Predictive Maintenance for High Reliability Equipment

Building Automation/HVAC
Brian Dempsey
Today’s Agenda:

• Commercial HVAC fundamentals overview
• What is predictive maintenance?
• Examples of predictive maintenance
  ▪ Smart filter replacement
  ▪ HVAC run capacitor failure
  ▪ Refrigerant leak detection
  ▪ Motor health vibration monitoring
Commercial HVAC Overview

- Chiller
- Boiler
Refrigeration Cycle Comparison

Residential System

Commercial System

Water is used in large commercial chillers to transport heat energy.
Why use water?
Water has the ability to sustain temperature over greater distances than refrigerants. So refrigerant is used in a small space to chill the water before pumping it to air handlers.
HVAC Chiller: **Functional Overview**

Sensor data used for predictive maintenance
HVAC Cooling Tower: Functional Overview

- Heat Out
- Outside Air from Condenser
- Outside Air to Condenser
HVAC Boiler: Functional Overview
Typical Commercial HVAC System
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• Examples of predictive maintenance
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  ▪ HVAC run capacitor failure
  ▪ Refrigerant leak detection
  ▪ Motor health vibration monitoring
What is Predictive Maintenance?

**Predictive Maintenance** - A **non-invasive** task intended to identify a specific condition of an asset. At the conclusion of a predictive task, the asset remains “good as old”. While the owner of the asset knows more about the condition of the asset, the condition of the asset has not been altered.

- The ultimate goal of the approach is to perform maintenance at a scheduled point in time when the maintenance activity is most **cost-effective** and before the equipment loses performance within a threshold.

- This results in a **reduction in unplanned downtime costs** because of failure where for instance costs can be in the hundreds of thousands per day depending on industry.

- Direct monitoring of equipment performance during normal operation to **anticipate** failure.
Predictive Maintenance: Challenges

- Implementing predictive maintenance programs can be more complex than periodic maintenance.
- Can be very difficult and costly to make accurate prognostications.

**Principle Driven**
- Prediction Approaches based on physical laws

**Data Driven**
- Prediction Approaches based on sensor data

**Gray Area**
- Implementing predictive maintenance programs can be more complex than periodic maintenance.
- Can be very difficult and costly to make accurate prognostications.

**Principle-Driven**
- Supplement Data that is difficult to measure
- Lead to a highly accurate predictive model

**Data-Driven**
- Using data acquired from equipment
- Develop predictive models based on statistical techniques
Preventative maintenance has less failures over time but higher overall cost due to material requirements.

Predictive maintenance cost is a balance between reactive and preventative. This lowers overall maintenance costs.

Reactive maintenance cost is significantly higher due to repair costs with higher number of failures over time.
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  ▪ HVAC run capacitor failure
  ▪ Refrigerant leak detection
  ▪ Motor health vibration monitoring
HVAC Coil Airflow Sensor Reference Design for Predictive Maintenance in Air Filter Replacement

Predictive Maintenance
Industry Challenge

Problem
Over time, air handler evaporator coils can become dirty, reducing airflow. This reduction in airflow results in:

1. Inadequate heat transfer
2. Increased the likelihood of coil freeze
3. Complete blockage of all airflow
4. Strain on HVAC system
Project Details

Proposed Solution

- Airflow Sensor Attached At Filter and Blower
- Measures Vibration Differential
- Temp Sensor Mounted To The Coil
- Compressor Cut-off Switch Based On Sensor Output Prevents Freezing

Solution Benefits

- Eliminate service charges
- Potentially save money on filters
- Know when to change filter based on efficiency
- Energy saving focused design
- Easy AC tech diagnosis based on MCU output
Description

This design provides a reference for monitoring airflow efficiency and temperature through heat ventilation and air conditioner (HVAC) systems. The reference design is used in conjunction with solid state relays and piezoelectric vibration sensors to monitor and react accordingly to low airflow and low temperature conditions through the air handler. The system also includes a calibration algorithm for consistent performance across all system setups.

Features

• Sensor polling only during HVAC system cycle
• Airflow differential based system alerts
• Temperature sub-threshold condenser cutoff relay
• Fan override run relay [optional]
• Powered off existing HVAC 24VAC Transformer
• $10^{15}$ write cycle endurance Ferroelectric RAM

Visit: ti.com/tidesigns

Part number: TIDA-01070
**Predictive Maintenance: HVAC Smart Filter Monitor (Wireless)**

**Target end equipments:**
- HVAC
- Predictive maintenance
- Air quality

**Reference design**
- Smart filter monitor

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**Piezoelectric vibration sensor**

- 3.3V
- $V_{\text{Sensor}} = 1.65V$

**Op-amp TLV4313**

**Temp LMT84**

**Temp/humidity HDC2080**

**MCU CC1312 Launchpad**

**Signal amplification and conditioning**

**LED indicator**

**New!**
HVAC Filter Monitoring: Field Testing Setup

- Blower Wheel Sensor
- Filter Sensor
- Anemometer Placement

Paper is used to simulate partial blockage and full blockage.

Piezoelectric sensors are placed in proper locations for data acquisition.

Clean Filter
Dirty Filter
## HVAC Smart Filter Monitor: Airflow Monitoring

### Trial Data

<table>
<thead>
<tr>
<th>Trial</th>
<th>Max Airflow at Filter</th>
<th>Return CFM</th>
<th>Avg Airflow</th>
<th>Return Air Condition</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>274</td>
<td>618.40156</td>
<td>255</td>
<td>No Blockage</td>
</tr>
<tr>
<td>2</td>
<td>333</td>
<td>751.56102</td>
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<td>No Blockage</td>
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<td>294</td>
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<td>294</td>
<td>663.54036</td>
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<td><strong>Average:</strong> 298.75</td>
<td>674.260825</td>
<td>269.25</td>
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<table>
<thead>
<tr>
<th>Trial</th>
<th>Max Airflow at Filter</th>
<th>Return CFM</th>
<th>Avg Airflow</th>
<th>Return Air Condition</th>
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<tbody>
<tr>
<td>5</td>
<td>646</td>
<td>269.166882</td>
<td>627</td>
<td>Partially Blocked</td>
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<tr>
<td>6</td>
<td>654</td>
<td>272.500218</td>
<td>634</td>
<td>Partially Blocked</td>
</tr>
<tr>
<td>7</td>
<td>655</td>
<td>272.916885</td>
<td>634</td>
<td>Partially Blocked</td>
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<tr>
<td>8</td>
<td>654</td>
<td>272.500218</td>
<td>634</td>
<td>Partially Blocked</td>
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<tr>
<td></td>
<td><strong>Average:</strong> 652.25</td>
<td>271.7710508</td>
<td>632.25</td>
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</table>

- **Large differential when air filter is not blocked.**
- **As the filter is blocked, the differential between the sensor data becomes significantly reduced.**

- **Higher vibration during blockage coincides with anemometer results.**
HVAC Smart Filter Monitor: Field Test Results

TIDA-01070 Board Output for **Clean and Dirty Filter**

TIDA-01070 Board Output For **Clean to Dirty Test**
Predictive HVAC Run-Capacitor Failure Monitor for Permanent Split Capacitor Motors

*Predictive Maintenance*
System Introduction

Air Handler

Blower Assembly

PSC Blower Motor

Blower Wheel
Run-capacitors are one of the most common causes of HVAC system malfunction due to their long run time and heavy use.

Easy retrofit design monitors the run capacitor. Capacitance is extracted mathematically and used to determine if the capacitor is in rated operating range.
New Approach: Capacitor Failure Detection

- This new method allows a *predictive indication* with respect to the failure of a run-capacitor in an HVAC system.

- *Run-capacitors are one of the most common causes of HVAC system malfunction due to their long run time and heavy use.* This method will help to predict a capacitor failure before it happens, preventing unnecessary wear and tear on the remainder of the system.

- *Easy retrofit design monitors the phase between the terminals of the run capacitor.* Capacitance is extracted mathematically and used to determine if the capacitor is in rated operating range.
PSC Motor Existing Application in HVAC

Diagram showing the connection of a PSC motor in an HVAC system. The diagram includes labels for L1 and L2, which are the lines in the system. The circuit includes a disconnect box, a contactor, a cartridge or plug fuse, and an outdoor condenser unit. The diagram also shows connections for the compressor or fan motor and other electrical components.
PSC Motor: Solution for Predictive Maintenance

Board is placed in series with main and auxiliary lines using blade connectors for easy retrofit

Power to board provided by L1 or L2 and GND from Contactor
PSC Motor Currents and Resulting Flux Density
Currents Phase Shift in Two-Phase Motor

Airgap Gap Flux Density
\( \phi = 90^\circ \)

Airgap Gap Flux Density
\( \phi = 65^\circ \)
Test Setup Overview

Capacitance is varied by adding or removing additional capacitors in series with run capacitor.

- PSC Motor
- Custom Motor Mount
- Platform
- Dynamometer Brake
- Dynamometer Brake Control

Dynamometer is used to extract the torque of the PSC motor with a load.
Test Results: Operating Points

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<tr>
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<tr>
<td>838.2</td>
<td>22.9</td>
<td>26.3</td>
<td>100%</td>
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<tr>
<td>817.5</td>
<td>21.8</td>
<td>16.7</td>
<td>64%</td>
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<td>804.0</td>
<td>21.0</td>
<td>12.1</td>
<td>46%</td>
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<td>777.5</td>
<td>19.7</td>
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Matlab Simulations: Easy Analysis for Any Motor

**Table:**

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<thead>
<tr>
<th>Name</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ia_r</td>
<td>Rotor current k_a</td>
</tr>
<tr>
<td>ia_b</td>
<td>Rotor current k_b</td>
</tr>
<tr>
<td>i_r</td>
<td>Rotor current i_a</td>
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<tr>
<td>i_d</td>
<td>Rotor current i_d</td>
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<tr>
<td>phi_r</td>
<td>Rotor flux phir_a</td>
</tr>
<tr>
<td>phi_d</td>
<td>Rotor flux phir_d</td>
</tr>
<tr>
<td>ias</td>
<td>Main winding stator current i_a</td>
</tr>
<tr>
<td>ibs</td>
<td>Auxiliary winding stator current i_b</td>
</tr>
<tr>
<td>phis</td>
<td>Stator flux phis_s(V.s)</td>
</tr>
<tr>
<td>phids</td>
<td>Stator flux phis_d(V.s)</td>
</tr>
<tr>
<td>vc</td>
<td>Voltage capacitor Vc</td>
</tr>
<tr>
<td>w</td>
<td>Rotor speed</td>
</tr>
<tr>
<td>Te</td>
<td>Electromagnetic torque Te</td>
</tr>
<tr>
<td>theta</td>
<td>Rotor angle theta</td>
</tr>
</tbody>
</table>

**Diagram:**

- **Continuous power output**
  - Single-Phase Asynchronous Machine
  - Capacitor-Start-Run
  - Total current
  - Speed (RPM)
  - Rotor current (A)
  - Speed (RPM)

**Note:**

Visit [https://www.mathworks.com/help/phystools/examples/1phaseasynchronousmachine.html](https://www.mathworks.com/help/phystools/examples/1phaseasynchronousmachine.html) for more details.
Motor Parameters and Simulation

PSC Motor Ramp Up Time

- Speed (RPM): Motor 1
- Speed (RPM): Motor 2

Points:
- X 0.4621 Y 900.1
- X 0.5348 Y 900.1

Graph showing the ramp up time of PSC motors.
Non-Invasive HVAC System Pressure Monitoring for Advanced Predictive Maintenance

Predictive Maintenance
• Most methods based on gauge attachment to pressure ports
• Retrofitting is not good because it is invasive; requires pump down of the system to integrate pressure sensors
• Small leaks can be overlooked and hard to find using leak detector devices
Non-Invasive **Pressure Measuring**

- Can use standard charging method with substituted pressure, or energy absorption from load and temperature to obtain refrigerant level.
- Indiscriminant of system size.
- Can be used to detect other HVAC system issues as well.
- Part of the HVAC predictive maintenance sector, introducing new concept not yet implemented in industry.
Proposed Solution

For this solution we are implementing a non-invasive method for refrigerant leak detection. This method is based on 5 measurements on the evaporator and condenser.

Measurement Parameters are:

- Indoor incoming air load (Temp/ Relative Humidity in Evap.)
- Outdoor air temperature (Condenser Coil)
- Incoming refrigerant temperature (Evaporator)
- Outgoing refrigerant temperature (Evaporator)
Proposed Solution Block Diagram

Indoor Air Handler
- HDC2080
- TMP235
- T_{IN,E}

CC3220
- RH_{E}
- T_{AE}

TPS7A78
- T_{OUT,E}

Outdoor Condenser
- TMP235
- T_{AC}

CC3220
- T_{AC}
- T_{AC}
- 110V
Field Application Overview

Load Temperature & Humidity for WBT and Enthalpy

Condenser coil intake dry bulb air temperature

Liquid/Suction Line Temperature
Calculation Algorithm for Refrigeration Status

\[ T_{AE} \] \rightarrow \text{Wet Bulb Temperature Algorithm} \rightarrow T_W \rightarrow \text{Ideal Superheat Lookup Table} \rightarrow \begin{cases} T_{SH,\text{OPT}} \end{cases} \rightarrow \text{Comparator} \rightarrow \text{Refrigerant Status}

\[ \begin{align*} T_{AC} & \rightarrow \text{Wet Bulb Temperature Algorithm} \rightarrow T_W \\ T_{IN,E} & \rightarrow \text{TOUT,E} - T_{IN,E} \\ T_{OUT,E} & \rightarrow \text{Refrigerant Status} \end{align*} \]
Variables Needed:
1. Suction line temperature
2. Evaporator Inlet Pressure (derived through the temp/pressure of refrigerant)
3. Outdoor coil inlet dry bulb temp
4. Indoor coil inlet wet bulb (use empirical formula based on temp and humidity)

Process:
1. Obtain variable values above
2. Find superheat value based on chart to left
3. Obtain superheat through suction line temperature @ service valve and temperature right after expansion valve indoor.
4. Suction Higher ±2°F → **Refrigerant under charged**
5. Suction Lower ±2°F → **Refrigerant over charged**
Predictive Maintenance: Matlab Simulations
Simulation Setup:
Environmental Temperature = 65.9°F
Initial Vapor Quality = 30%
Outdoor Condenser Temperature = 80°F

Simulation Results:
Superheat = 8.5K → 15.3°F
Required Superheat w/ given conditions= 16°F ± 2°F

- Simulation yields similar results with 4.375% Error
- Results are within bounds of superheat expectations
- The HVAC system is properly charged
Simulation Setup:
Environmental Temperature = 65.9°F
Initial Vapor Quality = 30%
Outdoor Condenser Temperature = 80°F
Initial evap. pressure reduced by ~30%

Simulation Results:
Superheat = 14K → 25.2°F
Required Superheat w/ given conditions= 16°F ± 2°F

- Simulation yields different results with 57.5% error
- Results are not within bounds of superheat as expected
- The HVAC system is not properly charged → Leak Detected
Simulation Results: HVAC Performance Analysis

- Compressor Pressures
- Compartment Heat Extracted
- Mass Flow Rate
- Compressor Pressure Ratio
- Compressor Power
- Evaporator Temperature
Leveraging System Performance to Detect Refrigerant Leaks

**No Leak**
- Pressure ratio: 4.8
- Compressor Power: 135W

**Refrigerant Leak**
- Pressure ratio: 5.6
- Compressor Power: 154W

These system measurements can be used to predict a failure based on increases in both compressor power consumption as well as compression ratio.
Motor Monitoring Using Wireless Vibration Sensor

Predictive Maintenance
Motor Drive Predictive Maintenance

• Monitoring the health of the motor can help prevent unplanned downtime by detecting early warning signs of needed maintenance or replacement

• Source of motor problems:
  - Damaged bearings
  - Oil whirl and whip in bearings
  - Shorted rotor bars
  - Motor unbalanced
  - Eccentricity failure
  - Bent or misaligned shaft
  - Loose stator laminations
  - Looseness of stator support
  - Mechanical looseness
Motor Drive Vibration Measurements

Motor drive vibration measurement TI Design (TIDA-01469) monitors the health of motors to accurately predict and schedule maintenance (or replacement) while minimizing costs and down time during industrial production.
Motor Drive Vibration Measurements (cont.)

- Sensor
- Analog Front End and MCU for FFT
- Power Management and Wireless Node

- Piezo Vibration Sensor
- Amplifier & Filter
- ADC
- MCU

- Voltage Reference

- Power Management
- Energy Harvesting

- CPU + Application
- RF Core
- Antenna Match
Reference Design Testing:
Field Test Setup
Reference Design Testing: Field Test Results

The frequency domain analysis of motor vibration can indicate potential issues before they occur.
Reference Design Testing: Battery Lifetime Analysis

The main parameters that affect the estimated battery life of the entire system are:
- Capacity rating of the battery
- Average standby-state current consumption
- Standby-state duration
- Average sampling and FFT current consumption
- Sampling and FFT duration
- Average advertising packet current consumption
- Advertising duration
- Average connection and data transmission current consumption
- Connection and data transmission duration

<table>
<thead>
<tr>
<th>WAKEUP PERIOD (MIN)</th>
<th>BATTERY LIFE (YEARS)</th>
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<tbody>
<tr>
<td>480</td>
<td>25.112064790</td>
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<tr>
<td>240</td>
<td>23.248417910</td>
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<td>120</td>
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<td>20</td>
<td>8.840325148</td>
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<tr>
<td>10</td>
<td>5.281879421</td>
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</table>
**Description**

This reference design is a low-power wireless subsystem solution that monitors motors using vibration sensing to determine if preventative maintenance is necessary. An FFT of the vibration data can be sent out to another device using either Bluetooth low energy or sub-1GHz wireless protocols. The low power usage and wireless capabilities of this subsystem solution enables it to run on a single coin cell battery, which allows for the device to be small, inexpensive and placed in difficult-to-reach locations. This makes this reference design an ideal alternative to both expensive maintenance that could have been preventatively avoided, as well as larger, more expensive monitors that require a wired connection.

**Features**

- Ultra-low-power design resulting in 10-year battery life from single CR2032 coin cell
- Offers mechanical vibration (20ksp/s) and temperature sensing
- Local computation of 2K FFT for vibration spectral analysis
- Programmable wake-up intervals for motor diagnostics
- Designed for SimpleLink sub-1GHz and Bluetooth Low Energy Wireless Connectivity LaunchPad (LAUNCHXL-CC1350)

Visit: [ti.com/tidesigns](http://ti.com/tidesigns)

Part number: **TIDA-01469**
Thank You!
Algorithm Development: Extracting Enthalpy Values

1. **Calculate the wet-bulb temperature**
   
   \[ T_w = T \cdot \tan^{-1}\left[0.151977 \cdot (RH\% + 8.313659)^{1/2}\right] + \tan^{-1}(T + RH\%) - \tan^{-1}(RH\% - 1.676331) + 0.00391838(RH\%)^{3/2} \cdot \tan^{-1}(0.023101 \cdot RH\%) - 4.686035 \]

2. **Calculate the saturation vapor pressure of load**
   
   \[ \vartheta = 1 - \frac{T}{T_e} \]
   
   \[ B\left(\frac{P_{sw}}{P_c}\right) = \frac{T_c}{T}\left(C_1\vartheta + C_2\vartheta^2 + C_3\vartheta^3 + C_4\vartheta^4 + C_5\vartheta^5\right) \]

   - \( T \) = Temperature in K
   - \( P_{sw} \) = Saturation vapor pressure (hPa)
   - \( T_c \) = Critical temperature, 647.096 K
   - \( P_c \) = Critical pressure 220 640 hPa
   - \( C_1 \) = Coefficients, \(-7.89951783\)
   - \( C_2 \) = 1.84408259
   - \( C_3 \) = 1.7866497
   - \( C_4 \) = 22.6867411
   - \( C_5 \) = -15.9618719
   - \( C_6 \) = 1.80112502

   * Superheat nominal value calculated from load enthalpy of load and supply

3. **Calculate the vapor pressure**
   
   \[ P_v = P_{sw}(T_{out}) - P_{sat} \cdot K \cdot (T_{dry} - T_{out}) \]

   - \( P_{sw} \) = Water vapour saturation pressure
   - \( P_{tot} \) = Total ambient pressure
   - \( K \) = Psychrometer constant 0.000662°C⁻¹

4. **Calculate the mixing ratio**
   
   The mixing ratio (mass of water vapour/mass of dry gas) is calculated using (14):
   
   \[ X = \frac{B-P_v}{P_{sw} - P_v} \frac{[g/kg]}{[g/kg]} \]

   - \( B = 621.9907 \) g/kg
   
   The value of B depends on the gas. 621.9907 g/kg is valid for air.
   
   In general the constant can be calculated using:
   
   \[ B = \frac{M(H_2O)/M(gas)}{1000} \frac{[g/kg]}{[g/kg]} \]

   - \( M(H_2O) \) = Molecular weight of water
   - \( M(gas) \) = Molecular weight of gas

5. **Calculate the load enthalpy**
   
   Enthalpy can be calculated from mixing ratio using (16):
   
   \[ h = T \cdot (1.01 + 0.00189X) + 2.5X \frac{(kJ/kg)}{(kJ/kg)} \]

   - \( T \) = Temperature (°C)
   - \( X \) = Mixing ratio (g/kg)
Non-Invasive Pressure Measuring: Other Considerations

- Temperature of liquid line must be taken directly after the expansion valve to obtain the starting temperature of refrigerant before thermal energy transfer begins.

- Suction line temperature must be taken at exit of AHU or input of compressor due to pressure variation in the evaporator coil based on thermal energy transfer.

- AHU pressure is typically 1.5” water column or 3.74 hPa. Relative to the STP ambient pressure of 1013.25 hPa, this accounts for a 0.37% increase in calculation pressure and is therefore neglected for simplicity.

- Thermal difference between refrigerant and the temp probe is neglected (can use deep learning to detect sudden, or subtle changes from normal levels).

- Temperature is measured ~10-15 minutes into cycle in order to allow for thermal equilibrium between liquid/suction line temperature and sensors.