a. Sensor shall be deemed outside of its widest possible operating range if any of the following are true:

1. Feedback less than 2 mA from any 4 to 20 mA transducer; or

2. Temperature reading less than 0°F from any temperature sensor.

b. Any sensor that goes outside of its widest possible operating range.

1. If the sensor is used for monitoring only: Level 3.

2. If the sensor is used for control: Level 2.

5.21.11. Automatic Fault Detection and Diagnostics

The Automatic Fault Detection and Diagnostics (AFDD) routines for hot water plants continually assess plant performance by comparing the values of BAS inputs and outputs to a subset of potential fault conditions. The subset of potential fault conditions that is assessed at any point depends on the Operating State of the plant, as determined by the positions of the isolation valves and statuses of pumps. Time delays are applied to the evaluation and reporting of fault conditions, to suppress false alarms. Fault conditions that pass these filters are reported to the building operator as alarms along with a series of possible causes.

These equations assume that the plant is equipped with isolation valves, as well as a pump status monitoring. If any of these components are not present, the associated tests, and variables should be omitted from the programming.

Note that these faults rely on reasonably accurate measurement of water temperature. Extra precision sensors installed in thermowells with thermal paste are recommended for best accuracy.

5.21.11.1. AFDD conditions are evaluated continuously for the plant.

5.21.11.2. The Operating State (OS) of the plant shall be defined by the commanded positions of the valves and status feedback from the pumps in accordance with the following table. For hybrid plants, determine the Operating State for each primary loop.

The Operating State is distinct from and should not be confused with the hot water plant stage.

OS#1 – OS#3 represent normal operation during which a fault may nevertheless occur, if so determined by the fault condition tests below.

Operating State	Boiler Isolation Valve or Dedicated Primary HW Pump Status	PHW Pump Status (if primary-only) or SHW Pump Status (if primary-secondary)
#1: Disabled	All Closed/Off	All Off
#2: One boiler enabled	One Open/On, All Others Closed/Off	Any On
#3: More than one boiler enabled	Any Open/On	Any On

5.21.11.3. The following points must be available to the AFDD routines for the hot water plant:

Retain the following two variables for primary-secondary plants and primary-only plants where pump speed is controlled to maintain differential pressure. Delete otherwise.

a. DP = Hot water loop differential pressure (each loop, where applicable)

b. DPSP = Hot water loop differential pressure setpoint (each loop, where applicable)

Retain the following variable if there is a flow meter in the primary loop. Delete otherwise.

c. $FLOW_P$ = Primary hot water flow (each primary loop, where applicable)

Retain the following variable if there is a flow meter in the secondary loop. Delete otherwise.

d. $FLOW_S$ = Secondary hot water flow (each secondary loop, where applicable)

Retain the following two variables for primary-only plants with a minimum flow bypass valve. Delete otherwise.

e. MFBPV = Hot water minimum flow bypass valve command; 0% ≤ MFBPV ≤ 100%

f. HW-MinFlowSP = Effective minimum hot water flow setpoint (equal to MinFlowRatio multiplied by the sum of HW-MinFlowX of operating boilers)

Retain the following variable for primary-secondary plants where pump speed is controlled to maintain differential pressure. Delete otherwise.

g. $Speed_{HWP}$ = Secondary hot water pump speed command; 0% ≤ SpeedHWP ≤ 100%

Retain the following variable for primary-only plants where pump speed is controlled to maintain differential pressure. Delete otherwise.

h. $Speed_{HWP}$ = Hot water pump speed command; 0% ≤ SpeedHWP ≤ 100%

i. $Status_{PHWP}$ = Lead primary hot water pump status (each primary loop, where applicable)

Retain the following variable for primary-secondary plants. Delete otherwise.

j. $Status_{SHWP}$ = Lead secondary hot water pump status (each secondary loop, where applicable)

k. HWST = Common hot water supply temperature

l. HWSTSP = Hot water supply temperature setpoint

m. HWRT = Average boiler entering water temperature (each loop)

Retain the following variable for plants headered primary pumps. Delete otherwise.

n. $HWISO_{B\text{-}x}$ = B-x hot water isolation valve commanded position (each boiler)

Retain the following variable for plants where system gauge pressure is monitored. Delete otherwise.

o. P_{GAUGE} = Hot water system gauge pressure

5.21.11.4. The following values must be continuously calculated by the AFDD routines:

a. 5-minute rolling averages with 1-minute sampling time of the following point values; operator shall have the ability to adjust the averaging window and sampling period for each point independently

1. $HWST_{AVG}$ = rolling average of the common hot water supply temperature (each primary loop, where applicable)
2. $HWRT_{AVG}$ = rolling average of the average boiler entering water return temperature.

Retain the following variable for plants where system gauge pressure is monitored. Delete otherwise.

3. $P_{GAUGE, AVG}$ = rolling average of hot water system gauge pressure

Retain the following variable for primary-secondary plants and primary-only plants where pump speed is controlled to maintain differential pressure. Delete otherwise.

4. DP_{AVG} = rolling average of loop differential pressure (each loop, where applicable)

Retain the following variable if there is a flow meter in the primary loop. Delete otherwise.

5. $FLOW_{P,\ AVG}$ = rolling average of primary hot water flow (each loop, where applicable)

Retain the following variable if there is a flow meter in the secondary loop. Delete otherwise.

6. $FLOW_{S,\ AVG}$ = rolling average of secondary hot water flow (each loop, where applicable)
7. $HWST_{B\text{-}x}$ = rolling average of B-x hot water supply temperature (each boiler)
8. $HWRT_{B\text{-}x}$ = rolling average of B-x hot water return temperature (each boiler)

b. $HWFlow_{B\text{-}X}$ (each boiler)

Retain the following section for plants with headered primary pumps. Delete otherwise.

1. For plants with headered primary hot water pumps: 1 if $HWISO_{B\text{-}X}$ = open, 0 if $HWISO_{B\text{-}X}$ = closed

Retain the following section for plants with dedicated primary pumps. Delete otherwise.

2. For plants with dedicated primary hot water pumps: 1 if $Status_{PHWP}$ = on, 0 if $Status_{PHWP}$ = off

c. ΔOS = number of changes in Operating State during the previous 60 minutes (moving window)

d. ΔStage = number of hot water plant stage changes during the previous 60 minutes (moving window)

e. $Starts_{B\text{-}x}$ = number of B-x starts in the last 60 mins (each boiler)

5.21.11.5. The following internal variables shall be defined. All parameters are adjustable by the operator, with initial values as given below:

The default values have been intentionally biased towards minimizing false alarms at the expense of missing real alarms. This avoids excessive false alarms that will erode user confidence and responsiveness. However, if the goal is to achieve the best possible energy performance and system operation, these values should be adjusted based on field measurement and operational experience.

Values for physical factors such as pump heat and sensor error can be measured in the field or derived from trend logs and hardware submittals. Likewise, the switch delays can be refined by observing the time required to achieve quasi steady state operation in trend data.

Other factors can be tuned by observing false positives and false negatives (i.e., unreported faults). If transient conditions or noise cause false alarms, increase the alarm delay. Likewise, failure to report real faults can be addressed by adjusting the temperature, pressure or flow thresholds.

Variable Name	Description	Default Value
ε_{HWT}	Temperature error threshold for hot water temperature sensors	5°F
Retain the following variable for primary-secondary and primary-only plants where pump speed is controlled to maintain differential pressure. Delete otherwise.		
ε_{DP}	Differential pressure error threshold for DP sensor	2 psi
ε_{FM}	Flow error threshold for flow meter	20 gpm
Retain the following variable for plants with variable speed pumps. Delete otherwise.		
ε_{VFDSPD}	VFD speed error threshold	5%

Variable Name	Description	Default Value
Retain the following variable for primary-only plants with a minimum flow bypass valve. Delete otherwise.		
ε_{MFBVP}	Minimum flow bypass valve position error threshold	5%
Retain the following variable for plants where system gauge pressure is monitored. Delete otherwise.		
ETPreChargePress	Hot water system expansion tank pre-charge pressure	See mechanical schedule (psig)
CondTemp	Boiler condensing temperature threshold	135°F
$BStarts_{MAX}$	Maximum number of boiler starts during the previous 60 minutes (moving window)	2
ΔOS_{MAX}	Maximum number of changes in Operating State during the previous 60 minutes (moving window)	2
$\Delta Stage_{MAX}$	Maximum number of hot water plant stage changes during the previous 60 minutes (moving window)	2
StageDelay	Time in minutes to suspend Fault Condition evaluation after a change in stage	30
AlarmDelay	Time in minutes that a Fault Condition must persist before triggering an alarm	30
TestModeDelay	Time in minutes that Test Mode is enabled	120

TestModeDelay ensures that normal fault reporting occurs after the testing and commissioning process is completed as prescribed in Section 5.21.11.12.

5.21.11.6. The following are potential Fault Conditions that can be evaluated by the AFDD routines. If the equation statement is true, then the specified fault condition exists. The Fault Conditions to be evaluated at any given time will depend on the Operating State of the hot water plant.

Edit the table below. Remove fault conditions that do not apply.

Retain the following fault condition for plants with any hot water pumps controlled to maintain differential pressure. Delete otherwise. Duplicate the following fault condition for each differential pressure sensor.			
FC#1	**Equation**	$DP_{AVG} > \varepsilon_{DSP}$ and $Status_{HWP} = Off$	**Applies to OS #1**
	Description	Differential pressure is too high with the hot water pumps off	
	Possible Diagnosis	DP sensor error	
Retain the following fault condition if there is a flow meter in the primary loop. Delete otherwise. Duplicate the following fault condition for each primary loop with a flow meter.			

<table>
<tr><td rowspan="3">FC#2</td><td>Equation</td><td>$FLOW_{P,\,AVG} > \varepsilon_{FM}$
and
$Status_{PHWP} = Off$</td><td rowspan="3">Applies to OS #1</td></tr>
<tr><td>Description</td><td>Primary hot water flow is too high with the hot water pumps off</td></tr>
<tr><td>Possible Diagnosis</td><td>Flow meter error</td></tr>
<tr><td colspan="4">Retain the following fault condition for primary-secondary plants with a flow meter in the secondary loop. Delete otherwise. Duplicate the following fault condition for each secondary loop flow meter.</td></tr>
<tr><td rowspan="3">FC#3</td><td>Equation</td><td>$FLOW_{S,\,AVG} > \varepsilon_{FM}$
and
$Status_{SHWP} = Off$</td><td rowspan="3">Applies to OS #1</td></tr>
<tr><td>Description</td><td>Secondary hot water flow is too high with the associated hot water pumps off</td></tr>
<tr><td>Possible Diagnosis</td><td>Flow meter error</td></tr>
<tr><td colspan="4">Retain the following fault condition for primary-secondary plants and primary-only plants where pump speed is controlled to maintain differential pressure. Delete otherwise. Duplicate the following fault condition for each differential pressure sensor and/or each secondary loop where pump speed is controlled to maintain differential pressure.</td></tr>
<tr><td rowspan="3">FC#4</td><td>Equation</td><td>$DP_{AVG} < DPSP - \varepsilon_{DP}$
and
$Speed_{HWP} \geq 99\% - \varepsilon_{VFDSPD}$</td><td rowspan="3">Applies to OS #2, #3</td></tr>
<tr><td>Description</td><td>Hot water loop differential pressure is too low with hot water pump(s) at full speed.</td></tr>
<tr><td>Possible Diagnosis</td><td>Problem with VFD
Mechanical problem with pump(s)
Pump(s) are undersized
Differential pressure setpoint is too high
HWST is too low
Primary flow is higher than the design flow of the operating boilers</td></tr>
<tr><td colspan="4">Retain the following fault condition for primary-only plants with a minimum flow bypass valve. Delete otherwise.</td></tr>
<tr><td rowspan="3">FC#5</td><td>Equation</td><td>$FLOW_{P,\,AVG} < HW\text{-}MinFlowSp - \varepsilon_{FM}$
and
$MFBPV \geq 99\% - \varepsilon_{MFBPV}$</td><td rowspan="3">Applies to OS #2, #3</td></tr>
<tr><td>Description</td><td>Primary hot water flow is too low with the minimum flow bypass valve fully open.</td></tr>
<tr><td>Possible Diagnosis</td><td>Problem with minimum flow bypass valve
Problem with boiler isolation valves
Minimum loop differential pressure setpoint too low</td></tr>
<tr><td colspan="4">For hybrid plants, duplicate the following fault condition for each primary loop.</td></tr>
</table>

FC#6	**Equation**	$HWST_{AVG} + \varepsilon_{HWT} < HWSTSP$	**Applies to OS #2, #3**
	Description	Hot water supply temperature is too low.	
	Possible Diagnosis	Mechanical problem with boilers Primary flow is higher than the design flow of the operating boilers Deviation between the internal boiler hot water supply temperature sensor and the plant hot water supply temperature is too high (i.e. boiler sensor is out of calibration).	
Retain the following fault condition for plants where system gauge pressure is monitored. Delete otherwise.			
FC#7	**Equation**	$P_{GAUGE,\ AVG} < 0.9 * ETPreChargePress$	**Applies to OS #1 – #3**
	Description	Hot water system gauge pressure is too low	
	Possible Diagnosis	Possible hot water system leak	
Retain the following fault condition for plants with a condensing boiler. Delete otherwise.			
FC#8	**Equation**	$HWRT_{AVG} - \varepsilon_{HWT} > CondTemp$	**Applies to OS #2, #3**
	Description	Hot water return temperature is too high for condensing to occur.	
	Possible Diagnosis	Hot water supply temperature setpoint is too high. Hot water load is too low. High bypass flow is raising the entering water temperature. Hot water coils are not designed for condensing at current loads.	
Retain the following fault condition for plants with a non-condensing boiler. Delete otherwise.			
FC#9	**Equation**	$HWRT_{AVG} + \varepsilon_{HWT} < CondTemp$	**Applies to OS #2, #3**
	Description	Hot water return temperature is too low. Condensing is likely to occur.	
	Possible Diagnosis	Hot water supply temperature setpoint is too low.	
Retain the following fault condition if any boiler has a network interface and the plant has a common hot water supply temperature sensor at the discharge of the boiler(s). Delete otherwise. For hybrid plants, duplicate the following fault condition for each primary loop.			
FC#10	**Equation**	$\lvert (\sum(HW\text{-}Flow_{B\text{-}X} * HWST_{B\text{-}X}) / \sum HW\text{-}Flow_{B\text{-}X}) - HWST_{AVG} \rvert > \varepsilon_{HWT}$	**Applies to OS #2**
	Description	Deviation between the active boiler hot water supply temperature and the common hot water supply temperature is too high.	
	Possible Diagnosis	A hot water supply temperature sensor is out of calibration	
Retain the following fault condition if any boiler has a network interface and the plant has a common hot water return temperature sensor at the inlet of the boiler(s). Delete otherwise. For hybrid plants, duplicate the following two fault condition for each primary loop.			

FC#11	**Equation**	$\lvert (\sum(HW\text{-}Flow_{B\text{-}X} * HWRT_{B\text{-}X}) / \sum HW\text{-}Flow_{B\text{-}X}) - HWRT_{AVG} \rvert > \varepsilon_{HWT}$	**Applies to OS #2**
	Description	Deviation between the active boiler hot water return temperature and the common boiler entering water temperature is too high.	
	Possible Diagnosis	A hot water return temperature sensor is out of calibration	
FC#12	**Equation**	$\Delta OS > \Delta OS_{MAX}$	**Applies to OS #1 – #3**
	Description	Too many changes in Operating State	
	Possible Diagnosis	Unstable control due to poorly tuned loop or mechanical problem	
FC#13	**Equation**	$\Delta StartsB\text{-}x > \Delta BStart_{MAX}$	**Applies to OS #2, #3**
	Description	Too many boiler starts	
	Possible Diagnosis	Boiler is cycling due to load loads Boiler is oversized and/or has insufficient turndown. Boiler stage-up threshold may be set too low.	
FC#14	**Equation**	$\Delta Stage > \Delta Stage_{MAX}$	**Applies to OS #1 – #3**
	Description	Too many stage changes	
	Possible Diagnosis	Staging thresholds and/or delays need to be adjusted	

5.21.11.7. A subset of all potential fault conditions is evaluated by the AFDD routines. The set of applicable fault conditions depends on the Operating State of the plant:

Edit the list of operating states and associated fault conditions to match those in the operating state and fault condition tables above.

a. In OS #1 (Disabled), the following Fault Conditions shall be evaluated:

1. FC#1: Differential pressure is too high with the hot water pumps off
2. FC#2: Primary hot water flow is too high with the primary hot water pumps off
3. FC#3: Secondary hot water flow is too high with the associated secondary hot water pumps off
4. FC#7: Hot water system gauge pressure is too low
5. FC#10: Too many changes in operating state
6. FC#12: Too many stage changes

b. In OS#2 (One boiler enabled), the following Fault Conditions shall be evaluated:

1. FC#4: Hot water loop differential pressure is too low with hot water pump(s) at full speed.
2. FC#5: Primary hot water flow is too low with the minimum flow bypass valve fully open.
3. FC#6: Hot water supply temperature is too low

4. FC#7: Hot water system gauge pressure is too low
5. FC#8: Hot water return temperature is too high for condensing to occur
6. FC#9: Hot water return temperature is too low. Condensing is likely to occur
7. FC#10: Deviation between the active boiler hot water supply temperature and the common hot water supply temperature is too high.
8. FC#11: Deviation between the active boiler hot water return temperature and the common boiler entering water temperature is too high.
9. FC#12: Too many changes in Operating State
10. FC#13: Too many boiler starts
11. FC#14: Too many stage changes

c. In OS#3 (More than one boiler enabled), the following Fault Conditions shall be evaluated:

1. FC#4: Hot water loop differential pressure is too low with hot water pump(s) at full speed.
2. FC#5: Primary hot water flow is too low with the minimum flow bypass valve fully open.
3. FC#6: Hot water supply temperature is too low
4. FC#7: Hot water system gauge pressure is too low
5. FC#8: Hot water return temperature is too high for condensing to occur
6. FC#9: Hot water return temperature is too low. Condensing is likely to occur
7. FC#12: Too many changes in Operating State
8. FC#13: Too many boiler starts
9. FC#14: Too many stage changes

5.21.11.8. For each boiler, the operator shall be able to suppress the alarm for any Fault Condition.

5.21.11.9. Evaluation of Fault Conditions shall be suspended under the following conditions:

a. When no pumps are operating.

b. When all equipment associated with a fault condition in maintenance mode.

c. For a period of StageDelay minutes following a change in plant stage.

5.21.11.10. Fault Conditions that are not applicable to the current Operating State shall not be evaluated.

5.21.11.11. A Fault Condition that evaluates as true must do so continuously for AlarmDelay minutes before it is reported to the operator.

5.21.11.12. Test Mode shall temporarily set StageDelay and AlarmDelay to 0 minutes for a period of TestModeDelay minutes to allow instant testing of the AFDD system and to ensure normal fault detection occurs after testing is complete.

5.21.11.13. When a Fault Condition is reported to the operator, it shall be a Level 3 alarm and shall include the description of the fault and the list of possible diagnoses from the table in 5.21.11.6.

5.10 Fan Coil Unit

5.22.1. See "Generic Thermal Zones" (Section 5.3) for setpoints, loops, control modes, alarms, etc.

5.22.2. See Section 3.1.7 for Cool_SAT, Heat_SAT, and DP100.