
<td>-5.9481</td>
<td>-5.9611</td>
<td>1.5782</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.4098</td>
<td>-0.0266</td>
<td>-0.1830</td>
<td>-0.1895</td>
<td>0.0791</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-7.7882</td>
<td>-1.6821</td>
<td>-5.3987</td>
<td>-5.1566</td>
<td>1.3955</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.1634</td>
<td>0.3000</td>
<td>-0.0492</td>
<td>-0.0380</td>
<td>0.0741</td>
</tr>
<tr>
<td>Normal Cooling Coil Valve Leakage (3%)</td>
<td>1</td>
<td>-3.4563</td>
<td>-1.1790</td>
<td>-3.0848</td>
<td>-2.9831</td>
<td>0.4867</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-3.3167</td>
<td>-1.1727</td>
<td>-3.1092</td>
<td>-2.9112</td>
<td>0.4324</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.6683</td>
<td>-0.1602</td>
<td>-0.2517</td>
<td>-0.3474</td>
<td>0.1853</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.6869</td>
<td>-0.1565</td>
<td>-0.2471</td>
<td>-0.3532</td>
<td>0.1887</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0244</td>
<td>0.0185</td>
<td>-0.0148</td>
<td>-0.0128</td>
<td>0.0050</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-4.6544</td>
<td>-1.2200</td>
<td>-3.4405</td>
<td>-3.3709</td>
<td>0.3714</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0696</td>
<td>0.0779</td>
<td>0.0190</td>
<td>0.0170</td>
<td>0.0150</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4417</td>
<td>0.4905</td>
<td>-0.0786</td>
<td>-0.0849</td>
<td>0.0842</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0326</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0091</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-3.8959</td>
<td>-1.3752</td>
<td>-3.3363</td>
<td>-3.2351</td>
<td>0.5018</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.4426</td>
<td>-0.0415</td>
<td>-0.2507</td>
<td>-0.2520</td>
<td>0.0775</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-3.3459</td>
<td>-1.1371</td>
<td>-3.1394</td>
<td>-2.9393</td>
<td>0.4488</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.1411</td>
<td>0.3512</td>
<td>-0.0437</td>
<td>-0.0280</td>
<td>0.0851</td>
</tr>
</tbody>
</table>
Table 15  Summary statistics for normal operation and two heating coil valve faults: valve
stuck at 10% open, and valve leakage of 3%.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Residual Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-0.2496</td>
<td>0.0235</td>
<td>-0.1398</td>
<td>-0.1208</td>
<td>0.0569</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.4970</td>
<td>-0.1168</td>
<td>-0.2736</td>
<td>-0.2694</td>
<td>0.0865</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-0.0310</td>
<td>-0.0091</td>
<td>-0.0257</td>
<td>-0.0247</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.0317</td>
<td>-0.0175</td>
<td>-0.0288</td>
<td>-0.0280</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0174</td>
<td>-0.0042</td>
<td>-0.0149</td>
<td>-0.0145</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-0.5673</td>
<td>-0.0125</td>
<td>-0.2988</td>
<td>-0.2966</td>
<td>0.0232</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0185</td>
<td>0.0129</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.4973</td>
<td>0.4906</td>
<td>-0.1022</td>
<td>-0.1081</td>
<td>0.0910</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0172</td>
<td>0.0501</td>
<td>0.0244</td>
<td>0.0232</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.5311</td>
<td>-0.2165</td>
<td>-0.3151</td>
<td>-0.3345</td>
<td>0.0666</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5409</td>
<td>0.0331</td>
<td>-0.1760</td>
<td>-0.2136</td>
<td>0.1184</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-0.5732</td>
<td>-0.1132</td>
<td>-0.3698</td>
<td>-0.3602</td>
<td>0.0912</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.2291</td>
<td>0.2280</td>
<td>-0.1036</td>
<td>-0.0909</td>
<td>0.0702</td>
</tr>
<tr>
<td>Heating Coil Valve Stuck Open (10%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.7021</td>
<td>4.4220</td>
<td>4.2699</td>
<td>4.0615</td>
<td>0.3772</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.1361</td>
<td>4.3740</td>
<td>4.0832</td>
<td>3.9533</td>
<td>0.4047</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.9980</td>
<td>0.1065</td>
<td>0.1010</td>
<td>0.1015</td>
<td>0.0018</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.1000</td>
<td>0.1022</td>
<td>0.1010</td>
<td>0.1011</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0162</td>
<td>-0.0128</td>
<td>-0.0150</td>
<td>-0.0147</td>
<td>0.0008</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.1854</td>
<td>4.1971</td>
<td>3.8448</td>
<td>3.8154</td>
<td>0.2765</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0692</td>
<td>0.0780</td>
<td>0.0191</td>
<td>0.0189</td>
<td>0.0109</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.6016</td>
<td>0.4902</td>
<td>-0.1374</td>
<td>-0.1422</td>
<td>0.0124</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0332</td>
<td>0.0511</td>
<td>0.0246</td>
<td>0.0237</td>
<td>0.0097</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.3078</td>
<td>4.1425</td>
<td>3.9383</td>
<td>3.8009</td>
<td>0.3604</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.6041</td>
<td>-0.0780</td>
<td>-0.2345</td>
<td>-0.2605</td>
<td>0.0917</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>2.1967</td>
<td>4.1603</td>
<td>3.8738</td>
<td>3.7474</td>
<td>0.3772</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.3378</td>
<td>0.1870</td>
<td>-0.2111</td>
<td>-0.2059</td>
<td>0.0649</td>
</tr>
<tr>
<td>Heating Coil Valve Leakage (3%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.0645</td>
<td>3.4524</td>
<td>3.3026</td>
<td>3.1508</td>
<td>0.2937</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.5991</td>
<td>3.3578</td>
<td>3.1180</td>
<td>3.0353</td>
<td>0.3086</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0768</td>
<td>0.0805</td>
<td>0.0788</td>
<td>0.0786</td>
<td>0.0012</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0791</td>
<td>0.0808</td>
<td>0.0798</td>
<td>0.0799</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-0.0168</td>
<td>-0.0123</td>
<td>-0.0149</td>
<td>-0.0147</td>
<td>0.0009</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.6587</td>
<td>4.8194</td>
<td>2.9314</td>
<td>2.9082</td>
<td>0.2290</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-0.0698</td>
<td>0.0781</td>
<td>0.0191</td>
<td>0.0189</td>
<td>0.0113</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-0.5653</td>
<td>0.4904</td>
<td>-0.1292</td>
<td>-0.1352</td>
<td>0.1001</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-0.0331</td>
<td>0.0507</td>
<td>0.0244</td>
<td>0.0235</td>
<td>0.0095</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.6816</td>
<td>3.1825</td>
<td>3.0586</td>
<td>2.8950</td>
<td>0.2890</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-0.5882</td>
<td>-0.0293</td>
<td>-0.2415</td>
<td>-0.2558</td>
<td>0.0953</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>1.6687</td>
<td>3.2453</td>
<td>2.9571</td>
<td>2.8465</td>
<td>0.2880</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-0.3364</td>
<td>0.1836</td>
<td>-0.2037</td>
<td>-0.1889</td>
<td>0.0717</td>
</tr>
</tbody>
</table>
B. APPENDIX B: SOURCE CODE FOR RESIDUAL IMPLEMENTATION

The source code for TYPE580.FOR is provided below. The code implements the integrated control and fault detection method, including all thirteen residuals defined in Chapter 3 of this report.

**********************************************************************
*                                                           *
* SUBROUTINE TYPE580(XIN,OUT,PAR,SAVED,IOSTAT)               *
*                                                           *
* New Sequencing Control Strategy (NSCS) for air handling units *
*                                                           *
* Created:    July 11, 1995  Cheol Park, NIST                 *
* Revised:    March 14, 1997                                 *
*             Reset the wait time counting if a significant deviation *
*             of a signal level from zero occurs before the wait time  *
*             elapses.                                          *
* Revised:    April 25, 1997                                 *
*             Damper control scaled.                           *
* Revised:    May 15, 1997                                   *
*             Initial state = 2, reset_level = 1.0             *
* Revised:    March 1, 2001                                  *
*             New output added for mode of operation           *
* Revised:    May 31, 2001                                   *
*             JCI Residuals added                             *
* Revised:    February 14, 2006                              *
*             JCI Residuals reordered (J. House)               *
*             See Seem and House "Evaluation of an AHU Fault Detection   *
*             Scheme Based on Finite State Machine Sequencing Control"
*                                                           *
* C----------------------------------------------------------------------
* C                                                           *
* INPUTS:                                                       *
* C xin(1) = supply air temperature sensor                     *
* C xin(2) = supply air temperature setpoint                   *
* C xin(3) = return air temperature sensor                     *
* C xin(4) = outdoor air temperature sensor                    *
* C xin(5) = mixed air temperature sensor                      *
* C xin(6) = changeover temperature for economizer             *
* C xin(7) = supply fan status (1 = on, 0 = off)               *
* C                                                           *
* OUTPUTS:                                                      *
* C out(1) = controller output for AHU HC valve actuator (0-1)  *
* C out(2) = controller output for AHU CC valve actuator (0-1)  *
* C out(3) = controller output for AHU damper actuator (0-1)    *
* C out(4) = abs. value of change in controller output for AHU HC valve actuator (0-1)  *
* C out(5) = abs. value of change in controller output for AHU CC valve actuator (0-1)  *
* C out(6) = abs. value of change in controller output for AHU damper actuator (0-1)  *
* C out(7) = AHU mode of operation (1,2,3,4)                    *
* C                                                           *
* PARAMETERS:                                                  *
* C par(1) = hc proportional gain (%/C)                        *
* C par(2) = hc integral time (s)                              *
* C par(3) = cc proportional gain (%/C)                        *
* C par(4) = cc integral time (s)                              *
* C par(5) = da proportional gain (%/C)                        *
* C par(6) = da integral time (s)                              *
* C par(7) = reschedule time (s)                              *
* C par(8) = number of times entered in sequence table          *
* C----------------------------------------------------------------------
par(9) = da_min: minimum damper opening
par(10) = da_max: maximum damper opening
par(11) = T_dead: temperature dead zone (C)
par(12) = t_wait: state_wait_time (s)
par(13) = eps: control signal tolerance

SAVED:
saved(1) = time of previous call
saved(2) = time of previous controller execution
saved(3) = time of previous sample
saved(4) = hc integral term from previous call
saved(5) = hc integral term from previous sample
saved(6) = hc output from previous call
saved(7) = hc output from previous sample
saved(8) = cc integral term from previous call
saved(9) = cc integral term from previous sample
saved(10) = cc output from previous call
saved(11) = cc output from previous sample
saved(12) = da integral term from previous call
saved(13) = da integral term from previous sample
saved(14) = da output from previous call
saved(15) = da output from previous sample
saved(16) = istate from previous call
saved(17) = istate from previous sample

*****************************************************************************

common /chrono/ time, tstep, ttime, tmin, itime
common /fault/ id_fault, idoloop_fault
real, dimension(7) :: xin
real, dimension(7) :: out
real, dimension(13) :: par
real, dimension(20) :: saved
integer, dimension(7) :: iostat
real, dimension(13) :: resid
integer :: control_state, istate, system_status
character (len=80) :: state_1_txt, state_2_txt, state_3_txt,
&                   state_4_txt,
&                   c1_up_txt, c2_down_txt, c2_up_txt,
&                   c3_down_txt, c3_up_txt, c4_down_txt
real :: reset_level = 1.0
integer :: tran_12, tran_21, tran_23, tran_32
real :: time_in_state1, time_in_state2,
&       time_in_state3, time_in_state4,
&       res_wait
real :: time_sat_hc, time_sat_cc, time_sat_dan,
&       time_sat_dax

data Pfan_des, Wsup_des, cp_des, cpa, f_des /7.14, 10.52, 1.02, 1.0, 0.3/
namelist /debug/ time, istate, control_state, u_hc, u_cc, u_da

state_1_txt = "HC Control, Min. OA, No Mech. Cooling"
state_2_txt = "Damper Control, No Heating, No Mech. Cooling"
state_3_txt = "CC Control, Max. OA, No Heating"
state_4_txt = "CC Control, Min. OA, No Heating"
c1_up_txt = "Control signal for HC saturated in no heating"
c2_down_txt = "Control signal for DA saturated in MIN"
c2_up_txt = "Control signal for DA saturated in MAX"
c3_down_txt = "Control signal for CC saturated in no cooling"
c3_up_txt = "T_oa > T_chg + T_dead"
c4_down_txt = "T_oa < T_chg - T_dead"
Tsa = xin(1) ! inputs
Tset = xin(2)
Tra = xin(3)
Toa = xin(4)
Tma = xin(5)
Tchg = xin(6)
system_status = nint(xin(7)) ! nearest integer

propg_hc = par(1) ! parameters
tint_hc = par(2)
propg_cc = par(3)
tint_cc = par(4)
propg_da = par(5)
tint_da = par(6)
rsec = par(7)
nseq = nint(par(8))
da_min = par(9)
da_max = par(10)
Tdead = par(11)
t_wait = par(12)
eps = par(13)
!
write(13,204) itime
INITIAL: if (itime <= 1) then
     do i = 1, 20
        saved(i) = 0.0
     end do
! **********************************
saved(16) = 1 ! Initial istate
! Changed 5/17/06 by J House
! *****************************
time_sat_hc = 0.0
time_sat_cc = 0.0
time_sat_dax = 0.0
time_sat_dan = 0.0
abs_del_uhc = 0.0
abs_del_ucc = 0.0
abs_del uda = 0.0
tran_12 = 0
tran_21 = 0
tran_23 = 0
tran_32 = 0
time_ln_state1 = 0.0
time_ln_state2 = 0.0
time_ln_state3 = 0.0
time_ln state4 = 0.0
! *****************************
res_wait = 0.0 ! Set to 0 initially since initial state is 1
! Changed 5/17/06 by J House
! *****************************
! if (id_fault == 0) then
| do i = 1,13
|  resid(i) = 0.0
| end do
| else
|  resid(1) = -0.1327
|  resid(2) = -0.3329
|  resid(3) = -0.0266
|  resid(4) = -0.0293
|  resid(5) = -0.015
|  resid(6) = -0.2875
|  resid(7) = -0.0218
|  resid(8) = 0.1542
|  resid(9) = 0.0087
|  resid(10) = -0.3127
|  resid(11) = -0.18
|  resid(12) = -0.1787
|  resid(13) = 0.1542
| end if
write(13,200)time,control_state,(resid(i),i=1,13),
& Tsa,Tra,Toa,Tma,
& tran_12,tran_21,tran_23,tran_32,
& time_in_state1,time_in_state2,
& time_in_state3,time_in_state4,
& res_wait

end if INITIAL

time_old  = saved(1)               ! old time
istate    = saved(16)

! time step change and system is on
TIME_CHANGE: if( time > saved(1) .and. system_status ==1) then
  do i = 2,16,2
    saved(i+1) =saved(i)         ! shift storage
  end do
  pid_i_term_hc  = saved(5)       ! get old pid integral term
  u_old_hc       = saved(7)       ! get old control output
  u_hc           = u_old_hc
  pid_i_term_cc  = saved(9)
  u_old_cc       = saved(11)
  u_cc           = u_old_cc
  pid_i_term_da  = saved(13)
  u_old_da       = saved(15)
  u_da           = u_old_da
  istate         = nint(saved(17))
  v_old_hc       = saved(18)
  v_old_cc       = saved(19)
  v_old_da       = saved(20)
  control_state  = istate

NSCS_CONTROL: select case (control_state)

  case (1)    !== State 1 ======================================
    call pid3(Tsa,Tset,0.0,0.0,0,1, propg_hc,tint_hc,0.0,
      pid_i_term_hc,0.0,u_old_hc,0.,rsec,nseq, u_hc, 1)
    call lu_limit(u_hc, 0.0, 1.0) ! bound of control signal
    call lscale (0.0, 1.0, 0.0, 1.0, 1, u_hc, v) ! 4/25/97
    v_hc = max(0.0,min(v,1.0))       ! limit control signal
    tran_12 = 0
    tran_21 = 0
    tran_23 = 0
    tran_32 = 0
    time_in_state1 = time_in_state1 + (time - time_old)
    time_in_state2 = 0.0
    time_in_state3 = 0.0
    time_in_state4 = 0.0

C ********************************************************************************
C
C The following residual (Residual 5) is calculated in State 1
C
C Residual 5: Equation 27 of Seem & House report
resid(5) = f_des - (Tma - Tra)/(Toa - Tra)
if (time - (int(time/1800)*1800.0) <= 0.01) then
  write(13,200)time,control_state,(resid(i),i=1,13),
  & Tsa,Tra,Toa,Tma,
  & tran_12,tran_21,tran_23,tran_32,
  & time_in_state1,time_in_state2,
  & time_in_state3,time_in_state4,
& res_wait
end if

! Check if control signals are saturated
if (abs(v_hc) < eps) then
  if (time_sat_hc >= t_wait) then
    end if

C **********************************************************************
C
C The following residual (Residual 3) is calculated at transitions
C from State 1 to State 2
C
C Estimate the fraction of outdoor air during the transition from state 1
to state 2
f_meas = (cpa*(Tsa - Tra) - (Pfan_des/Wsup_des))/
        (cpa*(Toa - Tra))
C Residual 3: Equation 18 of Seem & House report
resid(3) = f_des - f_meas
tran_12 = 1
write(13,200)time,control_state,(resid(i),i=1,13),
& Tsa,Tra,Toa,Tma,
& tran_12,tran_21,tran_23,tran_32,
& time_in_state1,time_in_state2,
& time_in_state3,time_in_state4,
& res_wait

C **********************************************************************
C
C The following residual (Residual 6) is calculated in State 2
C
C Residual 6: Equation 33 of Seem & House report
resid(6) = Tsa - Tma - Pfan_des/(Wsup_des*cp_des)
C
C The following residual (Residual 3) is calculated at transitions
C from State 1 to State 2
C
C Estimate the fraction of outdoor air during the transition from state 1
to state 2
f_meas = (cpa*(Tsa - Tra) - (Pfan_des/Wsup_des))/
        (cpa*(Toa - Tra))
C Residual 3: Equation 18 of Seem & House report
resid(3) = f_des - f_meas
tran_12 = 1
write(13,200)time,control_state,(resid(i),i=1,13),
& Tsa,Tra,Toa,Tma,
& tran_12,tran_21,tran_23,tran_32,
& time_in_state1,time_in_state2,
& time_in_state3,time_in_state4,
& res_wait

C **********************************************************************
C
C The following residual (Residual 6) is calculated in State 2
C
C Residual 6: Equation 33 of Seem & House report
resid(6) = Tsa - Tma - Pfan_des/(Wsup_des*cp_des)
! ***********************
  if (time - (int(time/1800)*1800.0) <= 0.01
     & .and. time_in_state2 > res_wait) then ! ADDED 5/8/06 by J House
     end if

C *************************************************************************
& Tsa, Tra, Toa, Tma,
& tran_12, tran_21, tran_23, tran_32,
& time_in_state1, time_in_state2,
& time_in_state3, time_in_state4,
& res_wait

endif

if (abs(v_da - da_max) < eps) then
    if (time_sat_dax >= t_wait) then

C ******************************************************************************
C
C The following residuals (Residuals 1, 10, and 11) are calculated at
C transitions from State 2 to State 3
C
C Residual 1: Equation 9 of Seem & House report
resid(1) = Tsa - Toa - (Pfan_des/(Wsup_des*cp_des))
C
C Residual 10: Equation 41 of Seem & House report
resid(10) = Tsa - Tma - (Pfan_des/(Wsup_des*cp_des))
C
C Residual 11: Equation 42 of Seem & House report
resid(11) = Toa - Tma
tran_23 = 1
write(13,200)time, control_state, (resid(i), i=1,13),
& Tsa, Tra, Toa, Tma,
& tran_12, tran_21, tran_23, tran_32,
& time_in_state1, time_in_state2,
& time_in_state3, time_in_state4,
& res_wait
time_sat_dax = 0.0
istate = 3 ! Transition from State 2 to State 3
!
res_wait = 0.0 ! ADDED 5/8/06 by J House
!
else
    time_sat_dax = time_sat_dax + (time - time_old)
end if
else if ( (da_max - v_da) > reset_level*eps ) then
    time_sat_dax = 0.0 ! reset wait time counting
end if

if (abs(v_da - da_min) < eps) then
    if (time_sat_dan >= t_wait ) then

C ******************************************************************************
C
C The following residual (Residual 4) is calculated at transitions
C from State 2 to State 1
C
C Estimate the fraction of outdoor air during the transition from state 1
to state 2
f_meas = (cpa*(Tsa - Tra) - (Pfan_des/Wsup_des))/
       (cpa*(Toa - Tra))
C
C Residual 4: Equation 20 of Seem & House report
resid(4) = f_des - f_meas
tran_21 = 1
write(13,200)time, control_state, (resid(i), i=1,13),
& Tsa, Tra, Toa, Tma,
& tran_12, tran_21, tran_23, tran_32,
& time_in_state1, time_in_state2,
& time_in_state3, time_in_state4,
& res_wait
time_sat_dan = 0.0
istate = 1 ! Transition from State 2 to State 1
!
res_wait = 0.0 ! ADDED 5/8/06 by J House
! ***************************************************************************
else
    time_sat_dan = time_sat_dan + (time - time_old)
end if
else if (v_da - da_min) > reset_level*eps then
    time_sat_dan = 0.0  ! reset wait time counting
end if

case (3)  !== State 3 =======================================================
call pid3(Tsa,Tset,0.0,0.0,0.0,1, propg_cc,tint_cc,0.0, &
    pid_d_term_cc,0.0,u_old_cc,0.0,reset_term, u_cc, 1)
call lu_limit(u_cc, 0.0, 1.0)
call lscale (0.0, 1.0, 0.0, 1.0, 1, u_cc, v) ! 4/25/97
v_hc = 0.0
v_da = da_max
v_cc = max(0.0,min(v,1.0))  ! limit control signal
tran_12 = 0
tran_21 = 0
tran_23 = 0
tran_32 = 0
time_in_state1 = 0.0
time_in_state2 = 0.0
time_in_state3 = time_in_state3 + (time - time_old)
time_in_state4 = 0.0
C **********************************************************************
C The following residuals (Residuals 7 and 8) are calculated in State 3
C
C Residual 7: Equation 34 of Seem & House report
resid(7) = 1.0 - (Tma - Tra)/(Toa - Tra)
C Residual 8: Equation 39 of Seem & House report
resid(8) = Toa - Tma
if (time - (int(time/1800)*1800.0) <= 0.01 &
    .and. time_in_state3 > res_wait) then
    write(13,200)time,control_state,(resid(i),i=1,13), &
    Tsa,Tra,Toa,Tma,
    tran_12,tran_21,tran_23,tran_32,
    &
    time_in_state1,time_in_state2,
    &
    time_in_state3,time_in_state4,
    &
    res_wait
endif
!
C **********************************************************************
C The following residuals (Residuals 2, 12, and 13) are calculated
C at transitions from State 3 to State 2
C
C Residual 2: Equation 10 of Seem & House report
resid(2) = Tsa - Toa - (Pfan_des/(Wsup_des*cp_des))
C Residual 12: Equation 43 of Seem & House report
resid(12) = Tsa - Tma -(Pfan_des/(Wsup_des*cp_des))
C Residual 13: Equation 44 of Seem & House report
resid(13) = Toa - Tma
tran_32 = 1
res_wait = 0.0
write(13,200)time,control_state,(resid(i),i=1,13), &
    Tsa,Tra,Toa,Tma,
    tran_12,tran_21,tran_23,tran_32,
case (4)    !== State 4 ==================================================

call pid3(Tsa,Tset,0.0,0.0,0.0,0.0,1, propg_cc,tint_cc,0.0, 
    pid_i_term_cc,0.0,u_old_cc,0.,rsec,nseq, u_cc, 1) 
& call lu_limit(u_cc, 0.0, 1.0) 
call lscale (0.0, 1.0, 0.0, 1.0, 1, u_cc, v) ! 4/25/97 
    v_hc = 0.0 
    v_cc = max(0.0,min(v,1.0))           ! limit control signal 
    v_da = da_min 
    tran_12 = 0 
    tran_21 = 0 
    tran_23 = 0 
    tran_32 = 0 
    time_in_state1 = 0.0 
    time_in_state2 = 0.0 
    time_in_state3 = 0.0 
    time_in_state4 = time_in_state4 + (time - time_old) 

C *****************************************************
C C The following residual (Residual 9) is calculated in State 4 
C C Residual 9: Equation 40 of Seem & House report 
C res(9) = f_des - (Tma - Tra)/(Toa - Tra) 
C if (time - (int(time/1800)*1800.0) <= 0.01 
    .and. time_in_state4 > res_wait) then 
    write(13,200)time,control_state,(resid(i),i=1,13), 
    Tsa,tra,Toa,Tma, 
    tran_12,tran_21,tran_23,tran_32, 
    time_in_state1,time_in_state2, 
    time_in_state3,time_in_state4, 
    res_wait 
    end if 
if ( Toa < (Tchg - Tdead)) then 
    istate = 3         ! Transition from State 4 to State 3 
    res_wait = 300.0 
end if 

else if (v_cc > reset_level*eps) then 
    time_sat_cc = 0.0           ! reset wait time counting 
end if 

if ( Toa > (Tchg + Tdead)) then 
    istate = 4         ! Transition from State 3 to State 4 
    res_wait = 300.0 
end if 

else 
    time_sat_cc = time_sat_cc + (time - time_old) 
end if
end select NSCS_CONTROL

saved(2) = time  ! Save time of controller execution
saved(4) = pid_i_term_hc  ! save new pid integral term
saved(6) = u_hc
saved(8) = pid_i_term_cc
saved(10) = u_cc
saved(12) = pid_i_term_da
saved(14) = u_da
saved(18) = v_hc
saved(19) = v_cc
saved(20) = v_da

abs_del_uhc = abs(v_hc - v_old_hc)
abs_del_ucc = abs(v_cc - v_old_cc)
abs_del uda = abs(v_da - v_old_da)

else                   ! Not a sample instant
C set output to value from previous sample
    v_hc = saved(18)     ! added 5/31/01
    v_cc = saved(19)
    v_da = saved(20)
end if   TIME_CHANGE

if (system_status == 0) then                ! system off
    v_hc  = 0.0
    v_cc  = 0.0
    v_da  = 0.0
    do i=2,20
        saved(i)=0.0
    end do
end if

saved(1) = time                             ! save current values
saved(16)= istate

out(1) = v_hc                                   ! outputs
out(2) = v_cc
out(3) = v_da
out(4) = abs_del_uhc
out(5) = abs_del_ucc
out(6) = abs_del_uda
out(? ) = istate

do i =1, 7
    iostat(i) = 1
end do

100 format (1x, a80)
200 format (f11.1,2x,i3,13(1x,f10.4),4(1x,f6.2),4(1x,i3),5(1x,f10.2))
300 format (f11.1,2x,i3,23(2x,f8.4))
end subroutine
C. APPENDIX C: BOUNDARY DATA

Three executables are used to produce the boundary data file for the simulations. The names of the three executable files are readtape.exe, weather.exe, and solair.exe. A brief description of the programs and the user responses necessary to produce a boundary data file for a one-year period for Chicago, Illinois are provided in Sections C.1-C.3. Also provided in Section C.4 is the source code solair.for, which is a FORTRAN program written to produce the solair temperatures found in the boundary data file.
C.1 I/O for READTAPE.EXE

The executable readtape.exe is obtained by compiling the HVACSIM+ program RDTAPE.FOR (Park et al., 1986). The program is used to read typical meteorological year (TMY) data for Chicago. The user provided inputs to produce an output file WTPOUT.DAT for the entire year of data are shown below in bold typeface. Prompts printed by the program to the screen are shown in italic typeface.

> readtape
Enter Input File name up to 12 characters ---
Chicago.tmy
What is the type of weather tape?
Enter 1 for (TRY), 2 (TMY), 3 (SOLMET), 4 (WYEC)
2
Where is the weather station?
Enter station ID number
14819
Enter the year (4 digits)
1955
Type the start date: Month,Day
1,1
Type the end date: Month,Day
12,31

---- The first day of the weather tape ----
STTN = 14819 WYR = 55 WMO = 1 WDY = 1
------- The start day -------
STTN = 14819 WYR = 55 WMO = 1 WDY = 1
------- The stop day -------
STTN = 14819 WYR = 66 WMO = 12 WDY = 31

365 DAYS WRITTEN ON THE OUTPUT FILE

-------- NORMAL END OF JOB --------

Output File: WTPOUT.DAT
C.2 I/O for WEATHER.EXE

The executable weather.exe is obtained by compiling the HVACSIM+ program CRWDTA.FOR (Park et al., 1986). The program can be used in different ways as described by Park et al. (1986). For this study, the program is used to read the output from readtape.exe. The output data file contains the month, day, hour, dry-bulb temperature (°C) humidity ratio, barometric pressure (kPa), wind speed (m/s), direct beam solar radiation (W/m²), sky diffusive radiation (W/m²), and total horizontal radiation (W/m²). User provided inputs to produce an output file WEATHER.DAT are shown below in bold typeface. Prompts printed by the program to the screen are shown in italic typeface.

```
> weather
Enter LATITUDE, LONGITUDE, and TIME ZONE:
=>
41.98, 87.60, 6
Enter one of the following:
 1 - to process the weather data in file WTPOUT.DAT
    (previously read from weather tape by program RDTAPE)
 2 - to generate clear sky design data
 3 - to generate cloudy sky design data
=>
1
Enter output file name (up to 12 characters)
or carriage return for default name: WEATHER.DAT
=>
(Press enter)
---- END OF CREATING WEATHER FILE -----
```

If the program runs correctly, a window will appear with the following message:

```
Program Terminated with exit code 0
Exit Window?
```

Select yes.

Output File: WEATHER.DAT
C.3 I/O for SOLAIR.EXE

The executable solair.exe is obtained by compiling the program SOLAIR.FOR. This program produces a boundary data file for use with the simulation model described by Norford and Haves (1997). The boundary data includes the ambient dry-bulb temperature and humidity ratio, sol-air temperatures for the space and plenum in each of six zones, and fractional occupancy, lighting, and equipment heat gain for the zones. The fractional occupancy, lighting, and equipment heat gains for zone 1 are identical to those for zone 4, and those for zone 3 are identical to zone 6. Thus, the boundary data file contains a total of 26 columns of data consisting of ambient dry-bulb and humidity ratio (two columns), space and plenum sol-air temperatures (12 columns), and fractional occupancy, lighting, and equipment heat gains (12 columns). For this study, the fractional occupancy, lighting, and equipment heat gains reported by Norford and Haves (1997) are used, whereas the building characteristics and the analysis necessary for the computation of the sol-air temperatures were taken from a companion report by DeSimone (1995). User provided inputs to produce an output file WEATHER2.DAT are shown below in bold typeface. Prompts printed by the program to the screen are shown in italic typeface.

> solair
   Enter LOCAL STANDARD MERIDIAN
   in units of degrees:
   =>
   90
   Enter the number of hours of weather data:
   =>
   8760
   Enter 1 for zone output, 2 for barrier output, and
   3 for boundary file:
   =>
   3
   Enter the file name of the weather data:
   =>
   weather.dat
   ---- END OF CREATING SOLAIR FILE ------

Output File: WEATHER2.DAT
C.4 Source Code for SOLAIR.FOR

The source code for SOLAIR.FOR is provided below. The code is based on the analysis and building characteristics described by DeSimon (1995). This program produces a boundary data file for use with the simulation model described by Norford and and Haves (1997). SOLAIR.FOR makes it possible to produce a boundary data file for the building modeled in DeSimon (1995) for any location for which typical meteorological year weather data are available.

C     Last change:
C **********************************************************************
C     SOLAIR : Create the solair temperatures for MIT building from
C              ASHRAE 825-RP.
C **********************************************************************
C
C     Version 1.0: June 8, 2001 John House
C
C     VARIABLES:
C     MONTH:    Month of year
C     LATD:     Latitude (degrees)
C     LONG:     Longitude (degrees)
C     TZN:      Time zone number (-)
C     =4 --- Atlantic
C     =5 --- Eastern
C     =6 --- Central
C     =7 --- Mountain
C     =8 --- Pacific
C
C     HR:       Time of day (h)
C     T:        Dry-bulb outdoor temperature (C)
C     W:        Humidity ratio (-)
C     P:        Barometric pressure (kPa)
C     V:        Wind speed (m/s)
C     C:        Sky clearness number [0,1], (-)
C     SOLDIR:   Direct solar radiation (W/m**2)
C     SOLSKY:   Sky diffusive radiation (W/m**2)
C     SOLHOZ:   Total horizontal radiation (W/m**2)
C
C     SUBPROGRAMS CALLED:
C       WTPINP, SOLAR
C
C **********************************************************************

PROGRAM   SOLAIR
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
CHARACTER*12 FNAME(9)
INTEGER   IFILE(9)
INTEGER   DAY
REAL      IRH,LSM,LAT,LON,LST,MLSN,IG_SV,IG_NV,IG_NV,IG_H
REAL     KEXTROOM(6),KEXTPLEN(6),KEXTROOF(6),KEXTM_RWALL(3,6),
       &       KEXTM_PWALL(3,6),KEXTM_RGLAZ(3,6),KEXTM_PGLAZ(3,6),
       &       KEXTM_ROOF(6)
DIMENSION TSOL_RW(3,6),TSOL_PW(3,6),TSOL_RG(3,6),
       &       TSOL_PG(3,6),TSOL_RF(6)
DIMENSION TAMB(8760),EDN(8760),C(12),SOL_DEC(12),ET(12)
DIMENSION HHR(8760), WAMB(8760), P(8760), V(8760),
& SOLSKY(8760), SOLHOZ(8760)

DIMENSION TSOLAIR_ROOM(6, 8760), TSOLAIR_PLEN(6, 8760), TSOLAIR_W(3),
& TSOLAIR_G(3), TSOLAIR_ROOM_15MIN(6),
& TSOLAIR_PLEN_15MIN(6)

DIMENSION FOC(6, 24), FLT(6, 24), FEQ(6, 24),
& FOC_15MIN(6), FLT_15MIN(6), FEQ_15MIN(6)

DATA KEXTROOM/ 77.8, 21.2, 596.0, 164.1, 327.2, 50.4 /,
& KEXTPLEN/ 17.7, 5.0, 224.1, 38.4, 86.1, 11.4 /,
& KEXTROOF/ 17.7, 5.0, 224.1, 38.4, 86.1, 11.4 /

C Index I=1 is south; 2 is west; and 3 is north
DATA ((KEXTM_RWALL(I,J), I=1,3), J=1,6) / 25.1, 7.1, 15.0 ,
& 0.0, 0.0, 13.9 ,
& 239.5, 115.3, 25.8 ,
& 0.0, 56.6, 51.6 ,
& 0.0, 0.0, 180.6 ,
& 11.1, 19.3, 0.0 /

C Index I=1 is south; 2 is west; and 3 is north
DATA ((KEXTM_PWALL(I,J), I=1,3), J=1,6) / 10.5, 2.6, 4.6 ,
& 0.0, 0.0, 5.0 ,
& 96.8, 32.0, 9.2 ,
& 0.0, 20.0, 18.4 ,
& 0.0, 0.0, 72.1 ,
& 3.9, 7.5, 0.0 /

C Index I=1 is south; 2 is west; and 3 is north
DATA ((KEXTM_RGLAZ(I,J), I=1,3), J=1,6) / 23.2, 4.2, 3.1 ,
& 0.0, 0.0, 7.3 ,
& 201.8, 0.0, 13.6 ,
& 0.0, 28.6, 27.3 ,
& 0.0, 0.0, 146.5 ,
& 5.7, 14.3, 0.0 /

DATA ((KEXTM_PGLAZ(I,J), I=1,3), J=1,6) / 0.0, 0.0, 18*0.0 /
DATA KEXTM_ROOF/ 0.0, 0.0, 86.1, 0.0, 13.9, 0.0 /

DATA ET/ -11.2, -13.9, -7.5, 1.1, 3.3, -1.4 ,
& -6.2, -2.4, 7.5, 15.4, 13.8, 1.6 /
DATA SOL_DEC/ -20.0, -10.8, 0.0, 11.6, 20.0, 23.45 ,
& 20.6, 12.3, 0.0, -10.5, -19.8, -23.45 /
DATA C/ 0.058, 0.060, 0.071, 0.097, 0.121, 0.134 ,
& 0.136, 0.122, 0.092, 0.082, 0.063, 0.057 /

DATA (FOC(1,I), I=1,24)
& / 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07,
& 0.07, 0.07, 0.18, 0.08, 0.07, 0.3, 0.28, 0.14, 0.17, 0.24, 0.35, 0.41,
& 0.22, 0.19, 0.14, 0.09, 0.05, 0.07 /

DATA (FOC(2,I), I=1,24)
& / 0.75, 0.5, 0.25, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
& 0.0, 0.0, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2,
& 0.2, 0.2, 0.2, 0.4, 0.6, 0.8, 1.0, 1.0, 1.0, 1.0 /

DATA (FOC(3,I), I=1,24)
& / 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
& 0.33, 0.67, 1.0, 1.0, 1.0, 0.5, 0.5, 1.0, 1.0, 1.0,
& 0.15, 0.1, 0.05, 0.0, 0.0, 0.0 /
DATA (FOC(4,I), I=1,24)
\[
\begin{array}{c}
0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07
\end{array}
\]

DATA (FOC(5,I), I=1,24)
\[
\begin{array}{c}
0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0
\end{array}
\]

DATA (FOC(6,I), I=1,24)
\[
\begin{array}{c}
0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0
\end{array}
\]

DATA (FLT(1,I), I=1,24)
\[
\begin{array}{c}
0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07
\end{array}
\]

DATA (FLT(2,I), I=1,24)
\[
\begin{array}{c}
24*1.0
\end{array}
\]

DATA (FLT(3,I), I=1,24)
\[
\begin{array}{c}
0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05
\end{array}
\]

DATA (FLT(4,I), I=1,24)
\[
\begin{array}{c}
0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07
\end{array}
\]

DATA (FLT(5,I), I=1,24)
\[
\begin{array}{c}
0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0
\end{array}
\]

DATA (FLT(6,I), I=1,24)
\[
\begin{array}{c}
0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05
\end{array}
\]

DATA (FEQ(1,I), I=1,24)
\[
\begin{array}{c}
0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0
\end{array}
\]

DATA (FEQ(2,I), I=1,24)
\[
\begin{array}{c}
24*1.0
\end{array}
\]

DATA (FEQ(3,I), I=1,24)
\[
\begin{array}{c}
0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0
\end{array}
\]

DATA (FEQ(4,I), I=1,24)
\[
\begin{array}{c}
0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07, 0.07
\end{array}
\]
DATA (FEQ(5,I), I=1,24) / 24*0.0 /

DATA (FEQ(6,I), I=1,24)
& / 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
& 0.33, 0.67, 1.0, 1.0, 1.0, 0.5,
& 0.5, 1.0, 1.0, 1.0, 1.0, 0.2,
& 0.15, 0.1, 0.05, 0.0, 0.0, 0.0 /

! MIT DATA
! DATA TAMB/ 23.6, 23.9, 23.3, 22.2, 22.2, 23.9,
! & 25.6, 28.3, 30.0, 31.7, 32.8, 33.3,
! & 28.9, 21.1, 23.9, 24.4, 24.4, 23.9 /

! DATA EDN/ 0.0, 0.0, 0.0, 0.0, 4.0, 89.0,
! & 279.0, 372.0, 340.0, 456.0, 711.0, 543.0,
! & 427.0, 489.0, 168.0, 165.0, 108.0, 140.0,
! & 8.0, 0.0, 0.0, 0.0, 0.0, 0.0 /

FNAME(1) = 'WEATHER1.DAT '
FNAME(2) = 'WEATHER2.DAT '
FNAME(3) = 'WEATHER3.DAT '
FNAME(4) = 'WEATHER4.DAT '
FNAME(5) = 'WEATHER5.DAT '
FNAME(6) = 'WEATHER6.DAT '
FNAME(7) = 'WEATHER7.DAT '
FNAME(8) = 'WEATHER8.DAT '

C Assign logical unit numbers
DO 3 I=1,9
   IFILE(I)=I
3 CONTINUE
INP=5

C Read input information.
PRINT *, ' ****************************************************** '
PRINT *, ' *                                                    * '
PRINT *, ' * CREATE A WEATHER DATAFILE WITH SOLAIR TEMPERATURES * '
PRINT *, ' ****************************************************** '

PRINT *, ' Enter LOCAL STANDARD MERIDIAN'
PRINT *, ' in units of degrees: '
READ(INP,*) LSM

PRINT *, ' Enter the number of hours of weather data:'
READ(INP,*) NHOURS

PRINT *, ' Enter 1 for zone output, 2 for barrier output, and '
PRINT *, ' 3 for boundary file:'
READ(INP,*) IOUT

PRINT *, ' Enter the file name of the weather data:'
READ(INP,*) FNAME(9)

OPEN(UNIT=IFILE(9),FILE=FNAME(9),STATUS='OLD')
READ(IFILE(9),2)MMONTH,DAY,LAT,LON,TZN,ISFLAG
MONTH = MMONTH

2 FORMAT(1X,2I5,3F10.2,I5)

OPEN(UNIT=IFILE(1),FILE=FNAME(1))
CLOSE(UNIT=IFILE(1),STATUS='DELETE')
OPEN(UNIT=IFILE(1),FILE=FNAME(1))

DO 6 L=1,NHOURS
  READ(IFILE(9),7)MMONTH,DAY,HHR(L),TAMB(L),WAMB(L),P(L),
  & V(L),EDN(L),SOLSKY(L),SOLHOZ(L)
  IF (IOUT == 3) THEN
    WRITE(IFILE(1),9)MMONTH,DAY,HHR(L),TAMB(L),WAMB(L),
    & P(L),V(L),EDN(L),SOLSKY(L),SOLHOZ(L)
  ENDIF
6 CONTINUE

7 FORMAT(1X,2I5,f5.1,7f10.4)
8 FORMAT(1X,2I5,f5.1,7f10.4)

C Assign values of properties
C Extterier film coefficients (DeSimone, pgs. 482,485,488)
HOUTWALL = 28.3   ! walls
HOUTGLAZ = 23.9   ! glazings
HOUTROOF = 28.0   ! roof
C Outer surface absorptance (DeSimone, pgs. 482,485,488)
ALPWALL  = 0.63   ! walls
ALPGLAZ  = 0.15   ! glazings
ALPROOF  = 0.55   ! roof
C Outer surface emissivity (DeSimone, pgs. 482,485,488)
EPSWALL  = 0.9    ! walls
EPSGLAZ  = 0.85   ! glazings
EPSROOF  = 0.9    ! roof
IRH      = 63.0   ! longwave h.t. between outer wall surface and sky
                ! (DeSimone, pg. 485)
UGLAZ    = 1.95   ! overall conductive h.t. coeff. for glazings
                ! (DeSimone, pg. 485)
SHGCGLAZ = 0.23   ! solar heat gain coeff. (DeSimone, pg. 485)
RHOG     = 0.14   ! ground reflectance (DeSimone, pg. 485)
C       = 0.136   ! sky diffuse factor (fcn. of month)
                ! Table 6-1 (McQuiston & Parker, 4th Ed.)
C constants for conversions of angles
PI       = 4.0 * atan(1.0)
RADDEG   = 360.0/(2.0*PI)
DEGRAD   = 2.0*PI/360.0
C solar constants (note: some constants are function of month)
                  ! Table 6-1 (McQuiston & Parker, 4th Ed.)
LSM       = 67.5   ! local standard time meridian (DeSimone, pg.489)
LON       = 71.0   ! local longitude (Blue Hill Observ., Canton, MA)
SOL_DEC   = 20.6*DEGRAD
SOL_DEC(MONTH) = SOL_DEC(MONTH)*DEGRAD ! solar declination angle
                  ! Table 6-1 (McQuiston & Parker, 4th Ed.)
LAT       = LAT*DEGRAD   ! local latitude (DeSimone, pg. 489)
c building surface azimuths (DeSimone, pg. 489)
PSI_S     = -15.0   ! south facing
PSI_W     = 75.0    ! west facing
PSI_N     = 165.0   ! north facing

IF (IOUT == 3) THEN
  OPEN(UNIT=IFILE(2),FILE=FNAME(2))
CLOSE(UNIT=IFILE(2), STATUS='DELETE')
OPEN(UNIT=IFILE(2), FILE=FNAME(2))

ELSE

DO 4 I = 2, 8
OPEN(UNIT=IFILE(I), FILE=FNAME(I))
CLOSE(UNIT=IFILE(I), STATUS='DELETE')
OPEN(UNIT=IFILE(I), FILE=FNAME(I))
4 CONTINUE
END IF

NDAYS = NHOURS/24

III = 0
Do 10 II = 1, NDAYS

! Assign MONTH according to day of year
IF (II<=31) THEN
  MONTH = 1
ELSEIF (II<=59) THEN
  MONTH = 2
ELSEIF (II<= 90) THEN
  MONTH = 3
ELSEIF (II<=120) THEN
  MONTH = 4
ELSEIF (II<=151) THEN
  MONTH = 5
ELSEIF (II<=181) THEN
  MONTH = 6
ELSEIF (II<=212) THEN
  MONTH = 7
ELSEIF (II<=243) THEN
  MONTH = 8
ELSEIF (II<=273) THEN
  MONTH = 9
ELSEIF (II<=304) THEN
  MONTH = 10
ELSEIF (II<=334) THEN
  MONTH = 11
ELSE
  MONTH = 12
ENDIF

Do 11 I = 1, 24
III = III + 1
HR = I ! Hour
AST = I + (ET(MONTH) + 4.0*(LSM-LON))/60.0 ! Apparent solar time
  ! DeSimone, Eq. 80
MLSN = 720.0 - AST*60.0 ! Minutes from local solar noon
  ! DeSimone, Eq. 79
HANG = MLSN/4.0 ! Hour angle
  ! DeSimone, Eq. 78
HANG_RAD = HANG*DEGRAD
SINBETA = cos(LAT)*cos(SOL_DEC(MONTH)*DEGRAD)*cos(HANG_RAD)+
  sin(LAT)*sin(SOL_DEC(MONTH)*DEGRAD) ! DeSimone, Eq. 77
BETA = asin(SINBETA) ! solar altitude
THETA_H = acos(SINBETA)*RADDEG ! horizontal incident angle
  ! DeSimone, Eq. 75
COSPHI = (sin(BETA)*sin(LAT)-sin(SOL_DEC(MONTH)*DEGRAD))/
  (cos(BETA)*cos(LAT)) ! DeSimone, Eq. 76
&
PHI = acos(COSPHI)*RADDEG ! solar azimuth
IF (I <= 12 .AND. PHI > 0) THEN
  PHI = -PHI
ELSEIF (I > 12 .AND. PHI < 0) THEN
PHI = -PHI
ENDIF

C Incident angles for vertical surfaces (DeSimone, Eq. 74)
THETA_SV = acos(cos(BETA) * cos((PHI - PSI_S) * DEGRAD))  
&           * RADDEG  ! south facing surfaces
THETA_WV = acos(cos(BETA) * cos((PHI - PSI_W) * DEGRAD))  
&           * RADDEG  ! west facing surfaces
THETA_NV = acos(cos(BETA) * cos((PHI - PSI_N) * DEGRAD))  
&           * RADDEG  ! north facing surfaces

C Direct solar radiation for vertical surfaces (DeSimone, Eq. 65)
EDN_SV = max(0.0, EDN(III) * cos(THETA_SV * DEGRAD))  ! south facing surf
EDN_WV = max(0.0, EDN(III) * cos(THETA_WV * DEGRAD))  ! west facing surf
EDN_NV = max(0.0, EDN(III) * cos(THETA_NV * DEGRAD))  ! north facing surf

C Direct solar radiation for horizontal surfaces
EDNH = EDN(III) * SINBETA  ! DeSimone, Eq. 75

C Diffuse sky radiation for vertical surfaces: DeSimone, Eqs. 68, 70-71
IF (cos(THETA_SV * DEGRAD) > -0.2) THEN
  Y = 0.55 + 0.437 * cos(THETA_SV * DEGRAD)
&             + 0.313 * cos(THETA_SV * DEGRAD)**2  ! Eq. 70
ELSE
  Y = 0.45  ! Eq. 71
ENDIF
EDS_SV = C(MONTH) * Y * EDN(III)  ! south facing surface, Eq. 68

IF (cos(THETA_WV * DEGRAD) > -0.2) THEN
  Y = 0.55 + 0.437 * cos(THETA_WV * DEGRAD)
&             + 0.313 * cos(THETA_WV * DEGRAD)**2  ! Eq. 70
ELSE
  Y = 0.45  ! Eq. 71
ENDIF
EDS_WV = C(MONTH) * Y * EDN(III)  ! west facing surface, Eq. 68

IF (cos(THETA_NV * DEGRAD) > -0.2) THEN
  Y = 0.55 + 0.437 * cos(THETA_NV * DEGRAD)
&             + 0.313 * cos(THETA_NV * DEGRAD)**2  ! Eq. 70
ELSE
  Y = 0.45  ! Eq. 71
ENDIF
EDS_NV = C(MONTH) * Y * EDN(III)  ! north facing surface, Eq. 68

C Diffuse radiation reflected from the ground to vertical surfaces: DeSimone, Eq. 72
EDGV = (EDN(III) * (C(MONTH) + SINBETA) * RHOG 
&           *(1.0 - cos(90.0 * DEGRAD))) / 2.0

C Diffuse radiation reflected from the ground to horizontal surfaces
EDGH = (EDN(III) * (C(MONTH) + SINBETA) * RHOG 
&           *(1.0 - cos(0.0 * DEGRAD))) / 2.0

C Shortwave solar gain on outer surface: DeSimone, Eqs. 64 & 66
IG_SV = EDN_SV + EDS_SV + EDGV  ! south facing vertical
IG_WV = EDN_WV + EDS_WV + EDGV  ! west facing vertical
IG_NV = EDN_NV + EDS_NV + EDGV  ! north facing vertical
IG_H = EDNH + EDSH + EDGH  ! horizontal

C Glazing transmittance
TAUGLAZ = SHGCGLAZ - UGLAZ * ALPGLAZ / HOUTGLAZ  ! DeSimone, Eq. 83

C Solar temperatures for various barrier types
TSOLAIR_R = TAMB(III) + 1.0 / HOUTROOF * (ALPROOF * IG_H 
&             - EPSROOF * IRH * (1.0 + cos(0.0 * DEGRAD)) / 2.0)  ! roof
  ! DeSimone, Eq. 60
TSOLAIR_W(1) = TAMB(III) + 1.0 / HOUTWALL * (ALPWALL * IG_SV

  }
TSOLAIR_W(2) = TAMB(III) + 1.0/HOUTWALL*(ALPWALL*IG_WV
- EPSWALL*IRH*(1.0+cos(90.0*DEGRAD))/2.0) ! west wall
DeSimone, Eq. 60

TSOLAIR_W(3) = TAMB(III) + 1.0/HOUTWALL*(ALPWALL*IG_NV
- EPSWALL*IRH*(1.0+cos(90.0*DEGRAD))/2.0) ! north wall
DeSimone, Eq. 60

TSOLAIR_G(1) = TAMB(III) + 1.0/HOUTGLAZ*(ALPGLAZ*IG_SV
- EPSGLAZ*IRH*(1.0+cos(90.0*DEGRAD))/2.0)
+ TAUGLAZ*IG_SV/UGLAZ ! south glazing
DeSimone, Eq. 61

TSOLAIR_G(2) = TAMB(III) + 1.0/HOUTGLAZ*(ALPGLAZ*IG_WV
- EPSGLAZ*IRH*(1.0+cos(90.0*DEGRAD))/2.0)
+ TAUGLAZ*IG_WV/UGLAZ ! west glazing
DeSimone, Eq. 61

TSOLAIR_G(3) = TAMB(III) + 1.0/HOUTGLAZ*(ALPGLAZ*IG_NV
- EPSGLAZ*IRH*(1.0+cos(90.0*DEGRAD))/2.0)
+ TAUGLAZ*IG_NV/UGLAZ ! north glazing
DeSimone, Eq. 61

Do 17 K=1,6
TSOLAIR_RTEMP=0.0
TSOLAIR_PTEMP=0.0
Do 15 J=1,3
TSOL_RW(J,K)=KEXTM_RWALL(J,K)*TSOLAIR_W(J)
/ KEXTRoom(K)
TSOL_PW(J,K)=KEXTM_PWALL(J,K)*TSOLAIR_W(J)
/ KEXTPLEN(K)
TSOL_RG(J,K)=KEXTM_RGLAZ(J,K)*TSOLAIR_G(J)
/ KEXTRoom(K)
TSOL_PG(J,K)=KEXTM_PGLAZ(J,K)*TSOLAIR_G(J)
/ KEXTPLEN(K)
TSOLAIR_RTEMP=TSOLAIR_RTEMP+TSOL_RW(J,K)+TSOL_RG(J,K)
TSOLAIR_PTEMP=TSOLAIR_PTEMP+TSOL_PW(J,K)+TSOL_PG(J,K)
15 Continue

TSOL_RF(K)=KEXTM_ROOF(K)*TSOLAIR_R/KEXTROOF(K)
TSOLAIR_ROOM(K,III)=TSOLAIR_RTEMP
TSOLAIR_PLEN(K,III)=TSOLAIR_PTEMP+TSOL_RF(K)
17 Continue

IF (IOUT == 1) THEN
write(IFILE(1),21)hr, hang, ast, sinbeta, beta_raddeg, cosphi, phi,
theta_h, theta_sv, theta_wv, theta_nv
write(IFILE(2),23)hr, tsol_rw(1,1), tsol_pw(1,1), tsol_rw(2,1),
& tsol_pw(2,1), tsol_rw(3,1), tsol_pw(3,1),
& tsol_rg(1,1), tsol_pg(1,1), tsol_rg(2,1),
& tsol_pg(2,1), tsol_rg(3,1), tsol_pg(3,1),
& tsol_rf(1), tsolar_room(1,iii), tsolar_plen(1,iii),
& tamb(iii)
write(IFILE(3),23)hr, tsol_rw(1,2), tsol_pw(1,2), tsol_rw(2,2),
& tsol_pw(2,2), tsol_rw(3,2), tsol_pw(3,2),
& tsol_rg(1,2), tsol_pg(1,2), tsol_rg(2,2),
& tsol_pg(2,2), tsol_rg(3,2), tsol_pg(3,2),
& tsol_rf(2), tsolar_room(2,iii), tsolar_plen(2,iii),
& tamb(iii)
write(IFILE(4),23)hr, tsol_rw(1,3), tsol_pw(1,3), tsol_rw(2,3),
& tsol_pw(2,3), tsol_rw(3,3), tsol_pw(3,3),
& tsol_rg(1,3), tsol_pg(1,3), tsol_rg(2,3),
& tsol_pg(2,3), tsol_rg(3,3), tsol_pg(3,3),
& tsol_rf(3), tsolar_room(3,iii), tsolar_plen(3,iii),
& tamb(iii)
write(IFILE(5),23)hr, tsol_rw(1,4), tsol_pw(1,4), tsol_rw(2,4),
& tsol_pw(2,4), tsol_rw(3,4), tsol_pw(3,4),
& tsol_rg(1,4), tsol_pg(1,4), tsol_rg(2,4),
& tsol_pg(2,4), tsol_rg(3,4), tsol_pg(3,4),
& tsol_rf(4), tsolar_room(4,iii), tsolar_plen(4,iii),
& tamb(iii)
write(IFILE(6),23)hr,tsol_rw(1,5),tsol_pw(1,5),tsol_rw(2,5),
& tsol_pw(2,5),tsol_rw(3,5),tsol_pw(3,5),
& tsol_rg(1,5),tsol_pg(1,5),tsol_rg(2,5),
& tsol_pg(2,5),tsol_rg(3,5),tsol_pg(3,5),
& tsol_rf(5),tsolair_room(5,iii),tsolair_plen(5,iii),
& tamb(iii)
write(IFILE(7),23)hr,tsol_rw(1,6),tsol_pw(1,6),tsol_rw(2,6),
& tsol_pw(2,6),tsol_rw(3,6),tsol_pw(3,6),
& tsol_rg(1,6),tsol_pg(1,6),tsol_rg(2,6),
& tsol_pg(2,6),tsol_rg(3,6),tsol_pg(3,6),
& tsol_rf(6),tsolair_room(6,iii),tsolair_plen(6,iii),
& tamb(iii)
ELSEIF (IOUT == 2) THEN
write(IFILE(1),21)hr,hang,ast,sinbeta,beta*raddeg,cosphi,phi,
  theta_h,theta_sv,theta_wv,theta_nv
write(IFILE(2),22)hr,beta*raddeg,theta_sv,edn(iii),edn_sv,
  eds_sv,edgv,ig_sv,tsolair_w(1)
write(IFILE(3),22)hr,beta*raddeg,theta_wv,edn(iii),edn_wv,
  eds_wv,edgv,ig_wv,tsolair_w(2)
write(IFILE(4),22)hr,beta*raddeg,theta_sv,edn(iii),edn_sv,
  eds_sv,edgv,ig_sv,tsolair_g(1)
write(IFILE(5),22)hr,beta*raddeg,theta_wv,edn(iii),edn_wv,
  eds_wv,edgv,ig_wv,tsolair_g(2)
write(IFILE(6),22)hr,beta*raddeg,theta_sv,edn(iii),edn_sv,
  eds_sv,edgv,ig_sv,tsolair_g(3)
write(IFILE(7),22)hr,beta*raddeg,theta_wv,edn(iii),edn_wv,
  eds_wv,edgv,ig_wv,tsolair_g(3)
write(IFILE(8),22)hr,beta*raddeg,theta_h,edn(iii),ednh,edsh,
  edgh,ig_h,tsolair_r
ENDIF
11  Continue
10  Continue
C  Give name to output file.

IF (IOUT == 3) THEN
  CALL BOUNDARY(NHOURS,TAMB,WAMB,TSOLAIR_ROOM,TSOLAIR_PLEN,
&    FOC,FLT,FEQ,IFILE)
END IF

21  format(2(3x,f5.0),3x,f6.1,3x,f7.2,3x,f5.0,3x,f7.2,5(3x,f5.0))
22  format(8(3x,f5.0),3x,f6.1)
23  format(3x,f5.0,16(3x,f6.1))
STOP '----- END OF CREATING SOLAIR FILE ------'
END
C **********************************************************************
C **********************************************************************
SUBROUTINE BOUNDARY(NHOURS,TAMB,WAMB,TSOLAIR_ROOM,TSOLAIR_PLEN,
&    FOC,FLT,FEQ,IFILE)
C **********************************************************************
C BOUNDARY : Write boundary data file for MIT building with
C weather data from any TMY data set.
C
C June 19, 2001
C
C SUBPROGRAMS CALLED:
C  None
C
C **********************************************************************}
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DIMENSION TAMB(8760),WAMB(8760)
DIMENSION TSOLAIR_ROOM(6,8760),TSOLAIR_PLEN(6,8760),
&    TSOLAIR_ROOM_15MIN(6),TSOLAIR_PLEN_15MIN(6)
C Use linear interpolation to convert hourly values to values at 15 minute intervals

ITIME=0
II=0
DO 100 III=1,NHOURS

II=II+1
ITIME=ITIME-1
DO 200 J=1,5

IF (III == 1) THEN
  TAMB_15MIN=TAMB(NHOURS)+(TAMB(III)-TAMB(NHOURS))*(J-1)/4
  WAMB_15MIN=WAMB(NHOURS)+(WAMB(III)-WAMB(NHOURS))*(J-1)/4
ELSE
  TAMB_15MIN = TAMB(III-1)+(TAMB(III)-TAMB(III-1))*(J-1)/4
  WAMB_15MIN = WAMB(III-1)+(WAMB(III)-WAMB(III-1))*(J-1)/4
ENDIF
DO 300 K=1,6   ! Loop for zones

C Room and plenum solair temperatures

IF (III == 1) THEN
  TSOLAIR_ROOM_15MIN(K) = TSOLAIR_ROOM(K,NHOURS)
  &
  +(TSOLAIR_ROOM(K,III)-TSOLAIR_ROOM(K,NHOURS))*(J-1)/4
  TSOLAIR_PLEN_15MIN(K) = TSOLAIR_PLEN(K,NHOURS)
  &
  +(TSOLAIR_PLEN(K,III)-TSOLAIR_PLEN(K,NHOURS))*(J-1)/4
ELSE
  TSOLAIR_ROOM_15MIN(K) = TSOLAIR_ROOM(K,III-1)
  &
  +(TSOLAIR_ROOM(K,III)-TSOLAIR_ROOM(K,III-1))*(J-1)/4
  TSOLAIR_PLEN_15MIN(K) = TSOLAIR_PLEN(K,III-1)
  &
  +(TSOLAIR_PLEN(K,III)-TSOLAIR_PLEN(K,III-1))*(J-1)/4
ENDIF

300 CONTINUE

IF (II == 1) THEN

DO 301 K=1,6

C Fractional occupancy, lighting and equipment heat gains

FOC_15MIN(K) = FOC(K,24)+(FOC(K,II)-FOC(K,24))*(J-1)/4
FLT_15MIN(K) = FLT(K,24)+(FLT(K,II)-FLT(K,24))*(J-1)/4
FEQ_15MIN(K) = FEQ(K,24)+(FEQ(K,II)-FEQ(K,24))*(J-1)/4

301 CONTINUE
ELSE

DO 302 K=1,6

C Fractional occupancy, lighting and equipment heat gains

FOC_15MIN(K)=FOC(K,II-1)+(FOC(K,II)-FOC(K,II-1))*(J-1)/4
FLT_15MIN(K)=FLT(K,II-1)+(FLT(K,II)-FLT(K,II-1))*(J-1)/4
FEQ_15MIN(K)=FEQ(K,II-1)+(FEQ(K,II)-FEQ(K,II-1))*(J-1)/4

302 CONTINUE

IF (II == 24 .AND. J == 5) THEN   ! Reset II
  II=0
ENDIF

ENDIF
C Boundary data file

WRITE(IFILE,400)ITIME*900.0,TAMB_15MIN,
   & TSOLAIR_ROOM_15MIN(3),TSOLAIR_ROOM_15MIN(5),
   & TSOLAIR_ROOM_15MIN(1),TSOLAIR_ROOM_15MIN(4),
   & TSOLAIR_ROOM_15MIN(6),TSOLAIR_ROOM_15MIN(2),
   & TSOLAIR_PLEN_15MIN(3),TSOLAIR_PLEN_15MIN(5),
   & TSOLAIR_PLEN_15MIN(1),TSOLAIR_PLEN_15MIN(4),
   & TSOLAIR_PLEN_15MIN(6),TSOLAIR_PLEN_15MIN(2),
   & FOC_15MIN(3),FOC_15MIN(5),FOC_15MIN(1),FOC_15MIN(2),
   & FLT_15MIN(3),FLT_15MIN(5),FLT_15MIN(1),FLT_15MIN(2),
   & FEQ_15MIN(3),FEQ_15MIN(5),FEQ_15MIN(1),FEQ_15MIN(2),
   & WAMB_15MIN

200    CONTINUE
100   CONTINUE
400    FORMAT(f10.1,13(2x,f6.2),12(2x,f5.3),2x,f6.4)

RETURN
END
D. APPENDIX D: INSTRUCTIONS FOR EXECUTING SIMULATIONS

A list of the fault cases and instructions for modifying input files, executing simulations, and post-processing output data are provided in this appendix.

D.1 Cases

The faults are identified by case numbers in the simulation code. The list below maps the case number to the actual fault.

Fault 0: Normal Operation
Fault 1: Supply Air Temperature Sensor Offset of -2°C
Fault 2: Supply Air Temperature Sensor Offset of +2°C
Fault 3: Return Air Temperature Sensor Offset of -2°C
Fault 4: Return Air Temperature Sensor Offset of +2°C
Fault 5: Mixed Air Temperature Sensor Offset of -2°C
Fault 6: Mixed Air Temperature Sensor Offset of +2°C
Fault 7: Outdoor Air Temperature Sensor Offset of -2°C
Fault 8: Outdoor Air Temperature Sensor Offset of +2°C
Fault 14: Recirculation Air Damper Stuck Open
Fault 15: Recirculation Air Damper Stuck Closed
Fault 16: Recirculation Air Damper Stuck Half-Way Open
Fault 17: Recirculation Air Damper Leakage (10%)
Fault 19: Stuck Cooling Coil Valve (20% open)
Fault 20: Leaking Cooling Coil Valve (3%)
Fault 23: Stuck Heating Coil Valve (10% open)
Fault 24: Leaking Heating Coil Valve (3%)

The fault case is selected by changing the first line in the input file “input_path_2ini.dat”. Modeling changes associated with the implementation of the faults are made in the FORTRAN file “fault3.inc”.

D.2 Executing a Case

To execute a case, open a command prompt window and type “go2_ini”. The user will be prompted to enter the time; ignore this and press enter. A new window named “modjci” will open, and the user will be asked for the name of the output file for the JCI Residuals. Choose a convenient naming convention, such as the following:

Fault 0 (normal operation) → JCI_rs_f00
Fault 1 → JCI_rs_f01
Fault 15 → JCI_rs_f15
The user will then be prompted to enter the name of the output file for the JCI performance indices. Again, choose a convenient naming convention, such as the following:

- Fault 0 (normal operation) → JCI_pi_f00
- Fault 1 → JCI_pi_f01
- Fault 15 → JCI_pi_f15

The simulation will then begin.

When the simulation has finished, use the “Print Screen” command to capture the plot that appears on the monitor and save the image in a file (for this discussion, the file name used will be “screen_plot.doc”). Next, close the graphic window. The user will be prompted to enter the new time; ignore this and press enter.

### D.3 Post-Processing Simulation Output

HVACSIM+ stores simulation output in the output file specified in “input_path_2ini.dat”. The output file name used for this study was “imp.out”. The executable “sortsb.exe” can be used to extract output data from the file “imp.out”. Instructions for doing this are provided below, beginning with the execution of sortsb.exe, which is started by typing “sortsb” at the command prompt. Input data are shown in bold type face, while text prompting input is shown in italic type face. Explanatory text is shown in parentheses.

```
> sortsb
Input File name: imp.out
Output File name: sb7_f00_1yr (change f00 according to the fault number)
Superblock #: 7
Number of output lines to be skipped =: 0
Number of seconds per unit time: 1
Extract another superblock: N
```

This step can be repeated to extract the data for superblock 8 and 9. The appropriate inputs for each superblock follow:

```
> sortsb
Input File name: imp.out
Output File name: sb8_f00_1yr (change f00 according to the fault number)
Superblock #: 8
Number of output lines to be skipped =: 0
Number of seconds per unit time: 1
Extract another superblock: N

> sortsb
Input File name: imp.out
Output File name: sb9_f00_1yr (change f00 according to the fault number)
```
Superblock #: 9
Number of output lines to be skipped =: 0
Number of seconds per unit time: 1
Extract another superblock: N

Information about the data stored in each superblock is provided in the file “imp.mod”. This file also provides a comprehensive model description in terms of the inputs, outputs, and parameters for each component of the model, as well as initial values for all variables used in the simulation.

Before executing the next case, it is recommended that the user copy the following files into a folder created for the specific fault under consideration (i.e., separate folders are recommended for each fault case):

- Imp.ini
- Imp.fin
- Imp.out
- Imp.sum
- Input_path_2ini.dat
- Fort.9
- Fort.13
- Fort.14
- Jci_rs_f00
- Jci_pi_f00
- Sb7_f00_1yr
- Sb8_f00_1yr
- Sb9_f00_1yr
- Screen_plot.doc