Smart Monitoring and Diagnostic System Application

DOE Transactional Network Project

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PNNL-SA-99235

Presentation Overview*

- SMDS performance degradation detection methodology
  - Basic method
  - RTUs with constant-speed fans
  - RTUs with multi-speed fans
  - Algorithms for automating the method
- Operational fault detection algorithms

- Cloud Implementation
  - Software architecture
  - Connecting with Transactional Network Platform
  - User interface

- Performance and results
  - Results from 7 Lawrence Berkeley National Laboratory RTUs and 4 Transformative Wave Technology RTUs
  - Results from algorithm testing

*Major sections are color coded and include a color tag with an abbreviated section title at the top right of each page.

SMDS Performance Degradation Detection Algorithm

-- Essence of the Method

Performance Degradation Detection—Essence of the Method

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Objective

- Detect degradation (or improvement) in the cooling performance of packaged air conditioners and heat pumps entirely automatically and using a minimum number of sensed variables

Basic approach

- Characterize the performance of the RTU cooling cycle with an empirically determined relationship between electric power demand (P) and outdoor-air temperature (OAT) for times when the unit is operating at steady state
- This is possible because steady-state power consumption is not affected by changes in cooling load (e.g., from changes in thermostat setting)
- Define steady state operation as times when the power demand does not change appreciably between successive measurement times
- Detect changes in the P vs. OAT relationship over time, which correspond to changes in the performance of the RTU cooling function (efficiency, capacity or both)
- Determine the energy consumption impact of the detected change to establish whether performance has degraded or improved

Performance Degradation Detection- Essence of the Method

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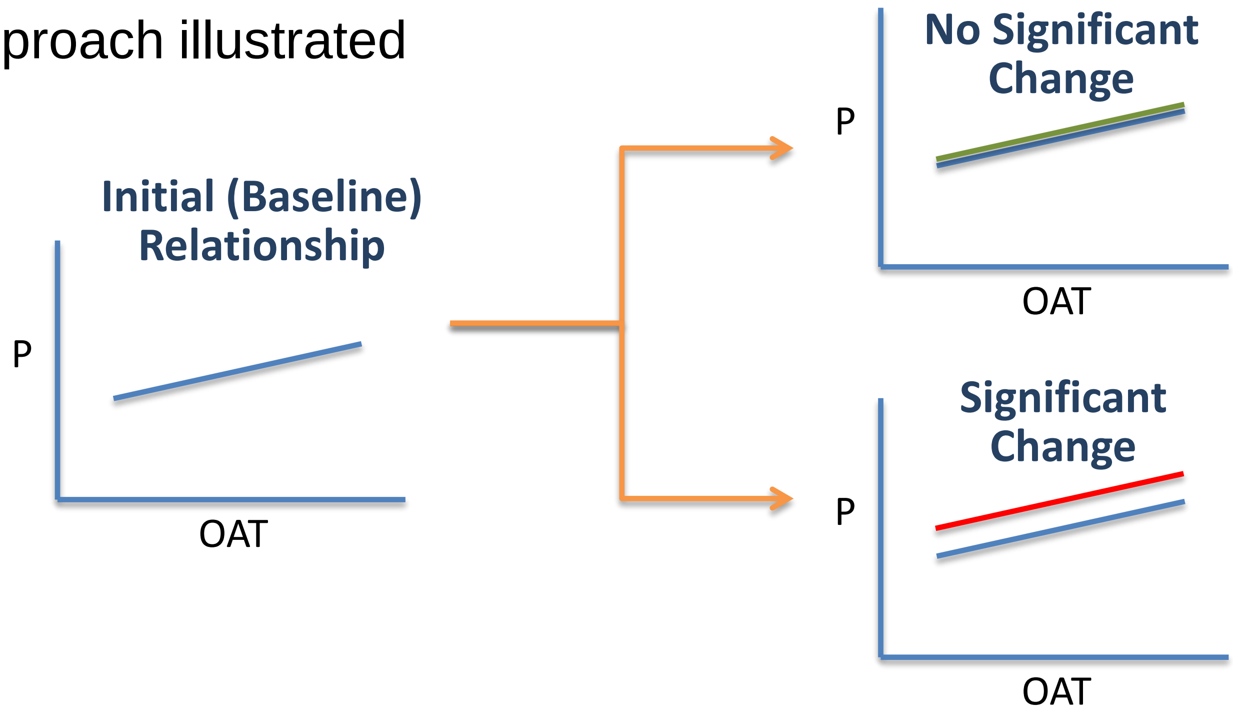
Basic approach (continued)

- The sign (positive or negative) of the detected average change in the P-OAT relationship does not reveal whether performance degradation or improvement has occurred; the sign of the change in energy use reveals this.
- Monitor P vs. OAT characteristics over time to detect when changes occur and quantify energy impacts when detected

Basic approach illustrated



SMDS Performance Degradation Detection Algorithm

-- Single-stage RTU with constant-speed fan

Performance Degradation Detection for One-stage RTU with constant-speed fan

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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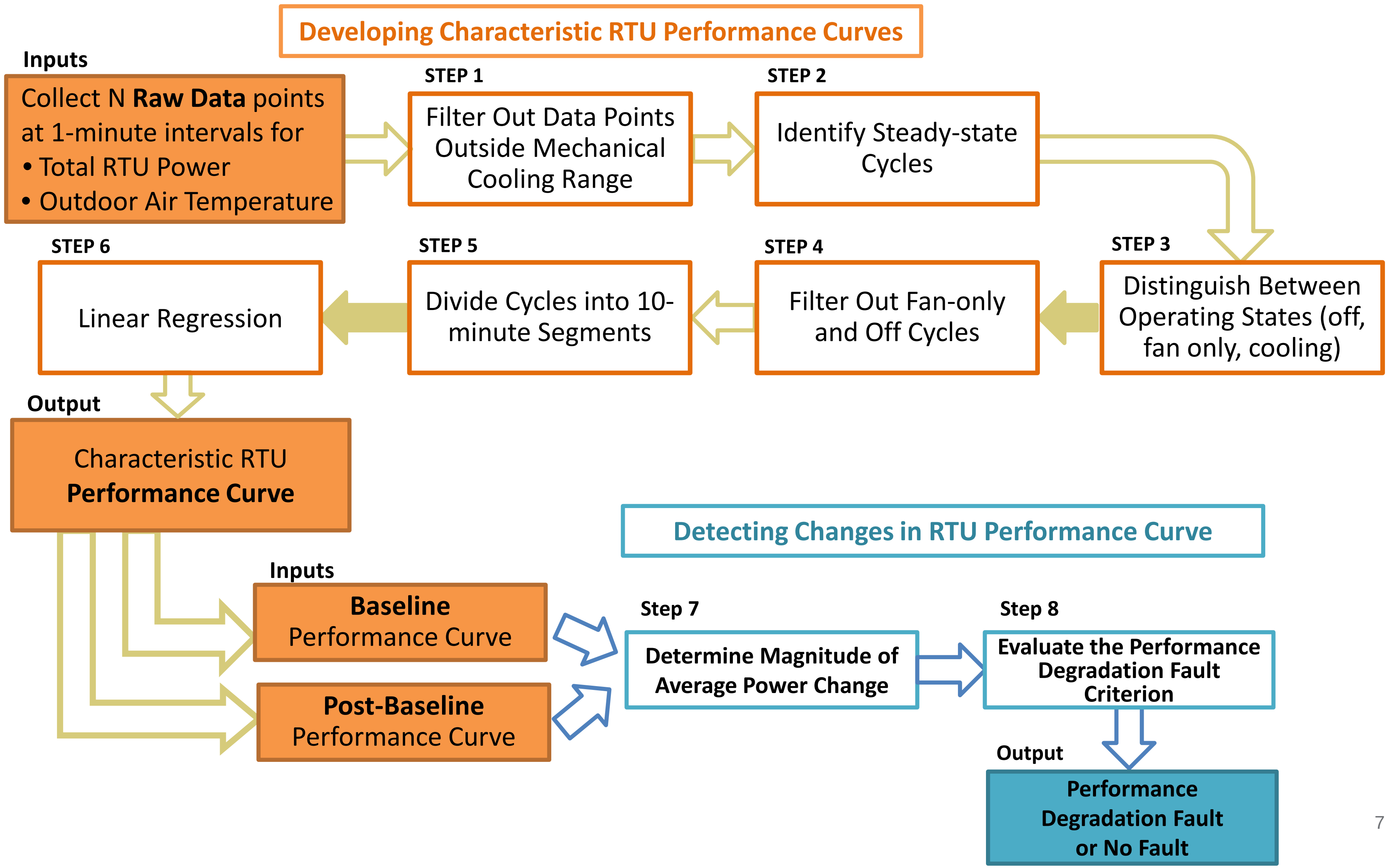

Raw Data for Three Weeks

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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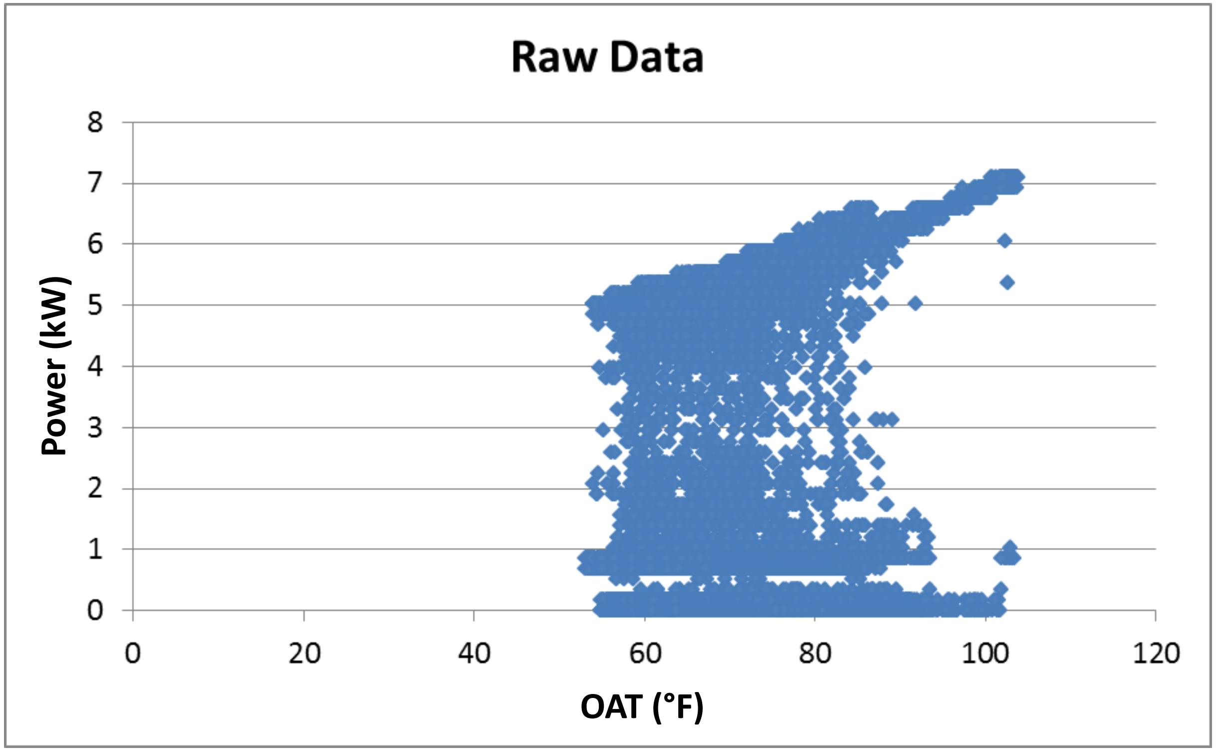

Data are shown for N = 30,240 data points measured at 1-minute intervals, which corresponds to the number of minutes in 3 weeks.

This value of N is currently required both to establish a baseline and to determine a performance curve for post-baseline periods. It was found to provide reliable results in applications to 90 RTUs.

Smaller values of N will be evaluated in the future.

Typical raw 1-minute interval data of a one-stage constant-speed fan RTU

Step 1: Filter Out Points Outside Ordinary Range of Mechanical Cooling

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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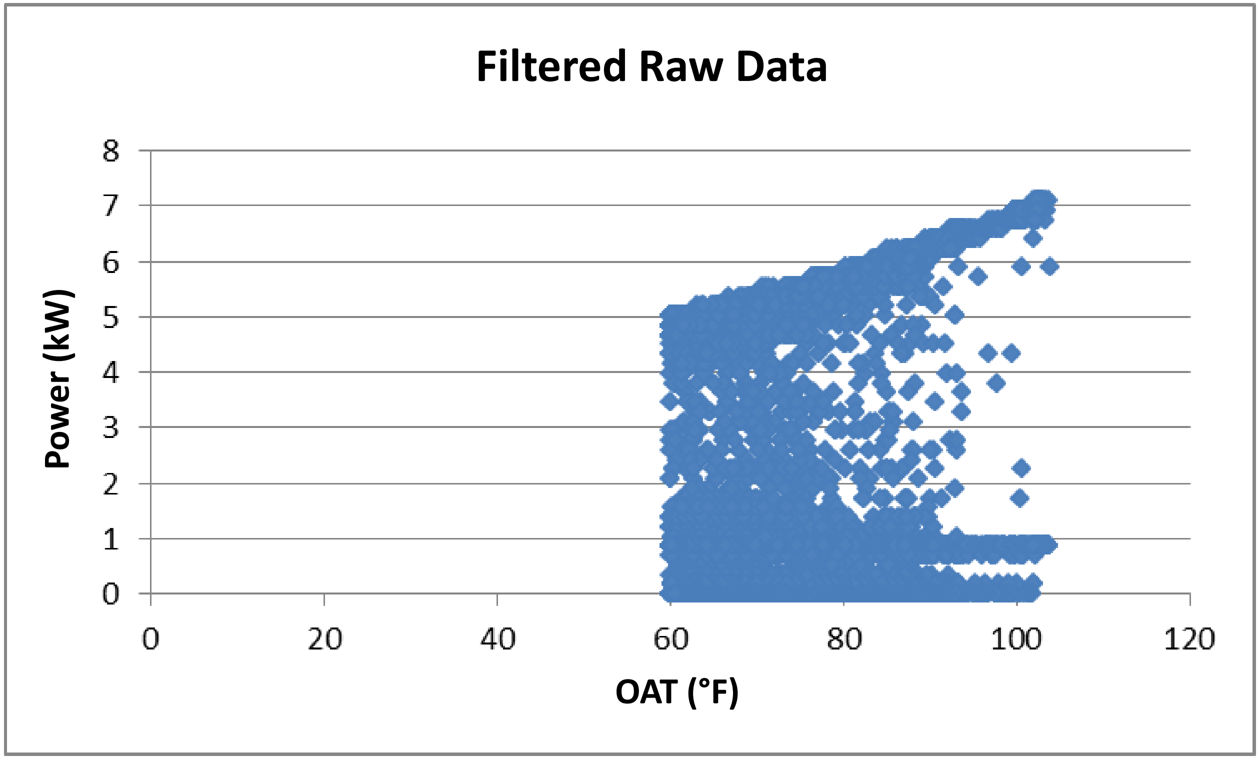

Step 1: Filter Out Points Outside the Ordinary Range of OAT for Mechanical Cooling (60ºF<T<120ºF)

Step 2: Identify Steady-state Cycles

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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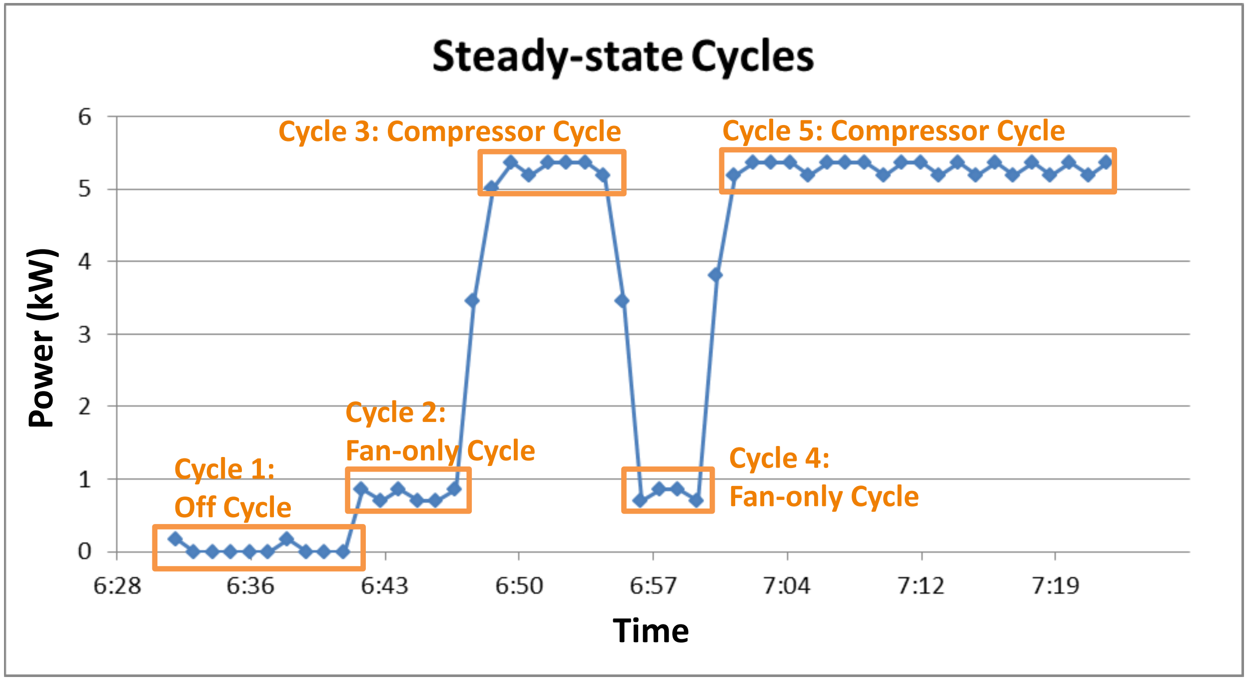

The average temperature and maximum power from the raw data in a steady-state cycle are assigned to the cycle:
Cycle Point (T_{avg}, P_{max})

The 5 steady-state cycles shown in the example at left can be represented by 5 **cycle points** on a Power vs. OAT plot:

Cycle Point 1: (63.2, 0.2)
Cycle Point 2: (63.7, 0.9)
Cycle Point 3: (64.0, 5.4)
Cycle Point 4: (63.5, 0.9)
Cycle Point 5: (63.9, 5.4)

Step 2: Identify Steady-State Cycles

Quantify the change in power demand between every pair of adjacent raw data points in the time series of measured data to identify steady-state cycles. Steady-state conditions occur when the change in power demand between consecutive points changes by no more than a threshold value (the default value is ±500W). Points not in steady-state cycles are points during transition from one steady state to another and are discarded.

Step 2: Identify Steady-state Cycles (cont'd)

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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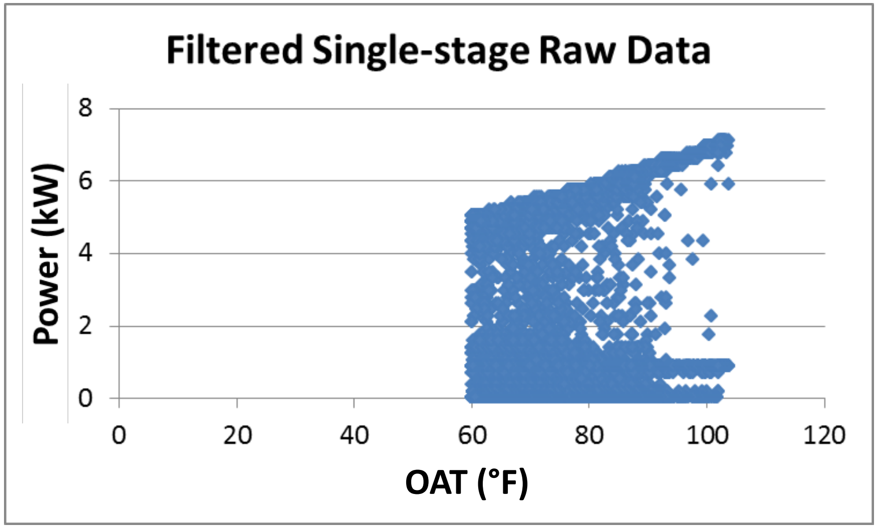
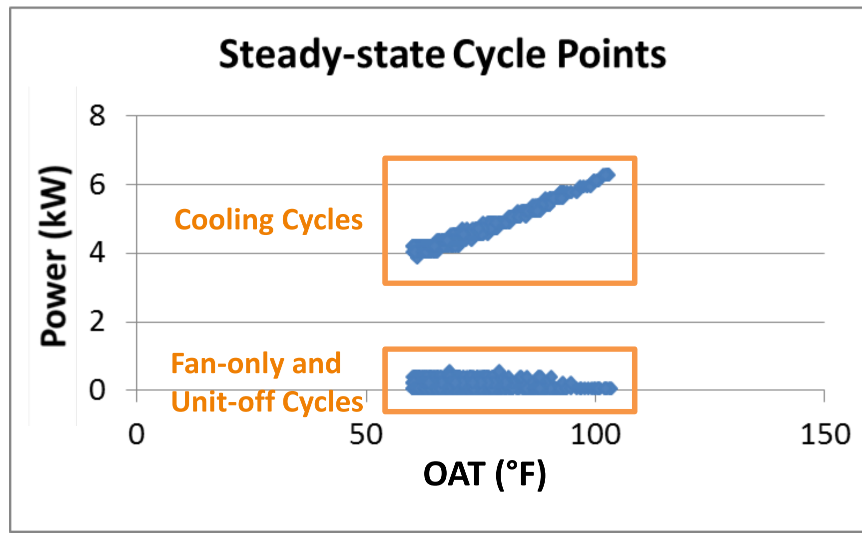


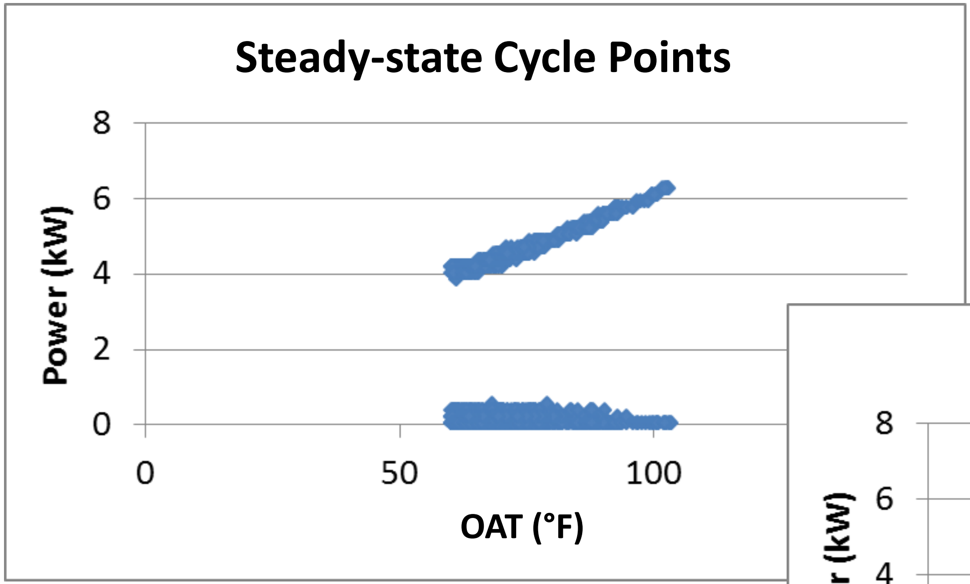


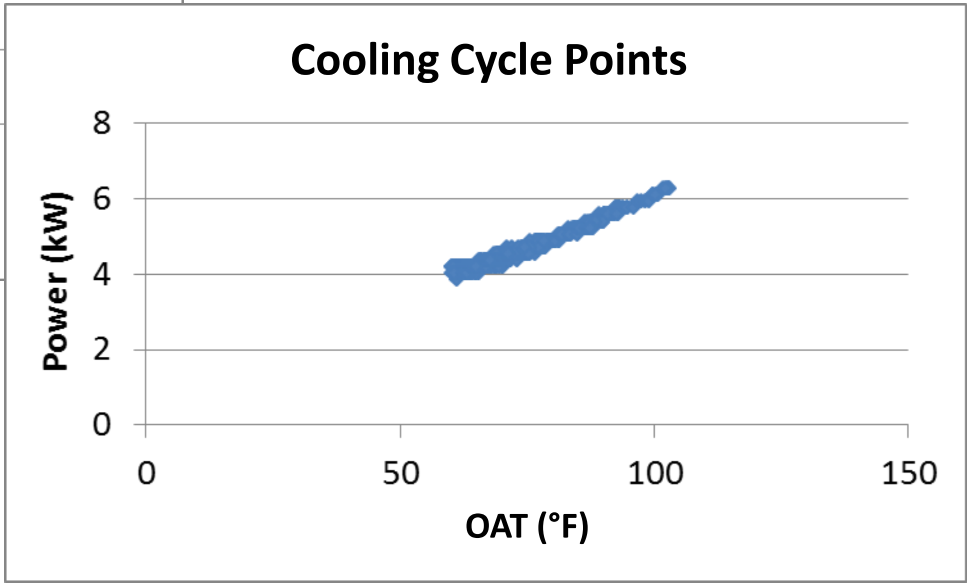
Step 3: Distinguish Between Operating States

Step 3: Distinguish Between Operating States
The states of RTU off, fan-only operation, and cooling can easily be distinguished visually in a Power vs. OAT plot of steady-state cycle points. An automated process for distinguishing between operating states is described later.

Step 4: Filter Out Fan-Only and Off Cycles

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan





Step 4: Filter Out Fan-only and Off Cycles

All steady-state cycle points with values of power less than or equal to the detected fan power for the RTU are filtered out, leaving only cycle points corresponding to cooling operation.

Step 5: Divide Cycles into Segments

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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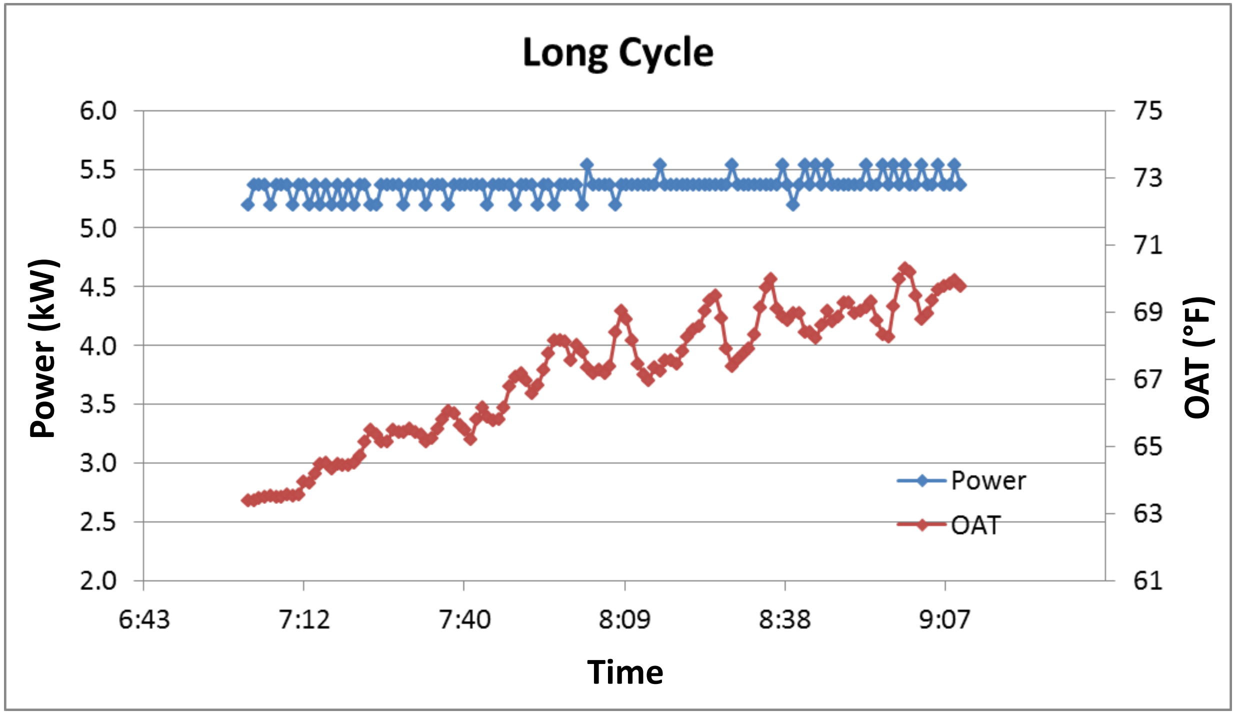

A long cycle can last for hours, with OAT potentially varying significantly.

Step 5: Divide Cycles into 10-minute and Shorter Segments
Cycles longer than 10 minutes are divided into as many 10-minute segments as possible plus one remainder segment less than 10 minutes. For example, a 129-minute long cycle is divided into 13 segments, 12 10-minute segments and 1 9-minute remainder segment.

Step 5: Divide Cycles into Segments

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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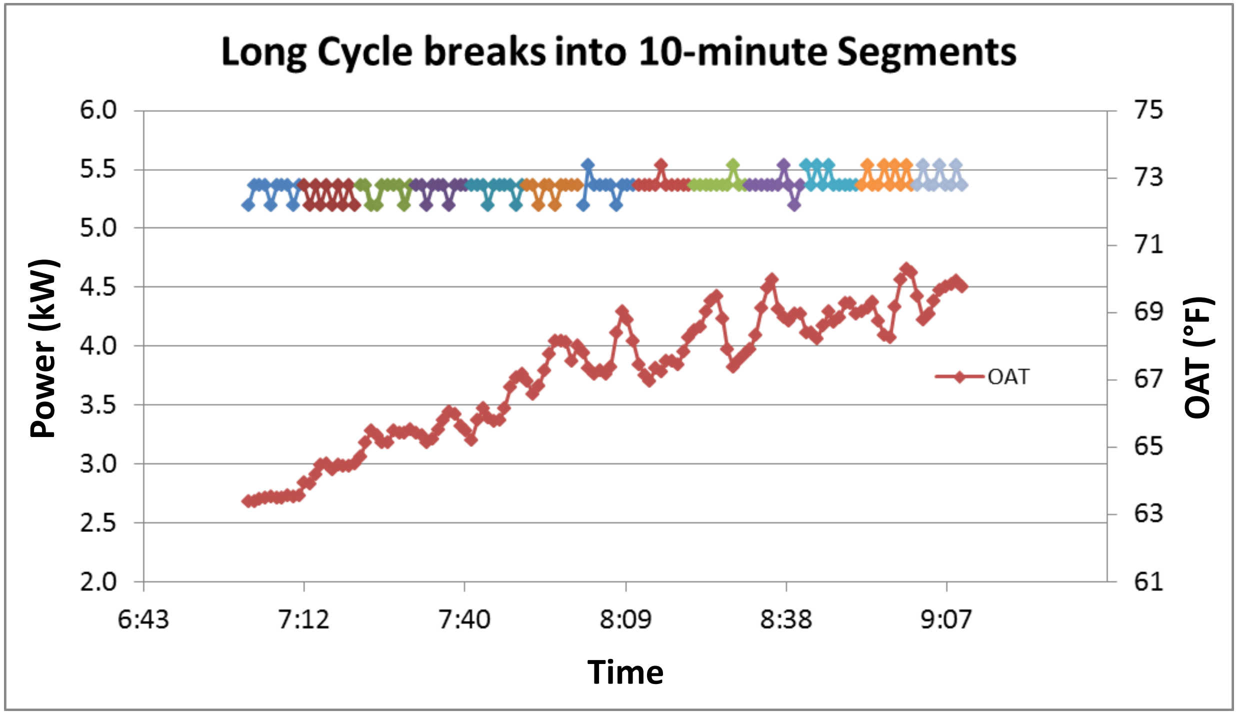


Dividing cycles into 10-minute and smaller segments

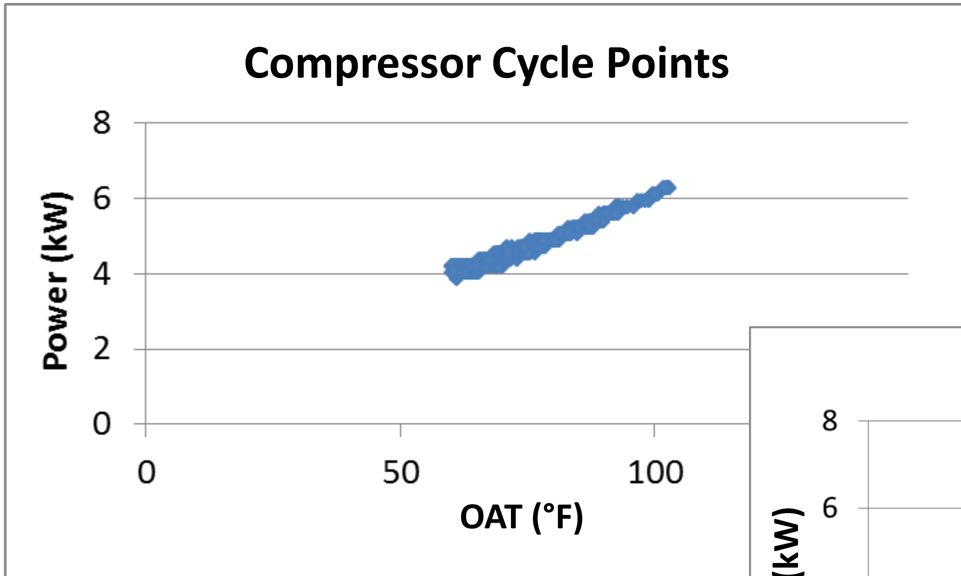
- ensures that long cycles are not weighted the same as shorter cycles, and
- maintains OAT relatively constant during a segment, which it may not for long cycles.

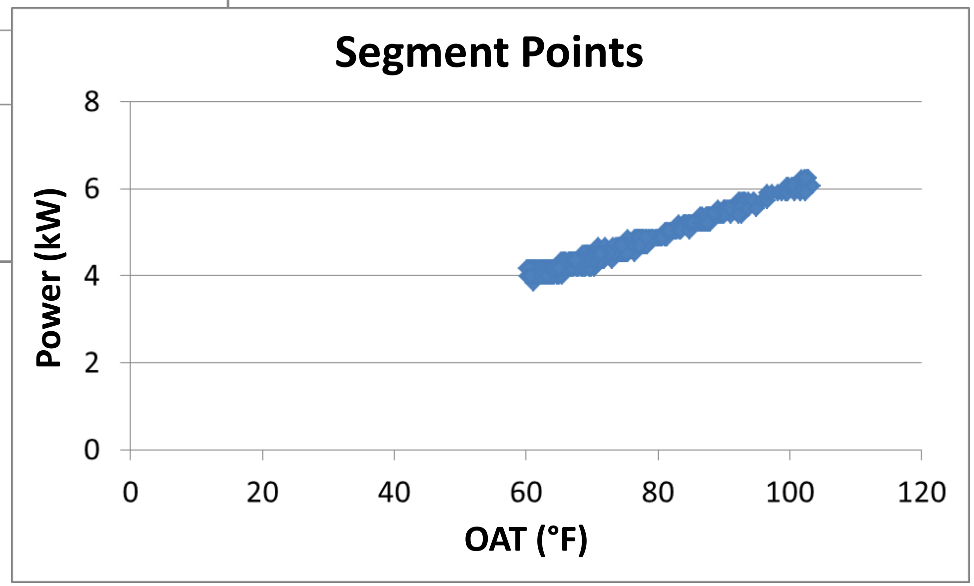
Step 5: Divide Cycles into 10-minute and Shorter Segments

Each segment is assigned the average of the raw point temperatures in the segment and the maximum of the point powers in the segment to characterize it: Segment Point (T_{avg}, P_{max})

Step 5: Divide Cycles into Segments

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan





Step 5: Divide Cycles into 10-minute and Shorter Segments
Dividing long cycles into 10-minute segments increases the number of data points for regression and generally decreases range of temperatures compared to long cycles.

Step 6: Perform Linear Regression

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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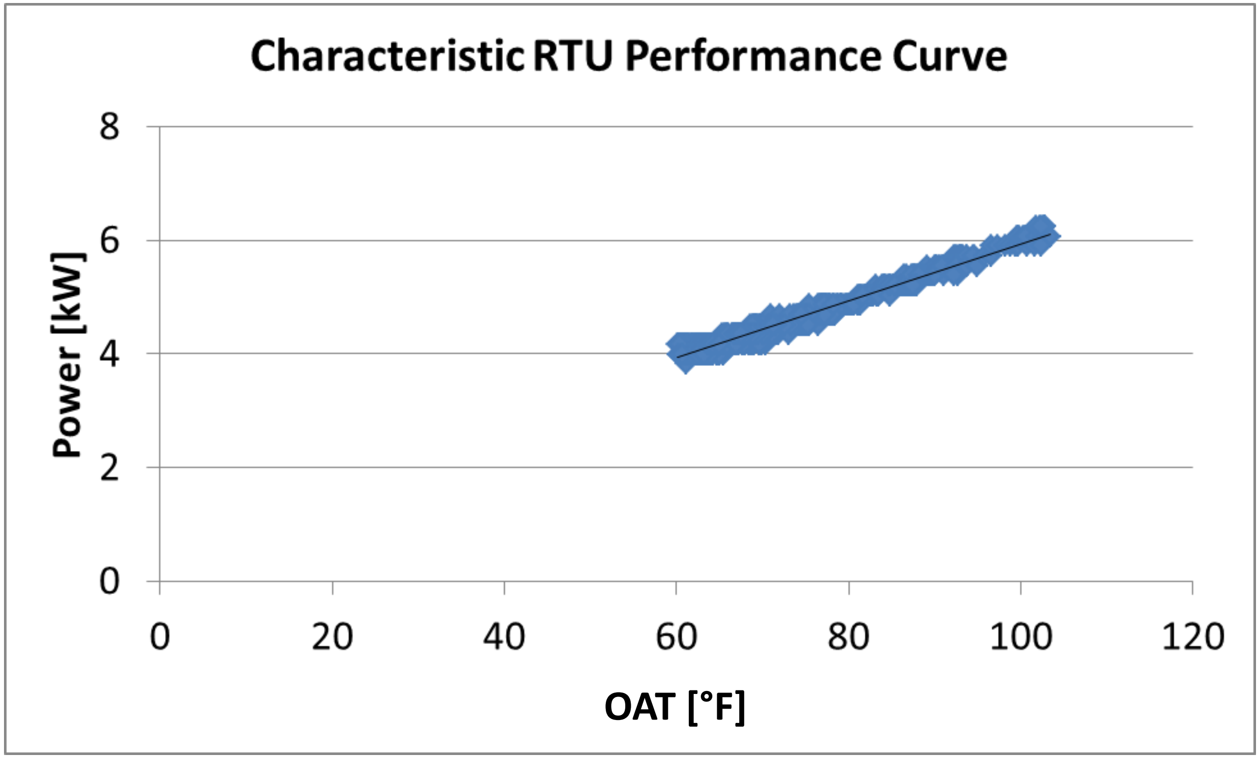

Regression Result:

Slope, a_1 = 0.05 kW/°F
Intercept, a_0 = 2.02 kW
R^2= 0.95

Step 5: Perform Linear Regression on Segment Points
The RTU performance curve is represented by the straight-line regression on the cooling segment points:
$P = a_0 + a_1 OAT,$
where a_0 is the slope and a_1 is the intercept of the line.

Steps 7 and 8: Detect Change in RTU Performance

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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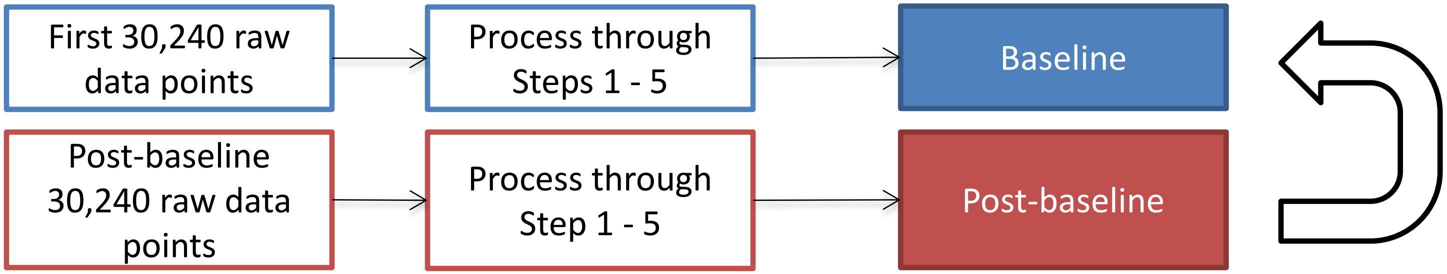


Compare the **Post-baseline** to **Baseline** performance curves

Baseline Data

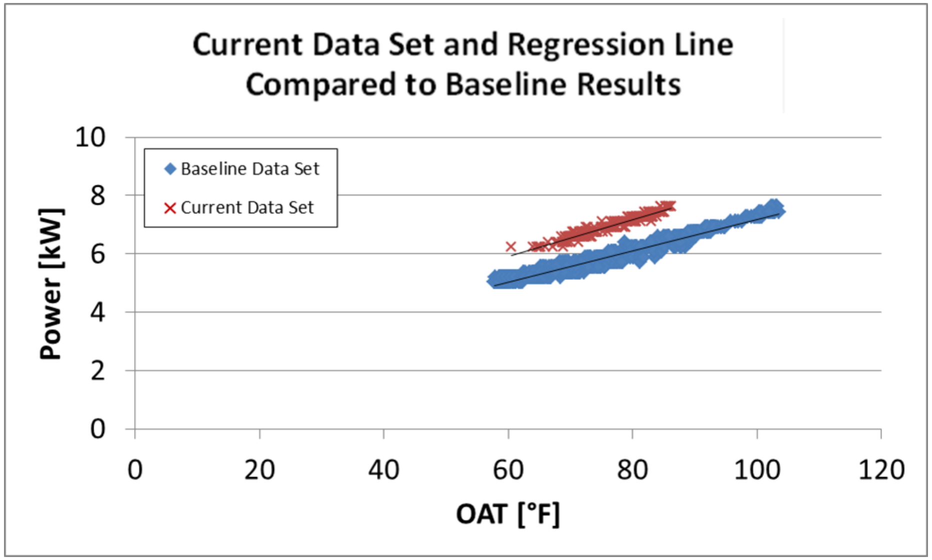
- $a_{0,baseline}$ = 2.02 kW
- $a_{1,baseline}$ = 0.05 kW/°F
- R^2 = 0.95

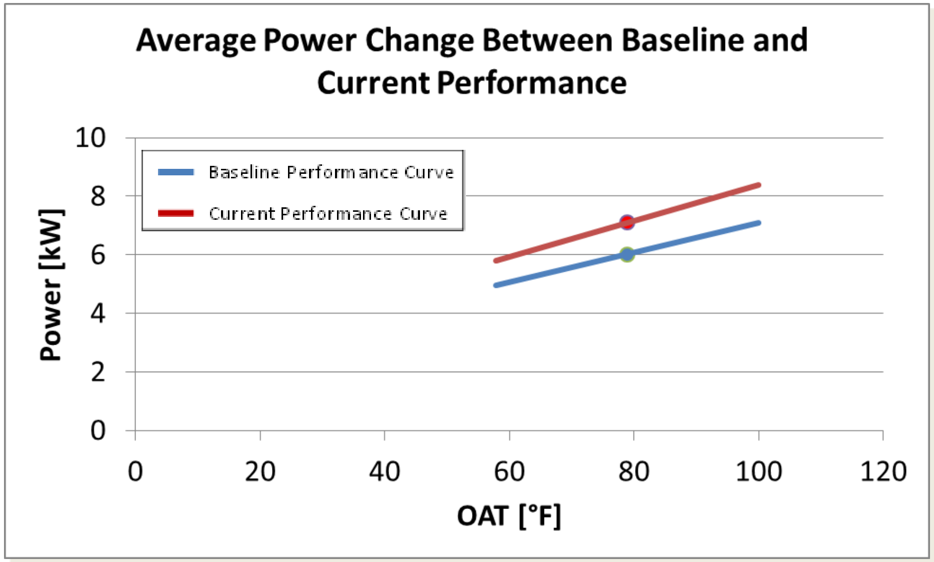
Current Data

- $a_{0,post}$ = 2.24 kW
- $a_{1,post}$ = 0.06 kW/°F
- R^2 = 0.94

Step 7: Determine Magnitude of Change

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan





Determine the Average Power Change

- **Temperature range and T_{mid}**

The temperature range is defined by the lowest temperature of the 2 data sets and the highest temperature of the 2 data sets.

$$T_{min} = minimum(T_{min,baseline}, T_{min,pos})$$
$$T_{max} = maximum(T_{max,baseline}, T_{max,post})$$

We determine the average change in power at the mid-point temperature , where

$$T_{mid} = \frac{T_{min} + T_{max}}{2}$$

- **Average Power Increase (%)**

$$P_{baseline} = a_{0,baseline} + a_{1,baseline} \times T_{mid}$$

$$P_{post} = a_{0,post} + a_{1,post} \times T_{mid}$$

$$\Delta P = \frac{P_{post} - P_{baseline}}{P_{baseline}}$$

- **Evaluate of degradation fault criterion**

If the average power increase (P_{inc}) is bigger than a threshold, the degradation fault has occurred.

Step 8: Evaluate Performance Degradation Criterion

Degradation Detection for **Single-stage** RTU with **Constant-speed** Fan

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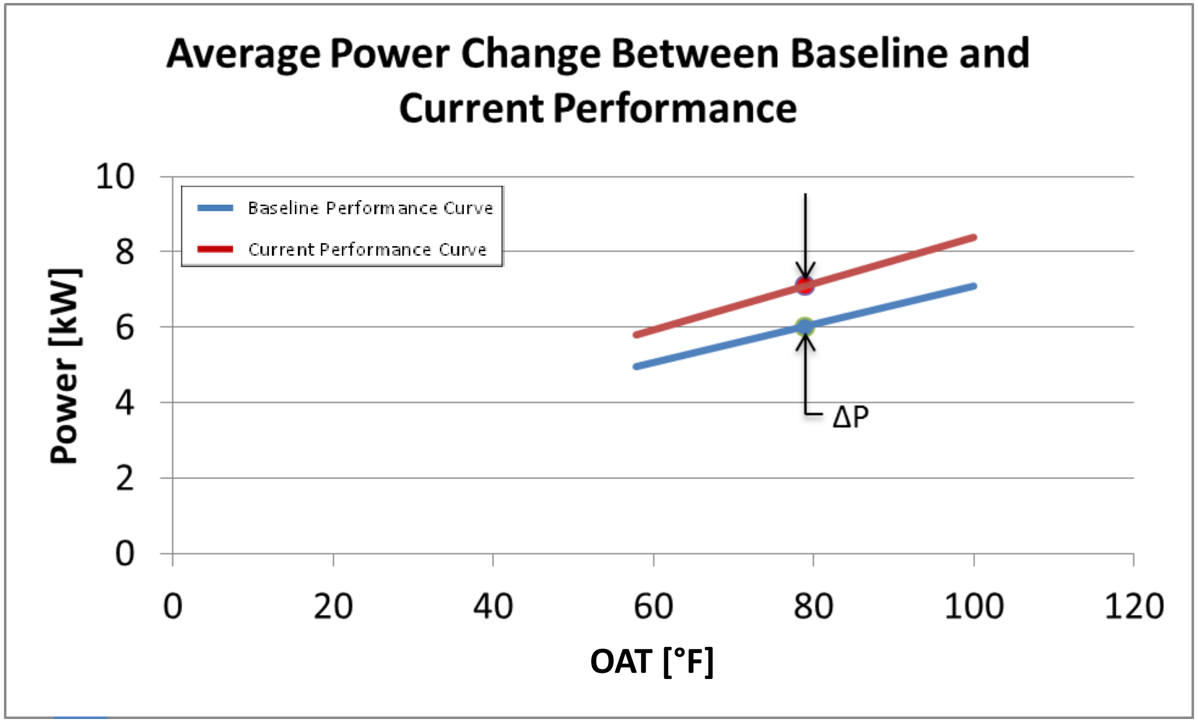


- $T_{mid} = 79^o$
- $\Delta P = 17.86\%$

We evaluate ΔP with respect to a pre-set threshold, $\Delta P_{threshold}$. If $\Delta P > \Delta P_{threshold}$, then a degradation fault has occurred.

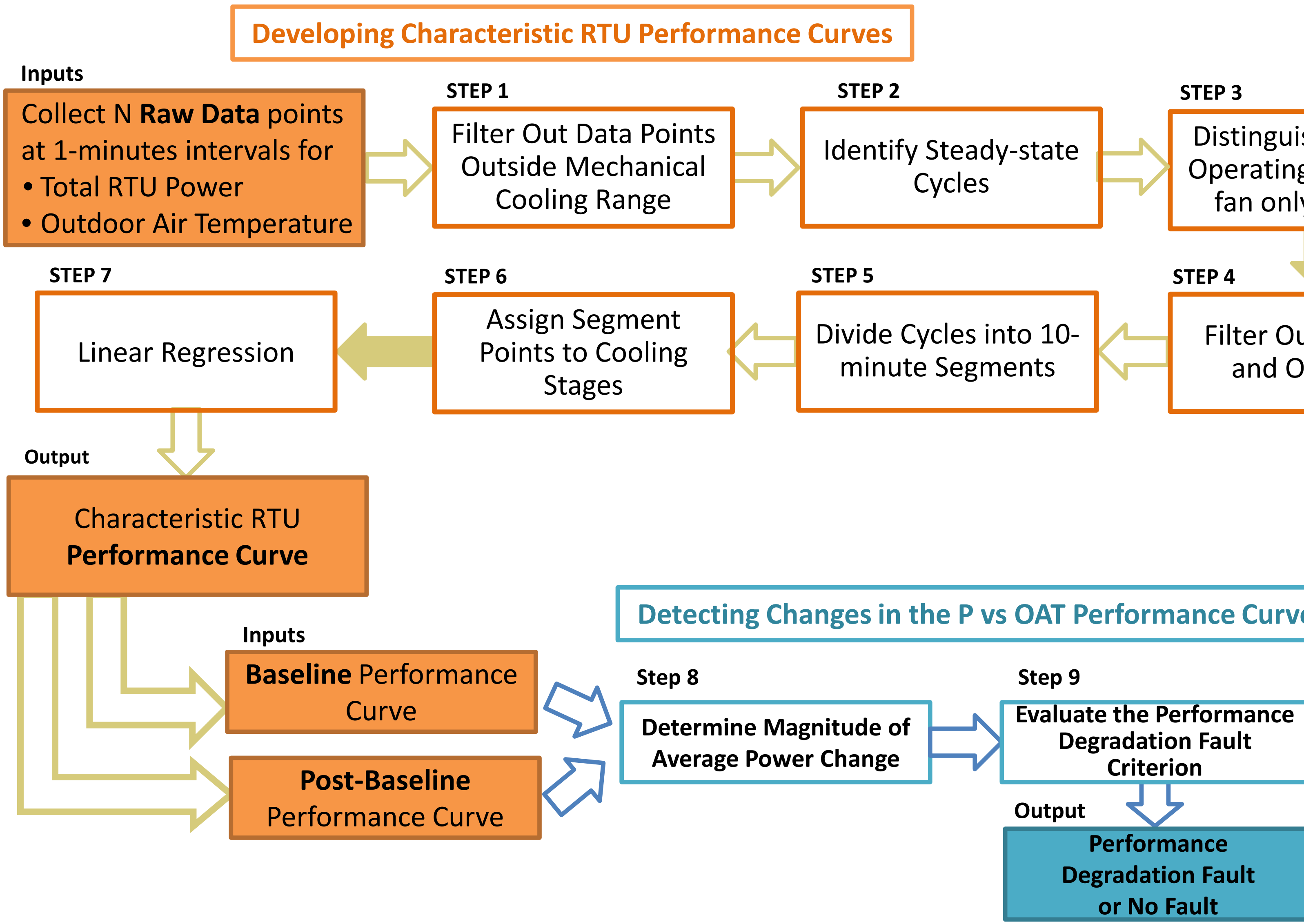
For example: If $\Delta P_{threshold} = 5\%$, we conclude that degradation has occurred for the performance change shown on the left.

SMDS Algorithm

-- two-stage RTU with constant-speed fan

Performance Degradation Detection for a Two-stage RTU with Constant-speed Fan

Degradation Detection for **Two-stage** RTU with **Constant-speed** Fan



Example of Raw Data for a Two -stage RTU

Degradation Detection for **Two-stage** RTU with **Constant-speed** Fan

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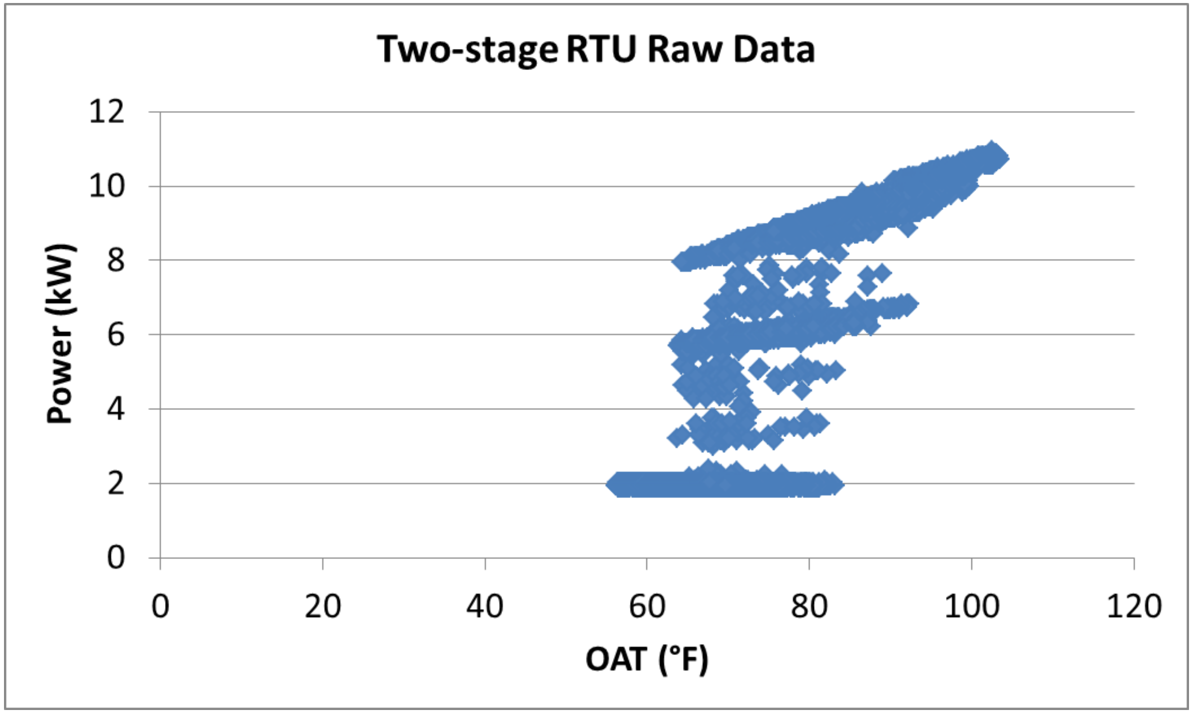
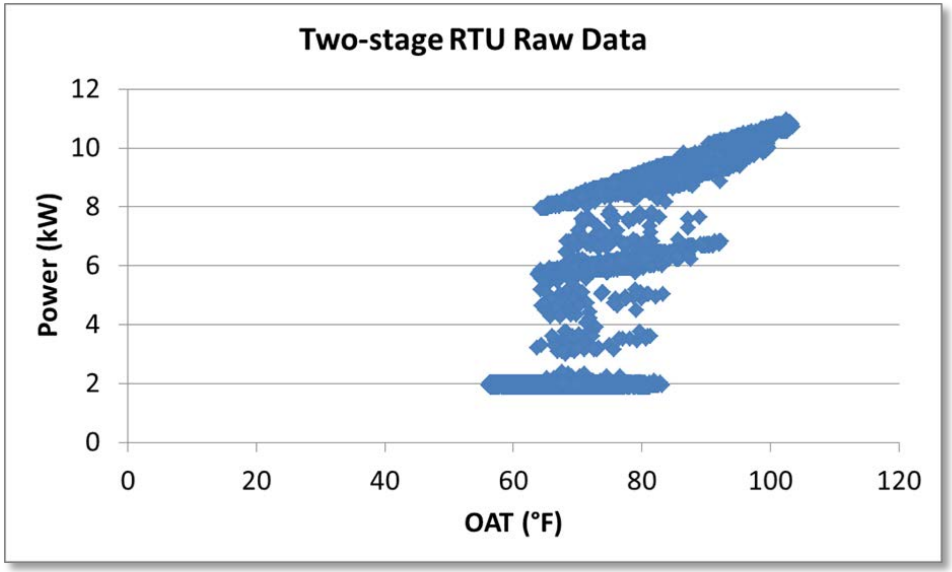


Raw 1-minute interval data of a two-stage constant speed fan RTU

Raw Data Processing Steps 1 - 6

Degradation Detection for **Two-stage** RTU with **Constant-speed** Fan



Apply Steps 1 - 6 as for the single-stage RTU to obtain the segment points.

Step 1: Filter out points for which OAT is out of mechanical cooling range.

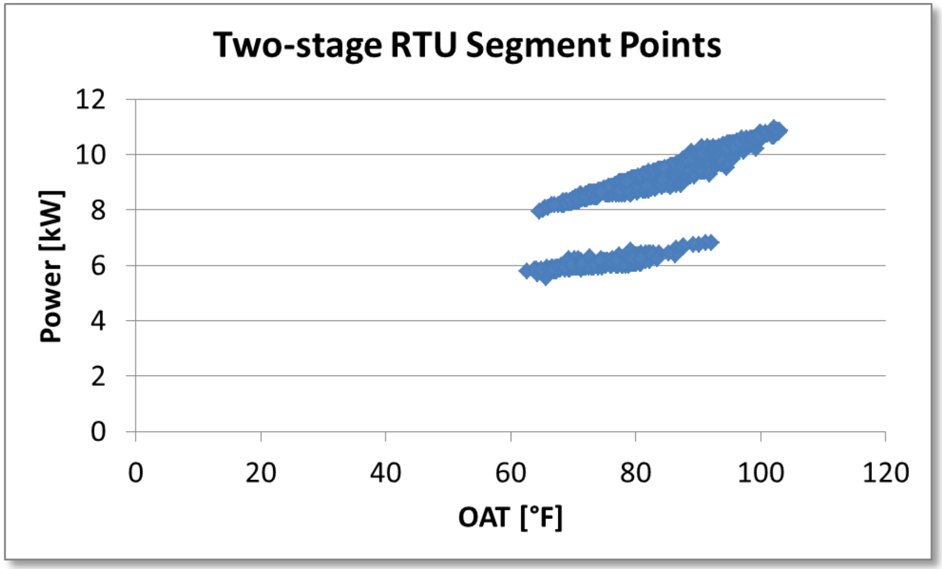
Step 2: Identify steady-state cycles

Step 3: Distinguish between operating states (off, fan only, cooling)

Step 4: Filter out fan-only and off cycle points

Step 5: Divide cycles into segments

Step 6: Assign segment points to cooling stages



Step 7: Linear Regression on Each Cooling Stage

Degradation Detection for **Two-stage** RTU with **Constant-speed** Fan

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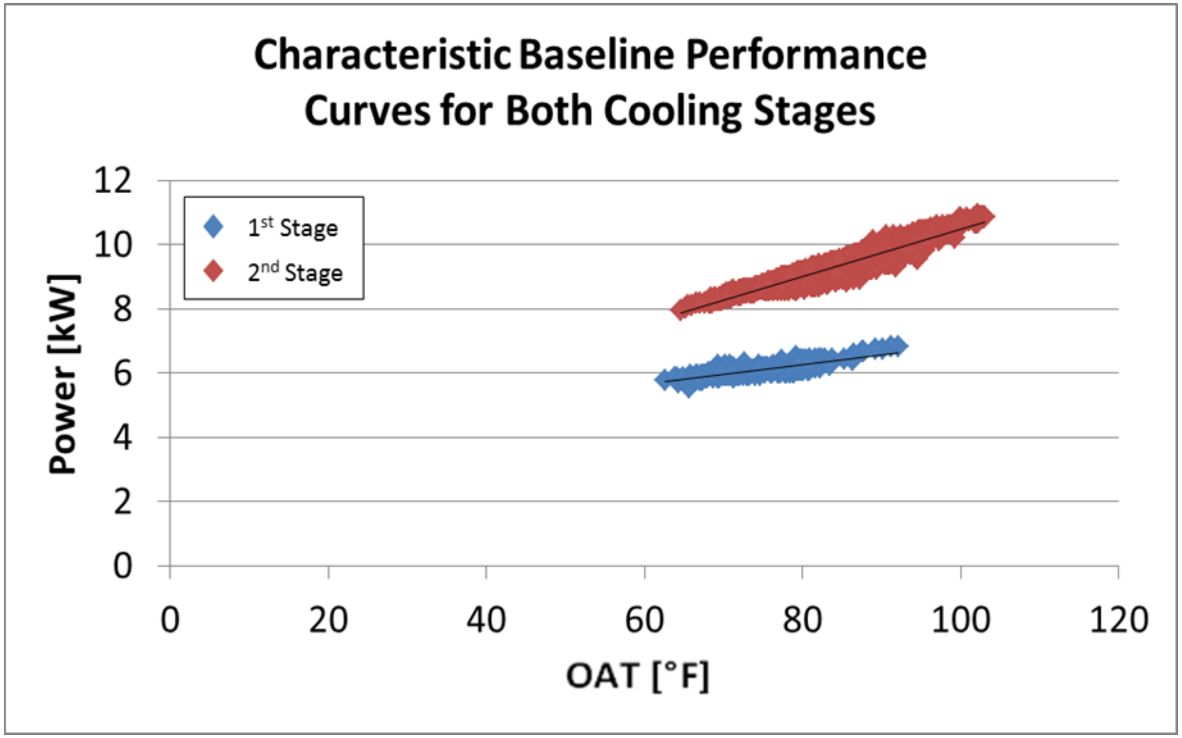

Regress on both stages.

- **1st stage regression line:**
  - Slope = 0.031 kW/°F
  - Intercept = 3.80 kW
  - R^2 = 0.73
- **2nd stage regression line:**
  - Slope = 0.074 kW/°F
  - Intercept = 3.11 kW
  - R^2= 0.91

Step 7: Regress on Current Data Sets for Each Stage to Determine the Current Performance Curves

Degradation Detection for **Two-stage** RTU with **Constant-speed** Fan

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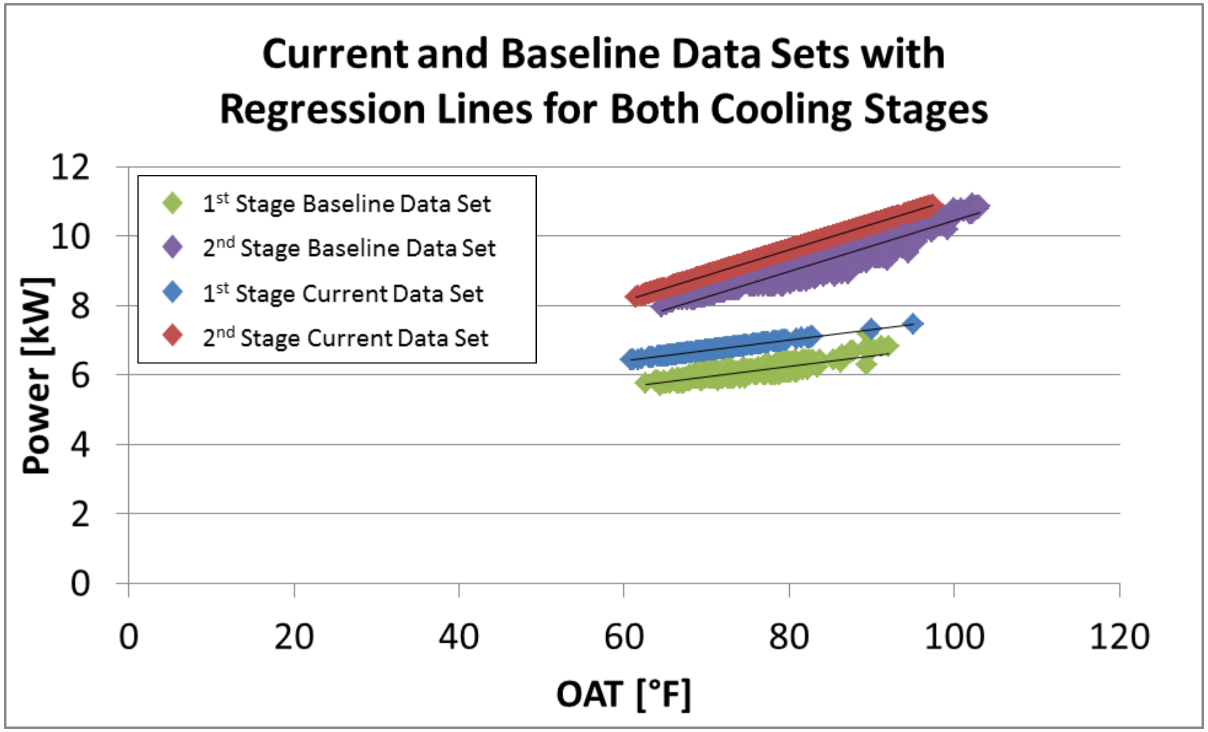

Baseline

- First Stage
  - Slope = 0.03 kW/°F
  - Intercept = 3.8 kW
  - R^2= 0.73
- Second Stage
  - Slope = 0.07 kW/°F
  - Intercept = 3.1 kW
  - R^2= 0.91

Current

- First Stage
  - Slope = 0.03 kW/°F
  - Intercept = 4.57 kW
  - R^2= 1.00
- Second Stage
  - Slope = 0.07 kW/°F
  - Intercept = 3.7 kW
  - R^2= 1.00

Steps 8 and 9: Determine the Average Power Change and Evaluate the Performance Degradation Fault Criterion

Degradation Detection for **Two-stage** RTU with **Constant-speed** Fan

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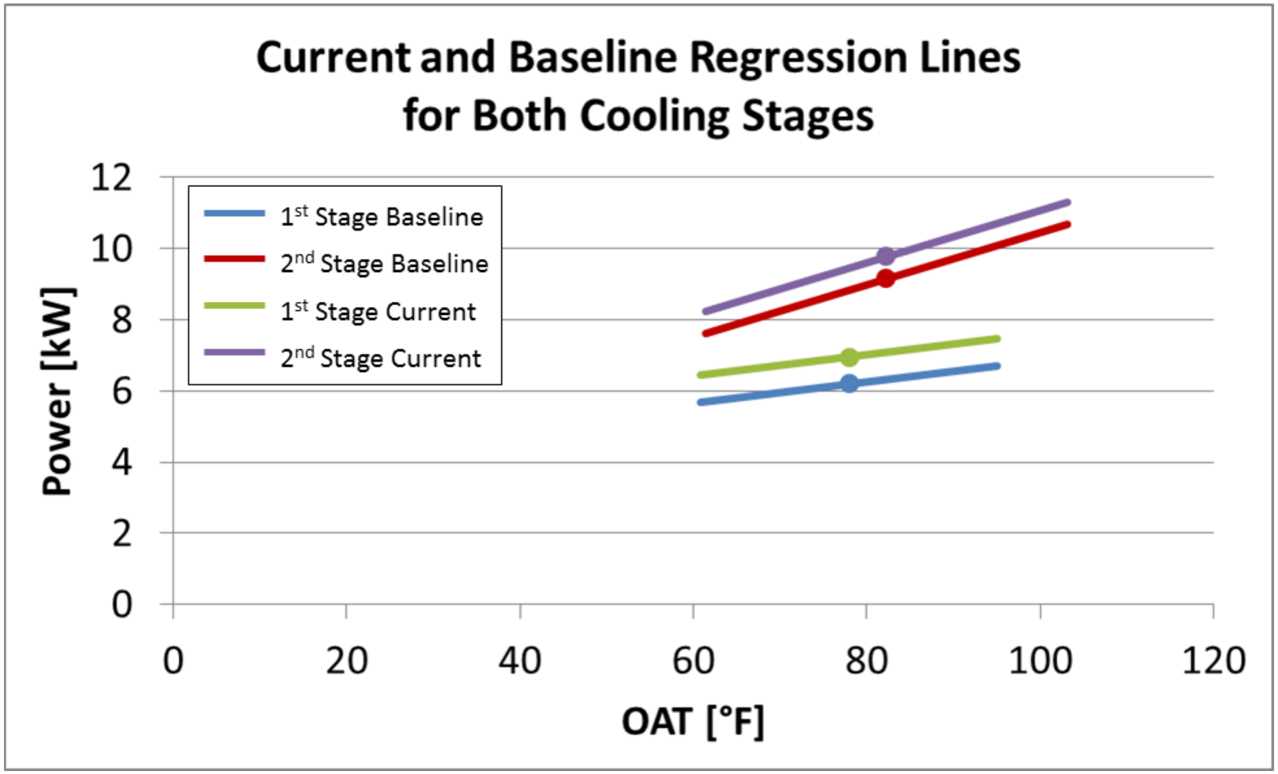

If the average power increase (ΔP) for a stage exceeds the Fault Threshold ($Threshold_{fault}$), then a fault is declared to exist.

For $Threshold_{fault}$ = 5%

- First Stage
  - $T_{mid} = 78^o$
  - ΔP_{stage1} = 11.3%
  - Fault
- Second Stage
  - $T_{mid} = 82^o$
  - ΔP_{stage2} = 8.2%
  - Fault

Automated Process

Automating Performance Degradation Detection

Automated Process

- The process for detecting performance degradation of an RTU cooling stage is relatively easy to perform visually
  - Distinguishing between points corresponding to fan-only operation and mechanical cooling points
  - Determining the number of cooling stages automatically using only the sensed data collected without any user-entered system information
  - Assigning data points to different cooling stages
- Automating these processes requires mathematical/computational techniques, which are described in the next two presentation sections

Automated Process

-- distinguishing between operating states (unit off, fan-only operation, and mechanical cooling)

Distinguishing Between Operating States

Automated Process
Distinguishing Between Operational States

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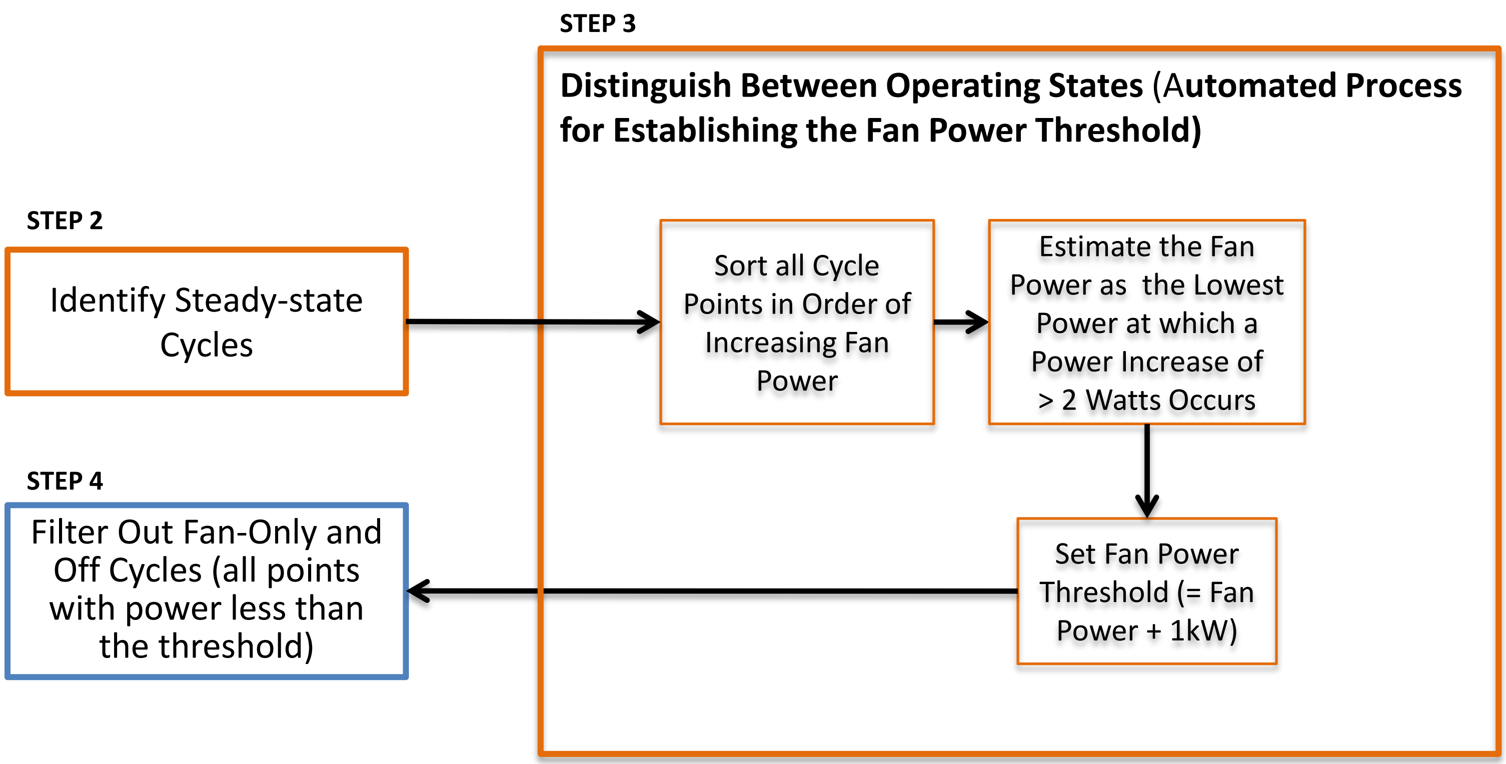
- This process is necessary to fully automate detection of performance degradation
- For context, see Step 3 of the flow chart on Slide 21



Step 3: Setting Fan Power Threshold

Automated Process
Fan Power Threshold

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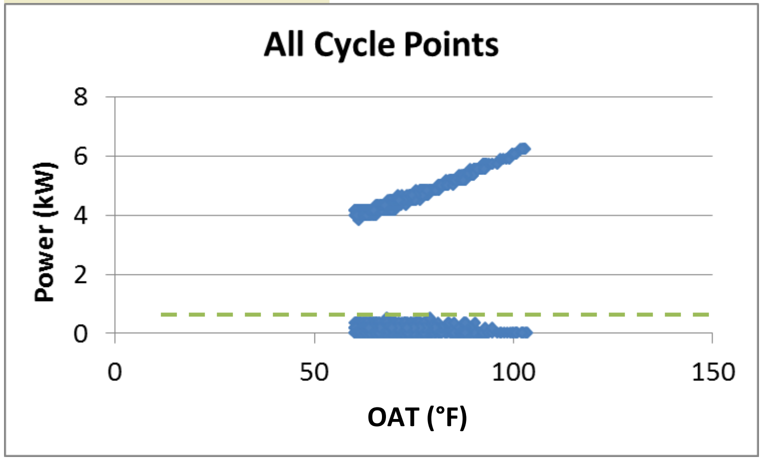
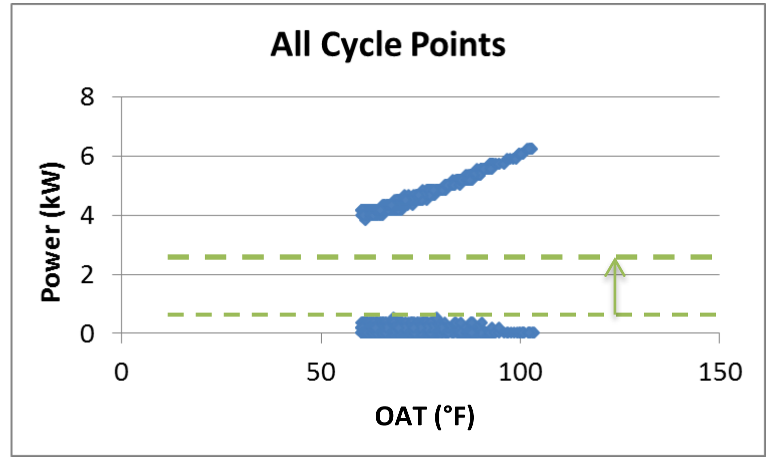
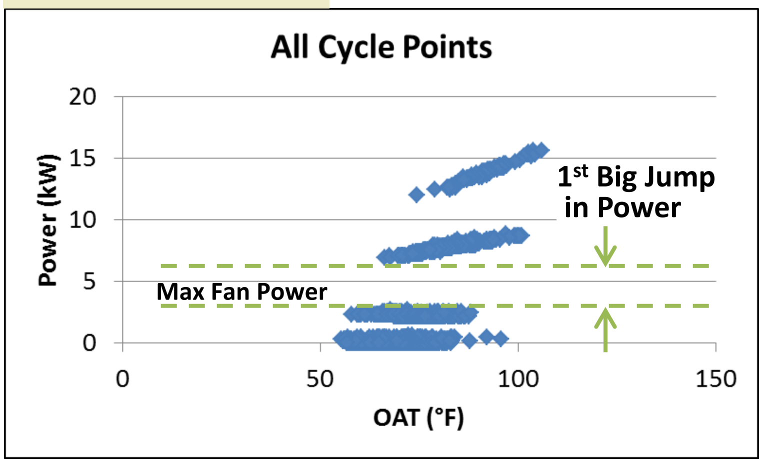
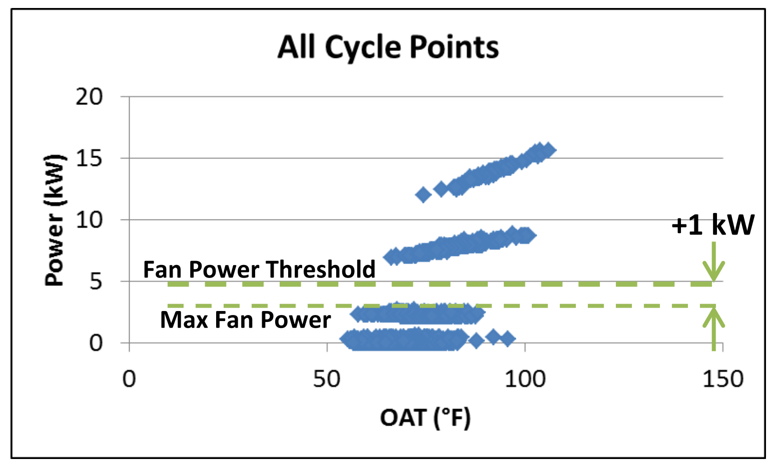
For One-stage unit





For Two-stage unit





We define the fan power threshold as 1 kW above the power of the point where the first big jump in power occurs.

Step 4: Filtering Out Fan-Only and Off Cycles

Automated Process
Fan Power Threshold

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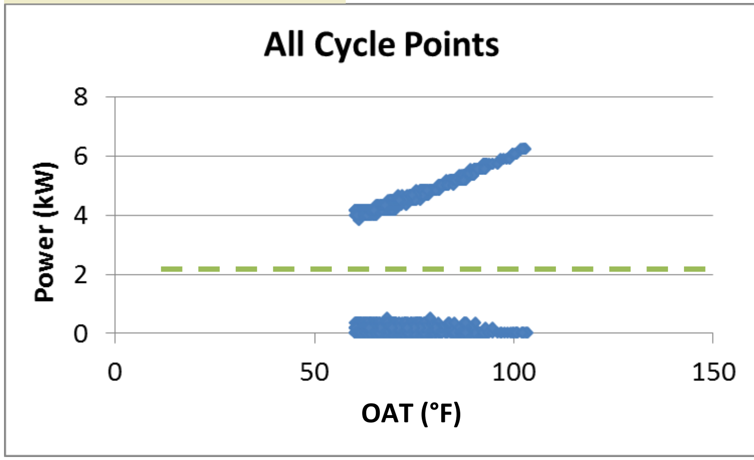
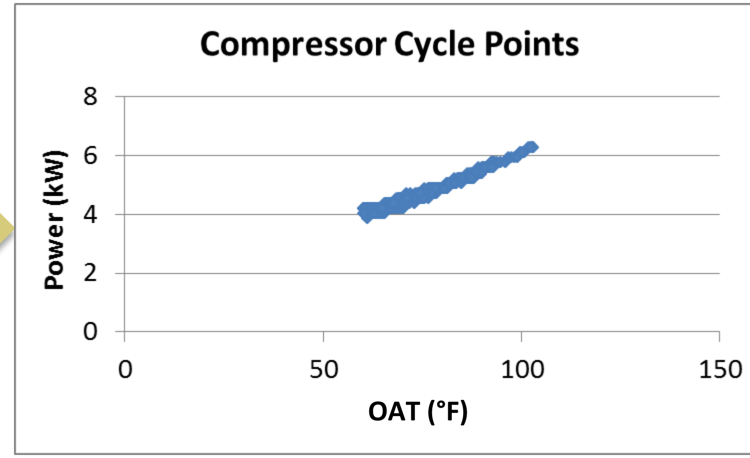
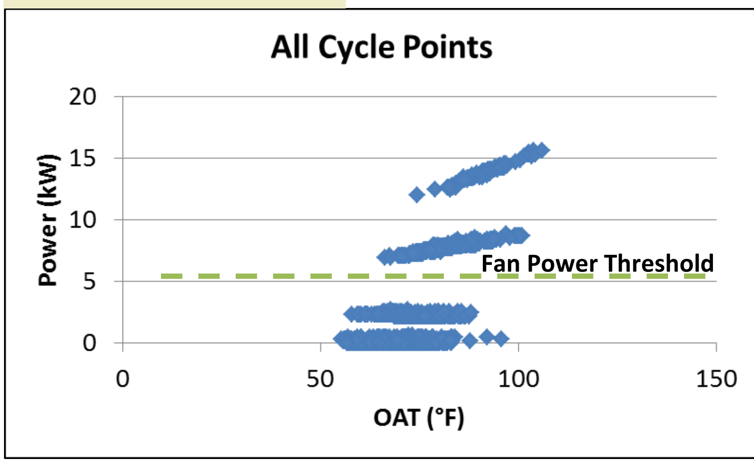
For One-stage unit



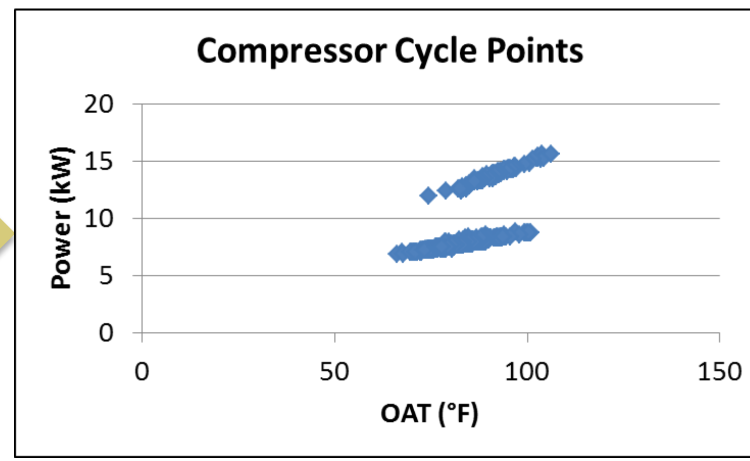
Filter



For Two-stage unit



Filter



To filter out fan-only and unit-off cycle points, we use a power threshold that lies between the fan-only points and lowest-power cooling points. Points below the threshold correspond to the system off or fan only operation.

Automated Process

-- Assign Segment Points to Cooling Stages

Assigning Segment Points to Cooling Stages

Automated Process
Cooling Stage Assignment

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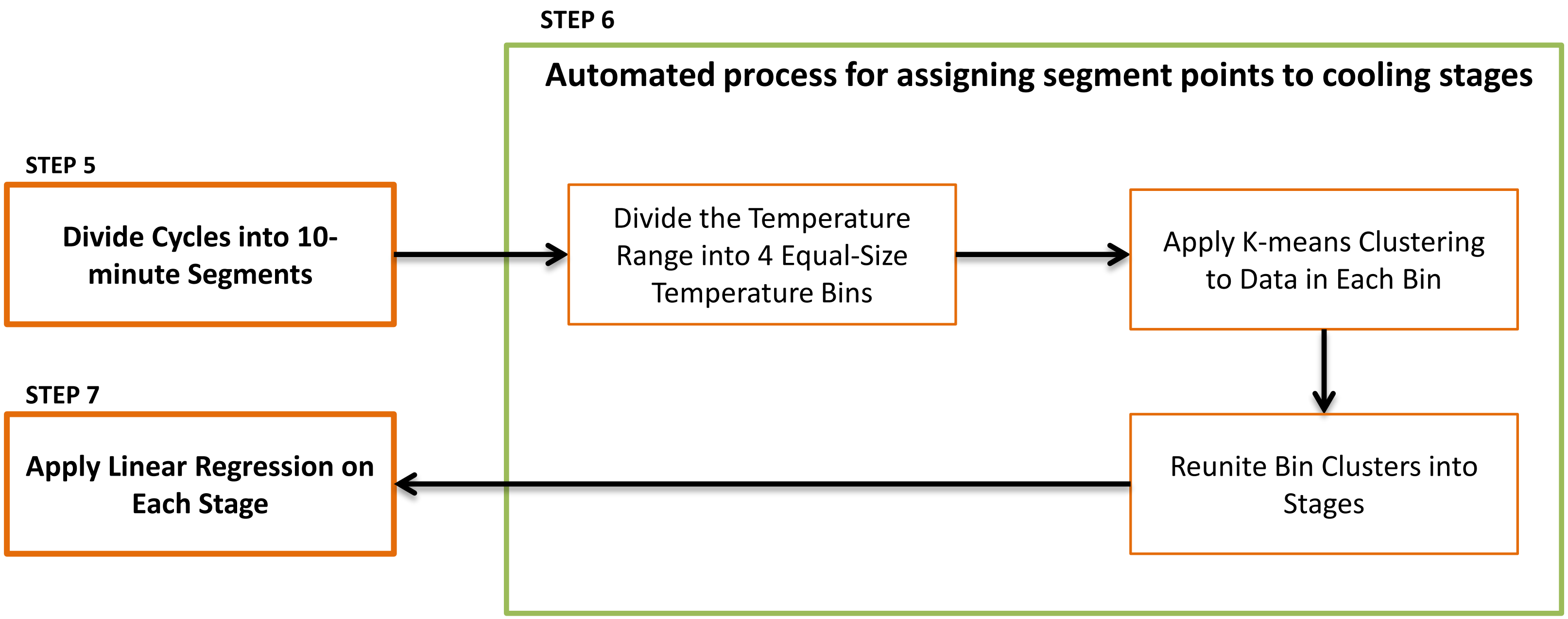
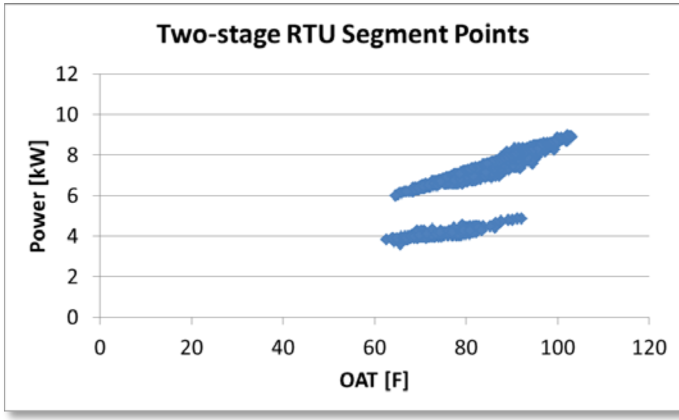
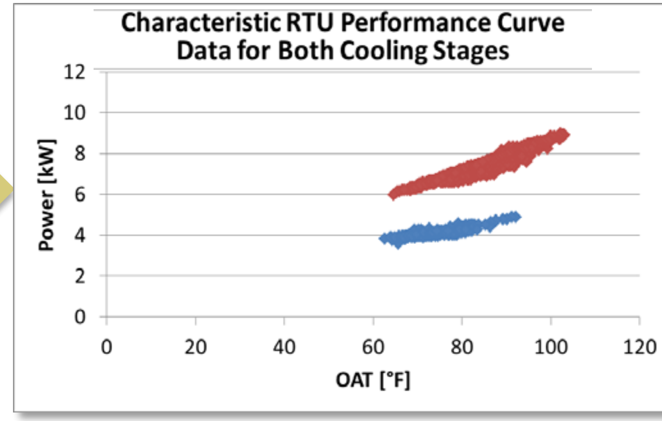


Separate Segment Points into Two Stages

Automated Process
Cooling Stage Assignment





It is easy for humans to visually separate the points into 2 clusters, but not nearly as straightforward for computers.

K-means clustering is used to automatically separate segment points into clusters representing two different cooling stages.

- Assumption made that there are not more than two cooling stages*
- Define two initial centroids, each corresponding to one cluster
- Calculate the Euclidean distance from each segment point to each of the two centroids
- Assign each data point to the cluster to which its Euclidean distance is smallest
- Re-calculate the new centroids by averaging the data point in each cluster
- Iterate until the cluster membership assignments do not change between iterations

*The method could be extended to more than 2 cooling stages.

Example of K-means Clustering

Automated Process
Cooling Stage Assignment

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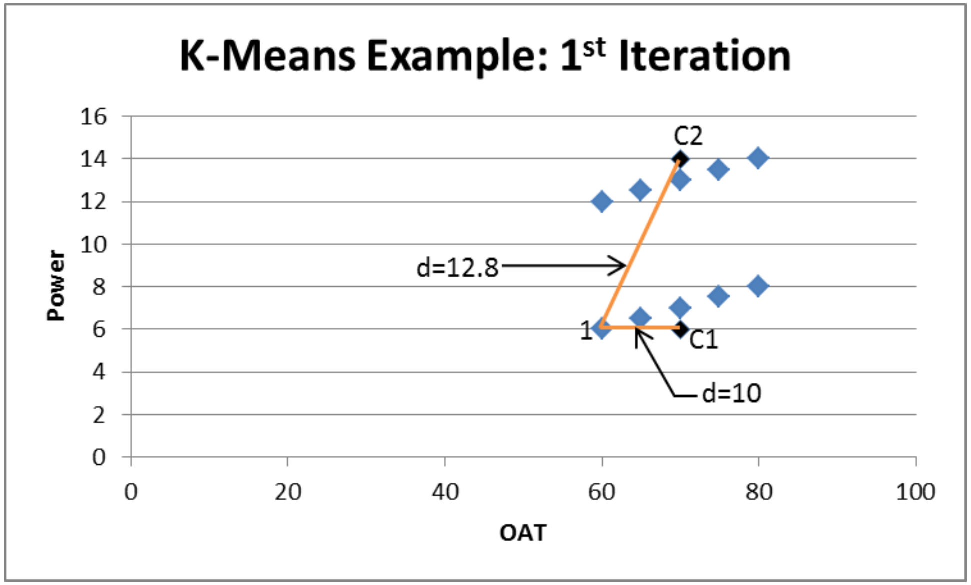
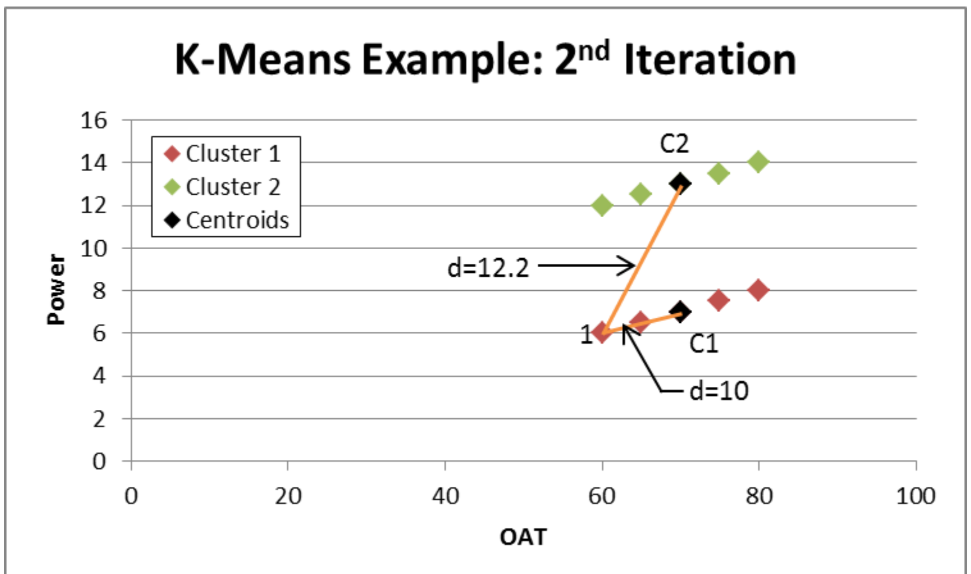




This is a simple example of K-means clustering on 10 points.

Initial centroids (C1 and C2) are assigned as

$$C1 = (P_{min}, T_{rangemidpoint})$$

$$C2 = (P_{max}, T_{rangemidpoint}),$$

where $T_{rangemidpoint}$ is the midpoint of the temperature range from the lowest to highest temperatures in the data set and P_{min} and P_{max} are the lowest and highest powers of the points in the data set, respectively.

In every iteration, each point is assigned to the closer centroid.

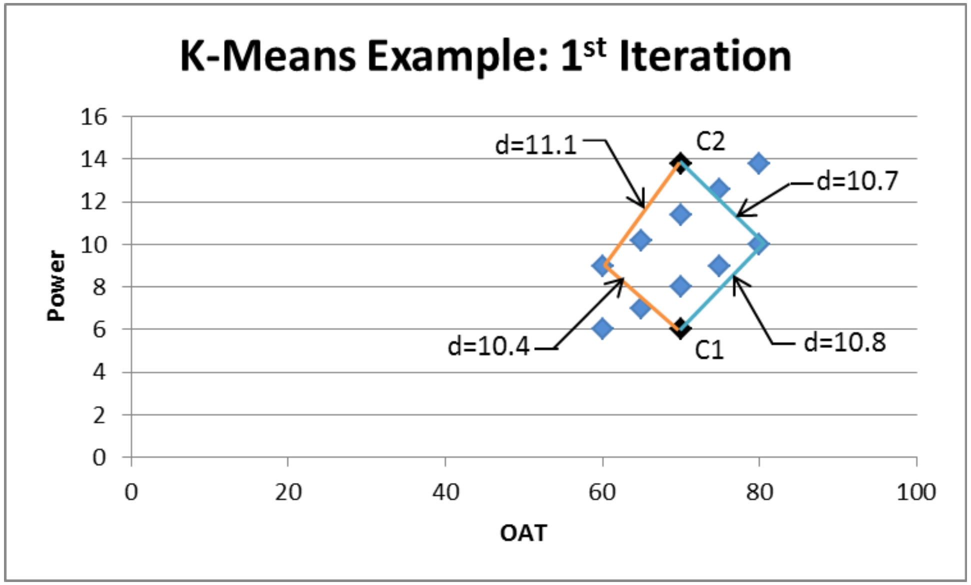
New centroids, C1 and C2, are then calculated for the points assigned to them and move according to the coordinates of their new members.

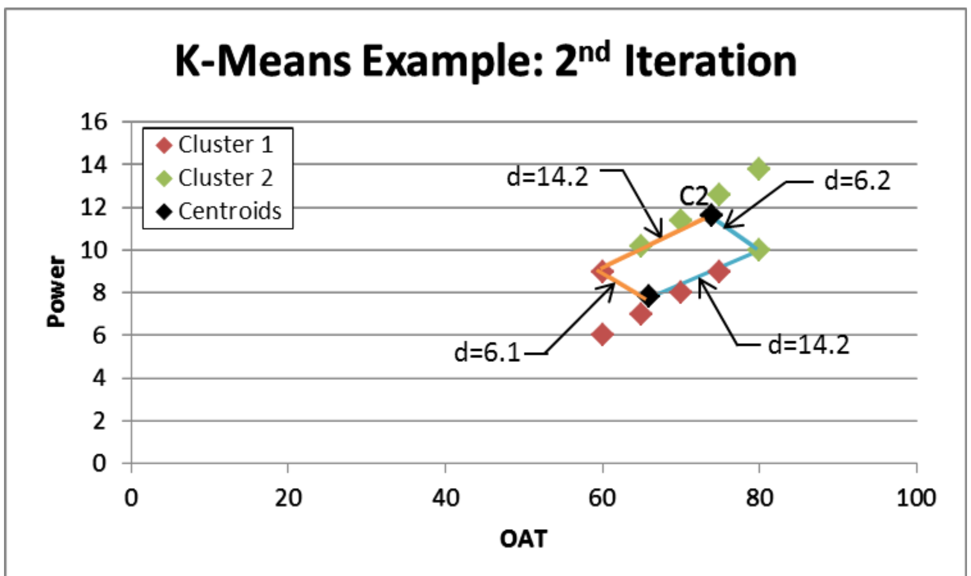
Iteration stops when membership in the clusters does not change between successive iterations.

In this example, the second iteration returns the same membership assignments as the first, and the clustering process is terminated. Visual examination verifies that the points were correctly assigned to clusters. Convergence can require more than two iterations.

An Issue with Steeply-Sloped Clusters

Automated Process
Cooling Stage Assignment





When one or both of the clusters has a steep slope, K-means clustering can fail to properly cluster points according to their cooling stages.

After the first iteration, the point membership assignments remain the same and iteration is terminated.

Visual examination reveals that the points are not correctly clustered.

Solution: K-means Clustering in Temperature Bins

Automated Process
Cooling Stage Assignment

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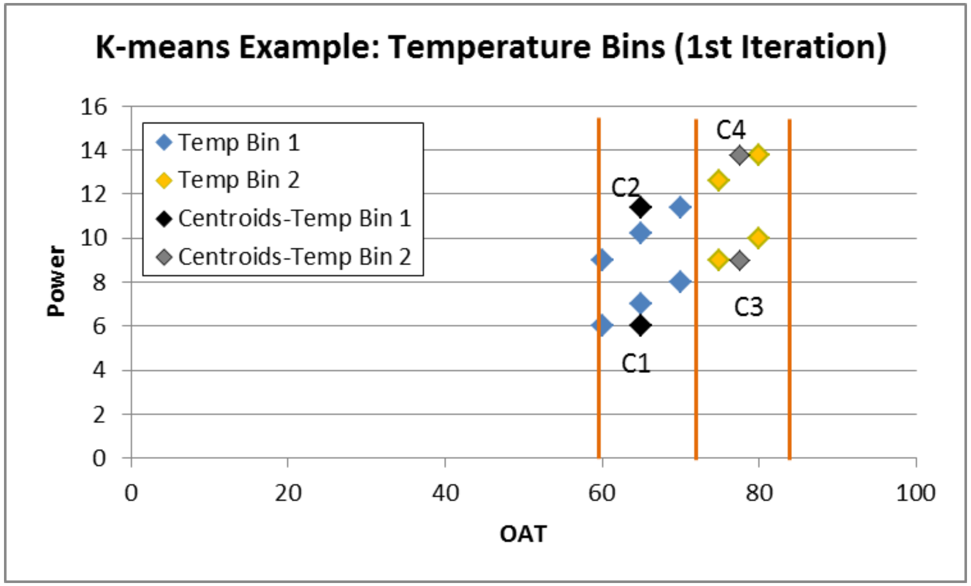

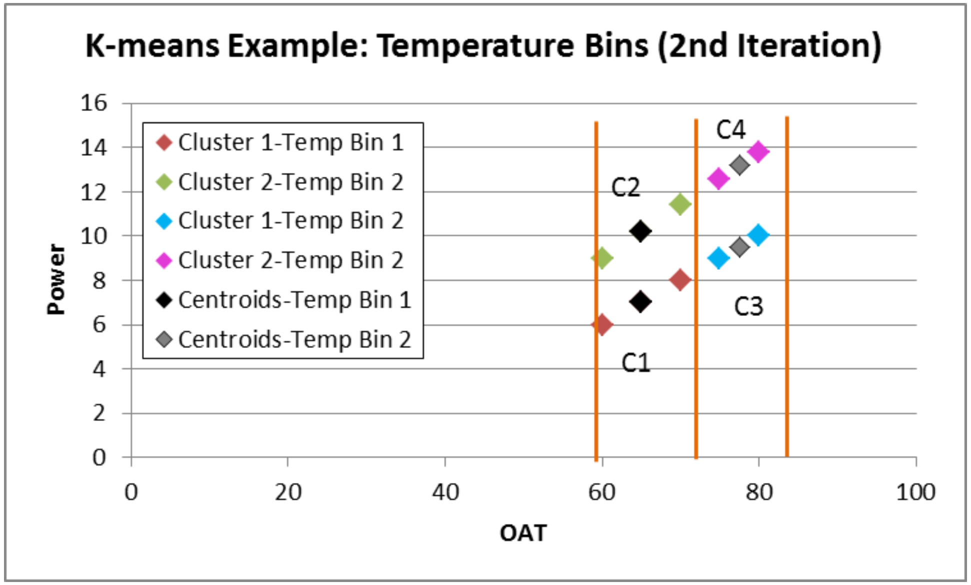

Because (P,OAT) segment-point data for cooling stages can have steep slopes and, as a result, have overlapping values of power, decreasing the temperature range over which the K-means method is applied can solve the problem of misassignment of points to clusters, while requiring very little computationally.

The temperature range is divided evenly into bins (as illustrated), and the K-means clustering method is applied to the points in each temperature bin separately.

The example shows that the points in each bin are clustered properly.

K-means Clustering for Actual RTU Data

Automated Process
Cooling Stage Assignment

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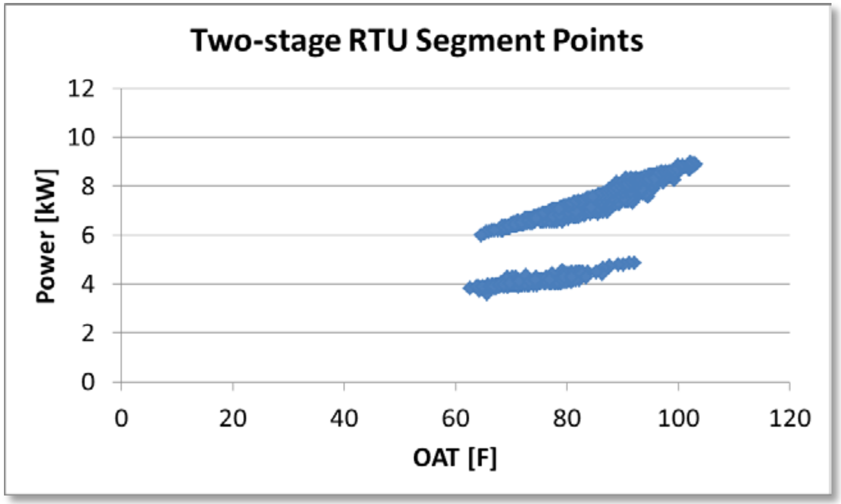
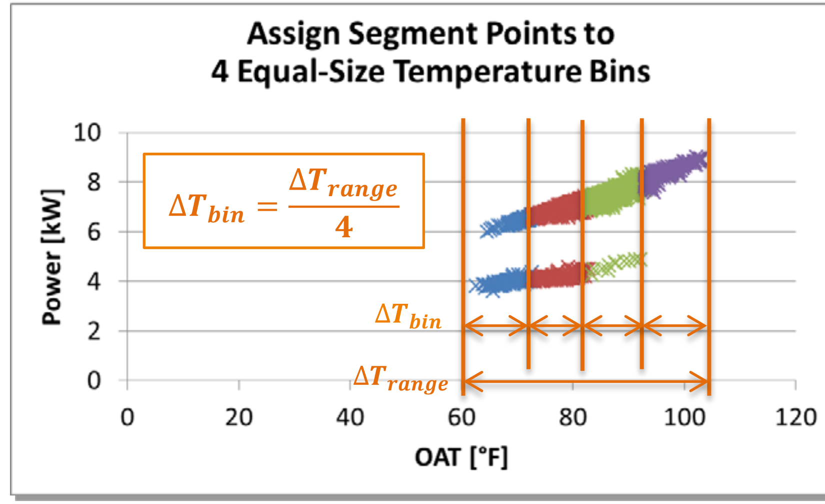
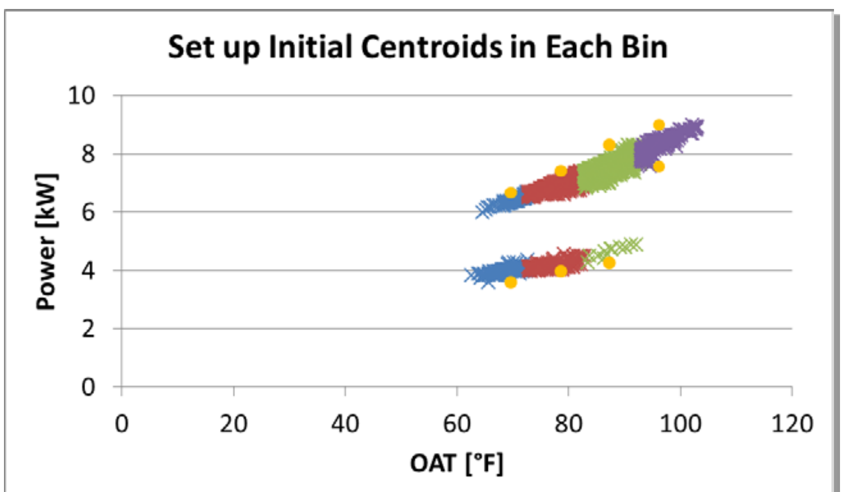


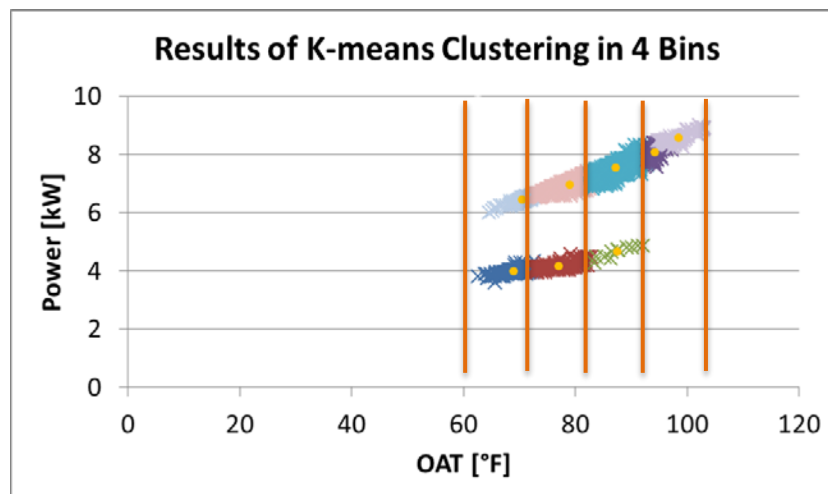
Starting point: all segment points in one group.



Step 1: Divide temperature range into four bins.



Step 2: Set up two initial centroids per bin.



Results: eight separate clusters, two in each bin.

Reunite Eight Clusters into Two Stages

Automated Process
Cooling Stage Assignment

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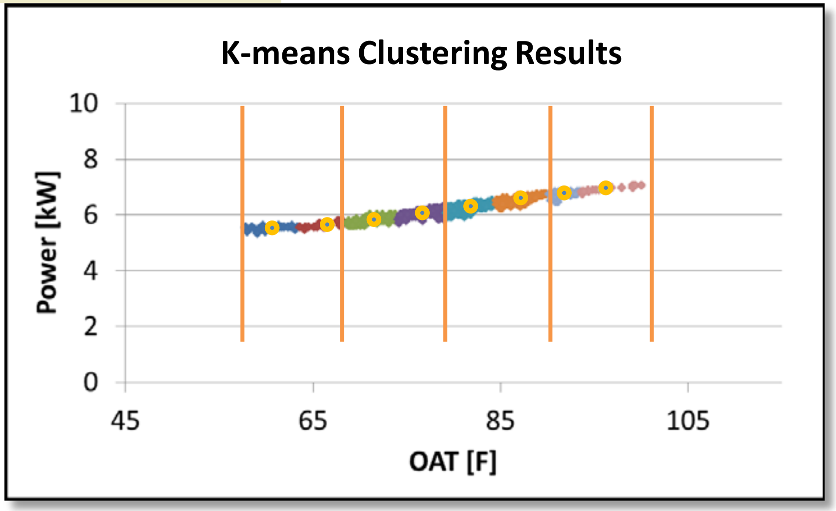
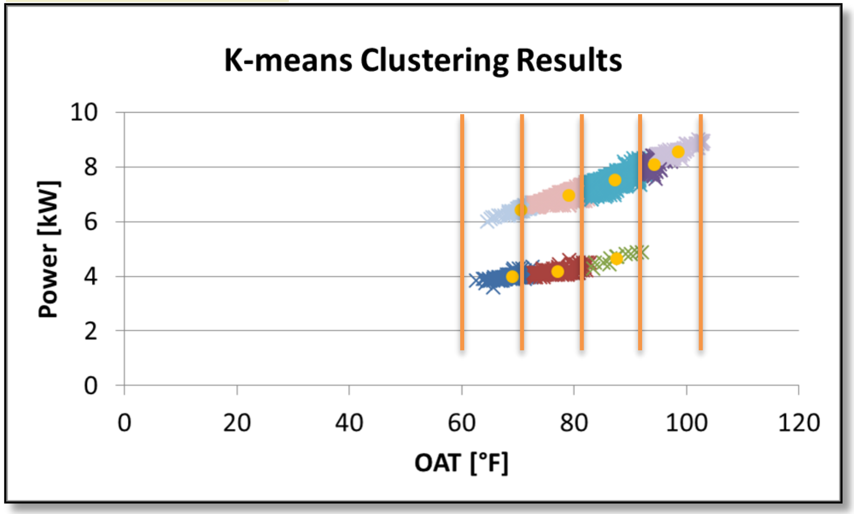
For 1-stage RTU



For 2-stage RTU



K-means clustering gives eight clusters, two in each temperature bin, but without any information on which cooling-stage each belongs to. A reuniting process is used to automatically assign these eight clusters to one or two stages.

Steps:

- For each temperature bin, decide if the two clusters belong to the same stage or separate stages. If one stage, group them together. If two stages, keep them separate.
- Across temperature bins, decide which stage each cluster belongs to.
- Detailed examples follow in the next 3 slides.

Grouping Clusters Within Each Temperature Bin

Automated Process
Cooling Stage Assignment

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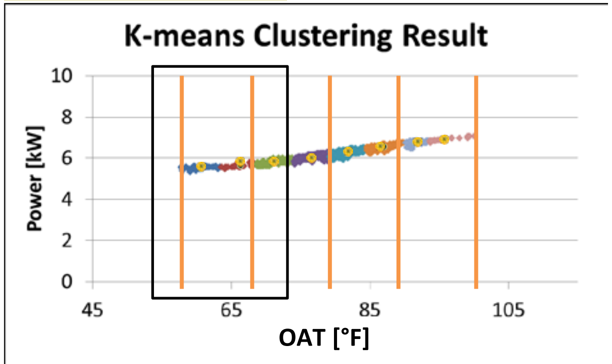
For 1-stage unit



If

$$\Delta T < \frac{\Delta T_{bin}}{4} \ and \ \Delta P < 1.5 \ kW$$

Or

$$\frac{\Delta P}{\Delta T} < 0.2$$

Then

group the two clusters in the bin.

Else

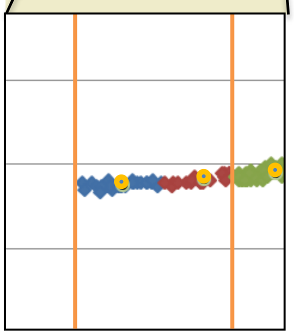
keep them **separate**.

In the example, the slope of a line between the two centroids in bin #1 is less than the 0.2 threshold. Thus, the two clusters in bin #1 should be grouped.

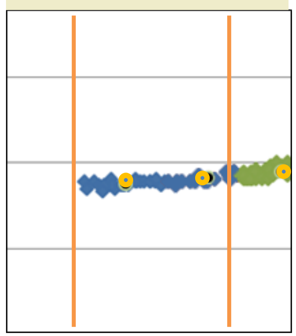
Follow the same procedure on bins #2 - #4.

In the example, all clusters in the same bin are grouped together.

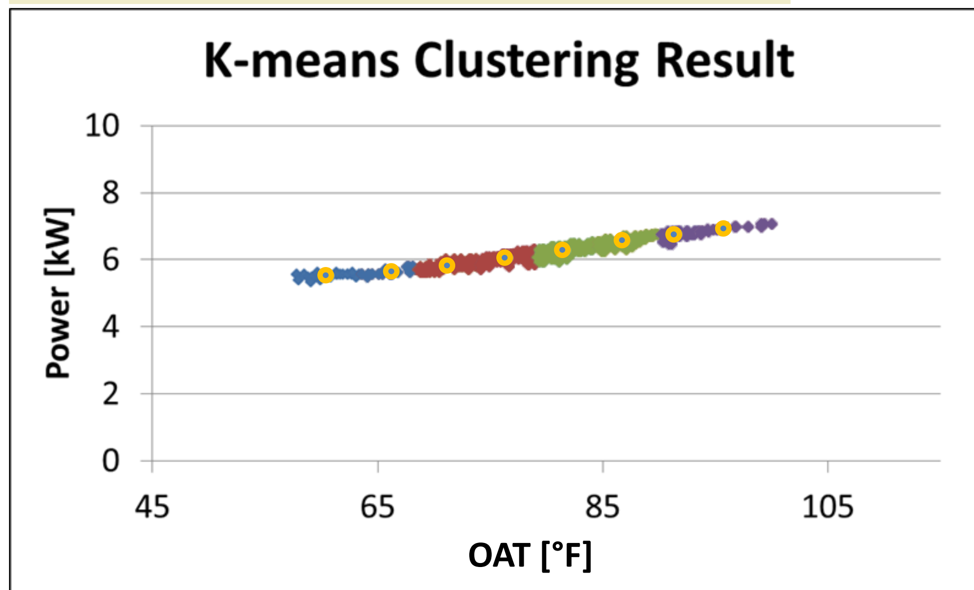
Bin #1



Bin #1 Grouped



Results: All clusters



Grouping and Separating Clusters in Temperature Bins

Automated Process
Cooling Stage Assignment

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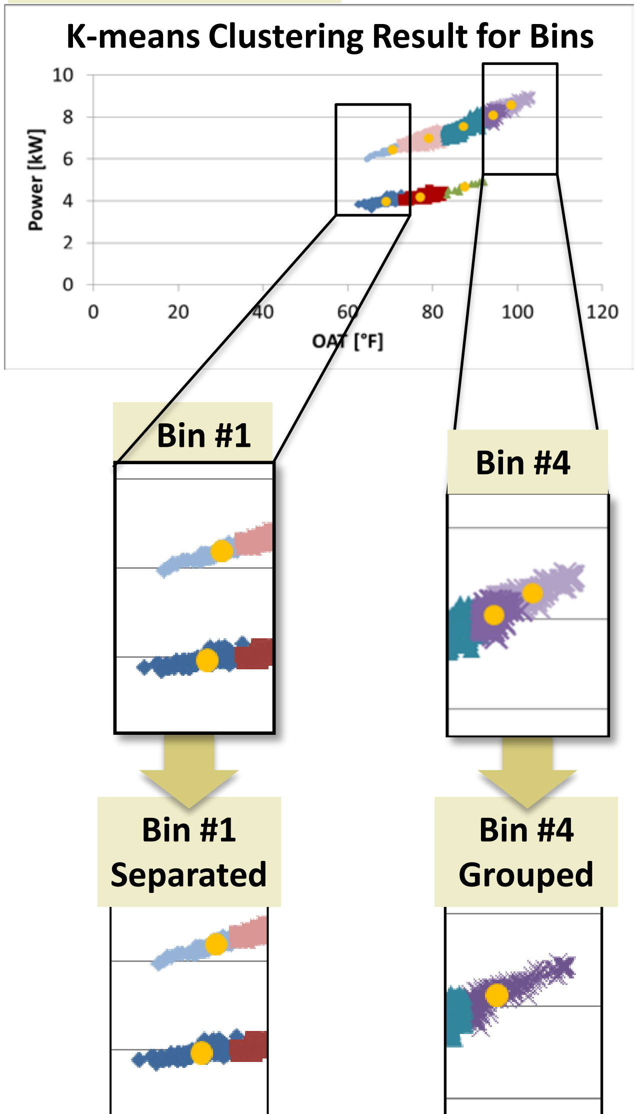
For Two-stage unit



Test

If

$$\Delta T < \frac{\Delta T_{bin}}{4} \text{ and } \Delta P < 1.5\ kW$$

Or

$$\frac{\Delta P}{\Delta T} < 0.2$$

Then

group the two clusters in the bin.

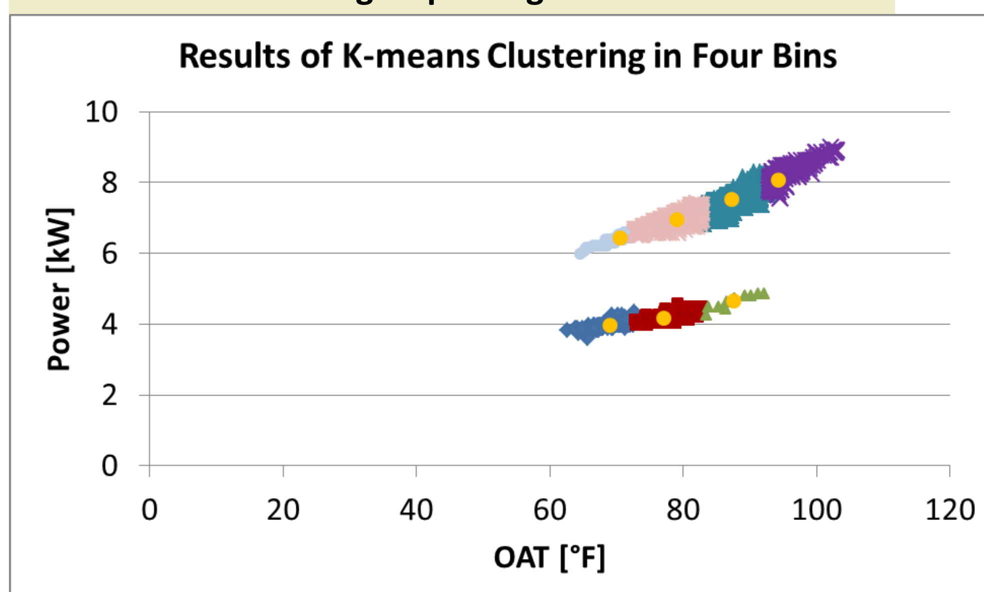
Else

keep them **separate**.

In the example, bins #1 - #3 failed the test. Thus, the clusters within them remain separate.

The slope of a line between the two centroids in bin #4 is less than the 0.2 threshold. Thus, the two clusters in bin #4 are grouped together.

Results: Clusters in Bins #1 - #3 are separate. The clusters in Bin #4 are grouped together.



Reuniting Clusters: Group or Separate Clusters Across Bins

Automated Process
Cooling Stage Assignment

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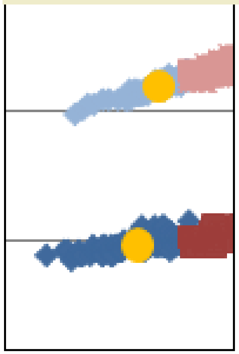
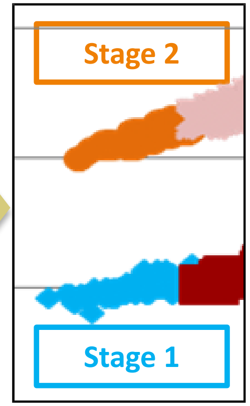
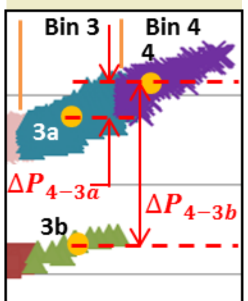
Bin #1 Separated



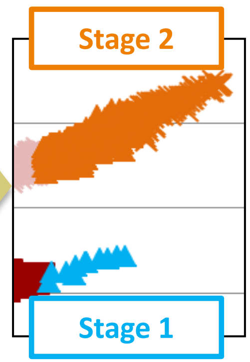
If a bin has separated clusters, the cluster with the **higher power** is assigned to **Stage 2,** and the cluster with the lower power is assigned to the **Stage 1**.



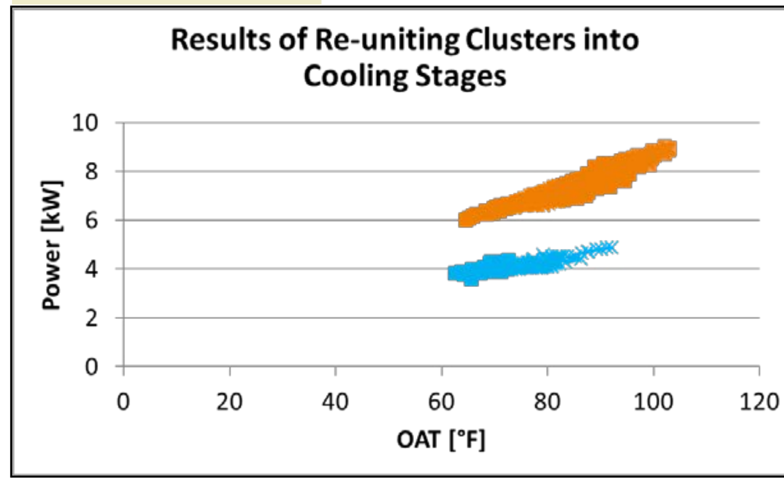
Bin #4 Grouped



If a bin has one cluster, it is assigned to the stage of an adjacent bin to which its centroid is closer as determined by the power (P) coordinate of the distance. For example, for the centroid of the single cluster in Bin 4 (point 4), $\Delta P_{4-3b} > \Delta P_{4-3a}$ and the cluster in Bin 4 is assigned to Stage 2, the stage to which the cluster with point 3a as its centroid is assigned.



Results



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SMDS Performance Degradation Detection Algorithm

-- RTUs with multi-speed fans

Method for Multi-speed Fan RTUs

Degradation Detection for **Single-stage RTU** with **Multi-speed** Fan

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Objective

- Extend the method for detection of degradation (or improvement) of the cooling cycle of standard packaged air conditioners and heat pumps automatically using a minimum number of sensors to units with multi-speed evaporator fans (i.e., supply fans).

Basic Approach

- Obtain the fan speed signal (or indicator) as a function of time from the variable-speed drive controlling the speed of the RTU supply fan.
- Adjust the P-OAT performance curves obtained using the method for RTUs with constant-speed fans for changes in fan speed.
- It was found that when the fan power is subtracted from each measurement of total RTU power, P-OAT curves for a specific stage of cooling but different fan speeds collapse to a single P-OAT performance curve.
- Apply the method for RTUs with constant-speed fans to the resulting data for multi-speed fan RTUs.

Method for Multi-speed Fan RTUs

Degradation Detection for **Single-stage RTU** with **Multi-speed** Fan

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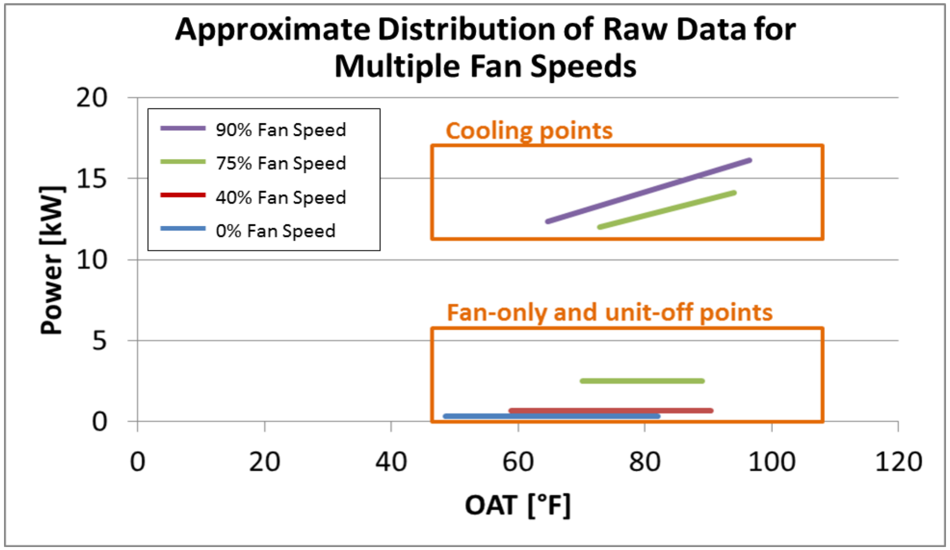
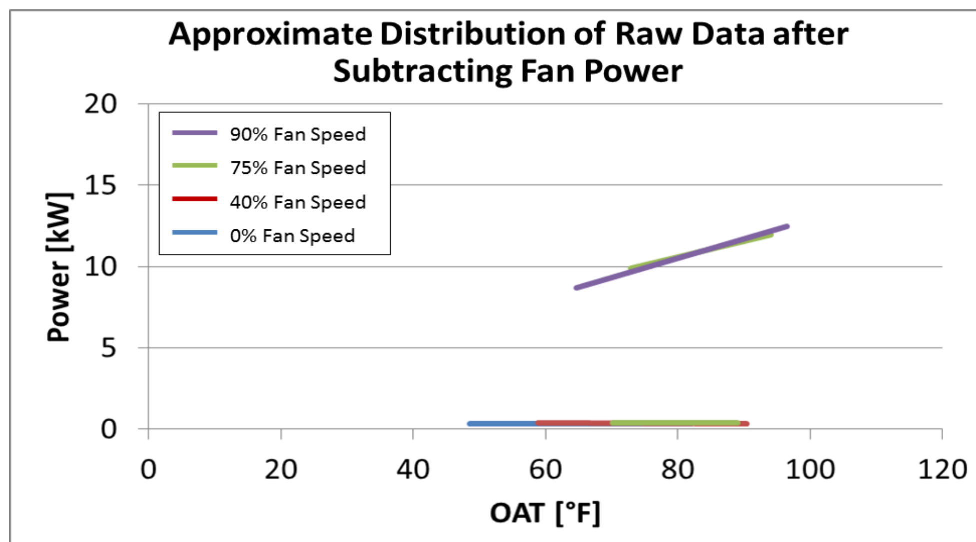


For the RTUs considered:

Cooling points have two speeds: 75% and 90% of full speed

Ventilation points have three speeds: 0%, 40% and 75% of full speed

Subtract the corresponding fan power from each measurement of total RTU power



After the fan power is subtracted, the raw data is distributed similarly to data for RTUs with constant-speed fans.

Actual Raw Data

Degradation Detection for **Single-stage RTU** with **Multi-speed** Fan

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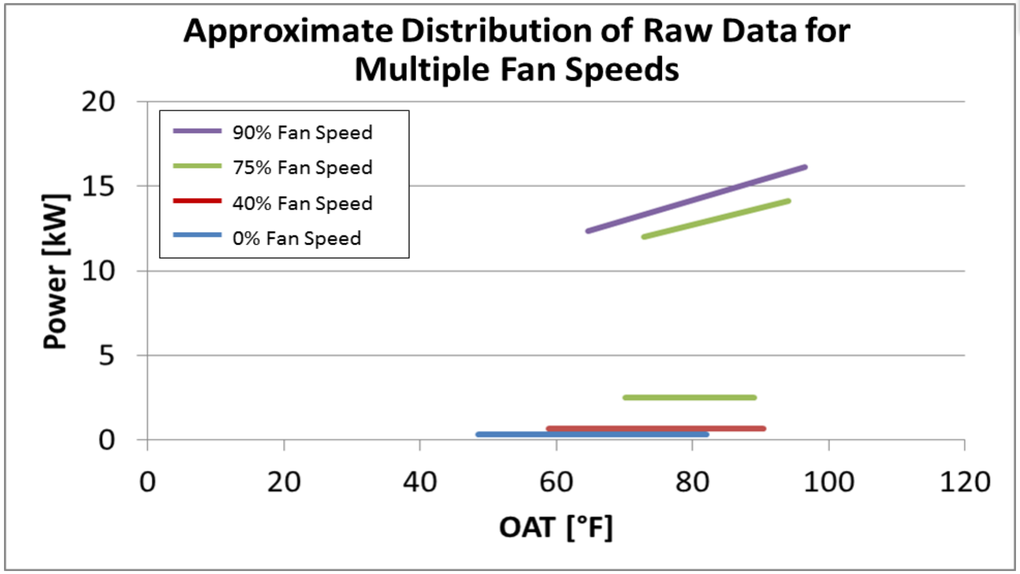

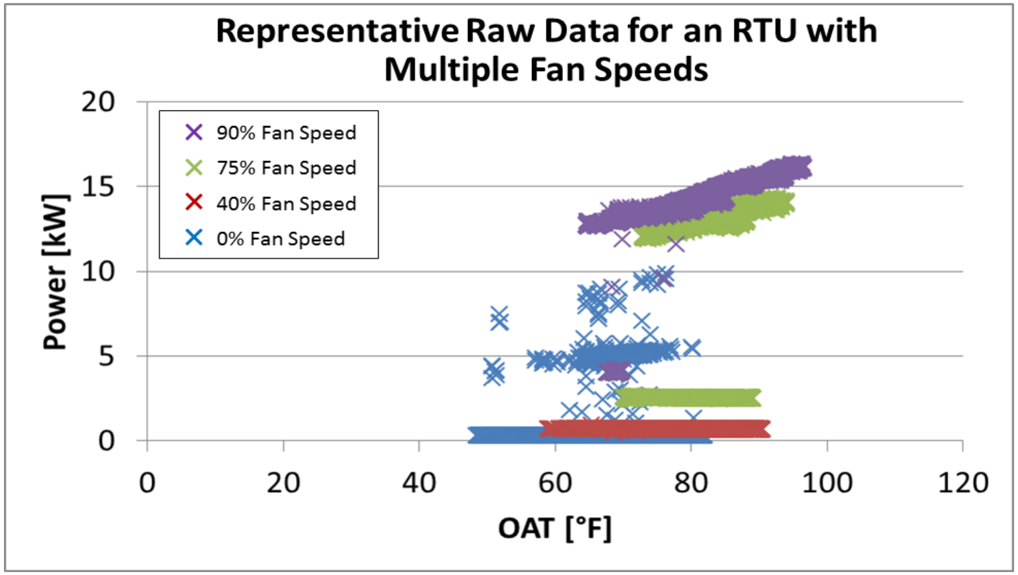

Degradation Detection for Multi-speed-fan RTUs

Degradation Detection for **Single-stage RTU** with **Multi-speed** Fan

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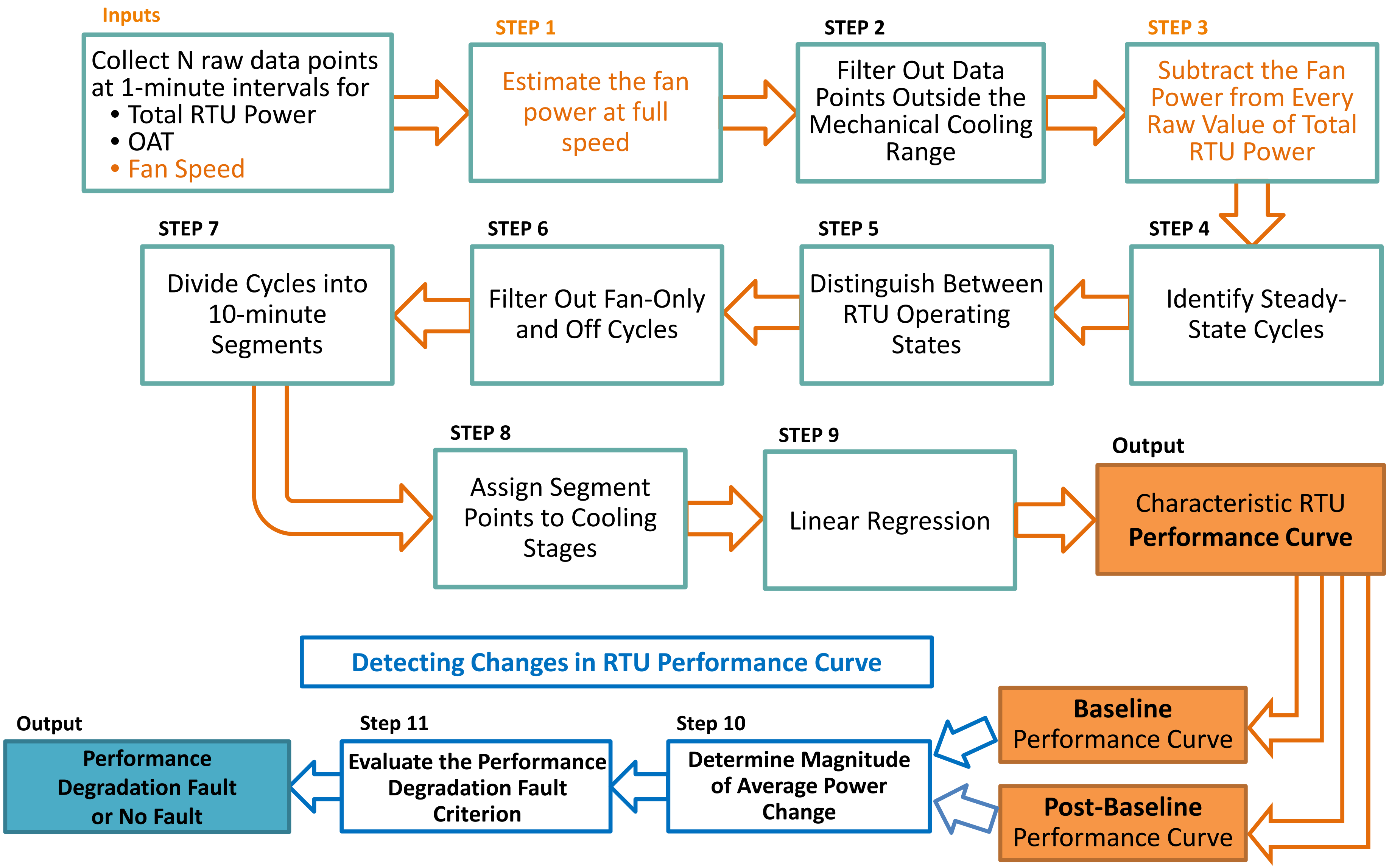

Step 1: Estimate the Fan Power at 100% Fan Speed

Degradation Detection for **Single-stage RTU** with **Multi-speed** Fan

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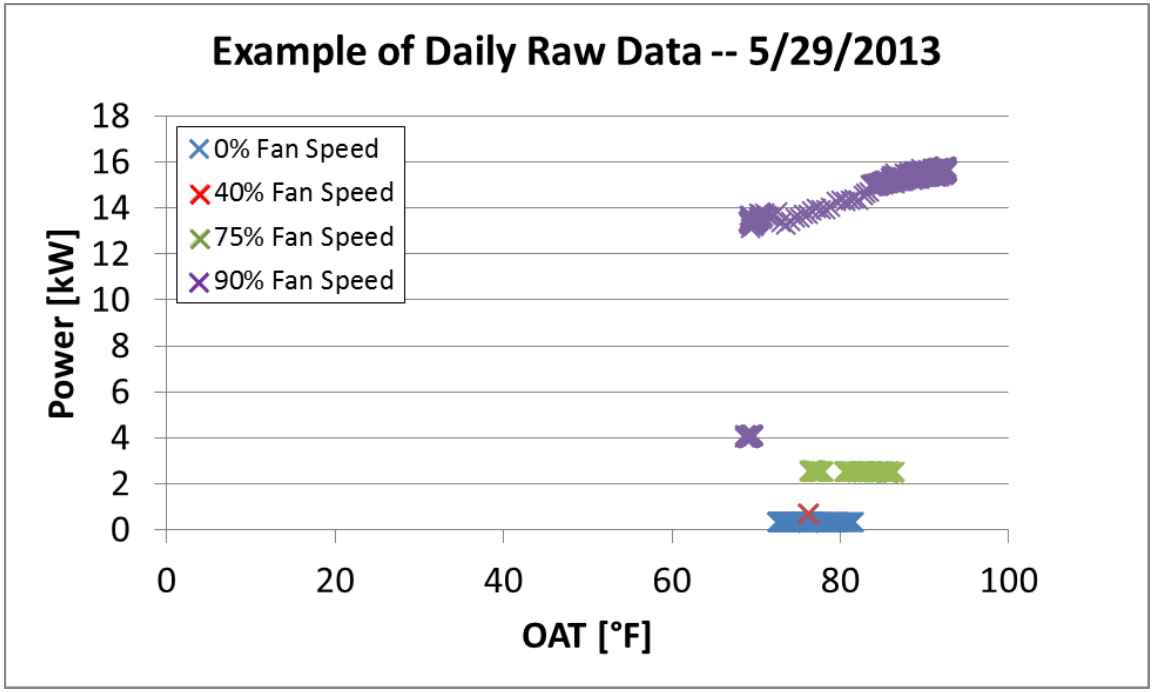


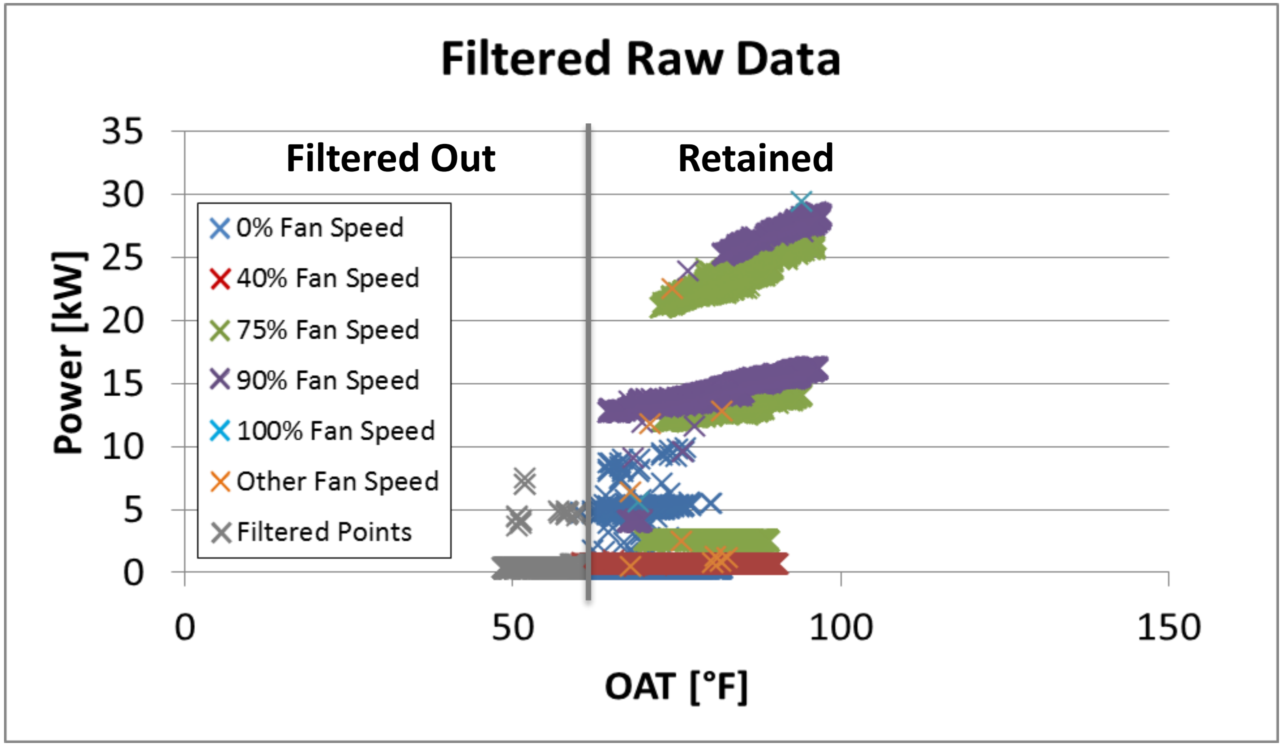
Data collected at 1-minute sampling intervals over each day (a maximum of 1440 points) are used to establish an initial estimate and then improve the estimate of the fan speed until either measurements for 100% fan speed are present in a daily data set or sufficient data are collected that a baseline P-OAT performance curve can be established for the RTU.

- Considering one fan speed at a time starting with the greatest fan speed for which data are available (90% for the data shown), identify the point with the lowest power immediately after which an increase in power greater than 2 kW occurs.
- The power increase for the data shown occurs at approximately 4 kW and the increase is about 9 kW.
- Estimate the full fan power (at 100% fan speed) using the fan power law.* For the data shown: $P_{fanpower} = 4.03/(0.9)^{2.5} = 5.24$ kW.

*The exponent of 2.5 was determined empirically over many RTUs.

Filter Out Points Outside Ordinary Mechanical Cooling Conditions

Degradation Detection for **Single-stage RTU** with **Multi-speed** Fan



The data set shown consists of N total data points, where N is presently set equal to 30,240, the number of minutes in a 3-week period. This value of N has been shown to provide consistent, reliable results for the degradation detection method. Lower values of N will be explored in the future to determine the viability of their use.

- Below OAT = 60°F, mechanical cooling is unlikely to occur in most buildings; therefore, data in this range are filtered out.

Subtract Fan Power from Each Raw Data Point

Degradation Detection for **Single-stage RTU** with **Multi-speed** Fan

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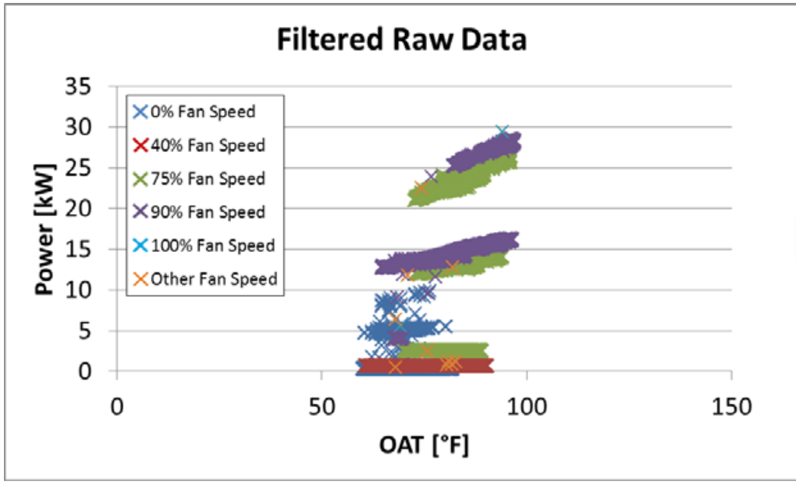

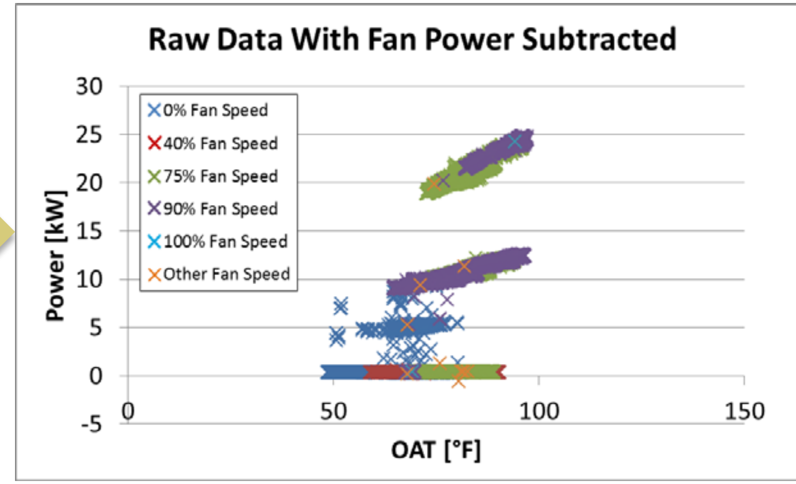

- Estimate the fan power at each fractional fan speed $F_{fanspeed}$ using the fan power law:

  $$P_{fan,F} = (F_{fanspeed})^{2.5} \cdot P_{100\%fanpower},$$

  where $P_{fan,F}$ is the fan power at fractional fan speed *F* and $P_{100\%fanpower}$ is the full fan speed.
- Subtract the appropriate fan power from the total RTU fan power of each data point, *i*:

  $$P'_i = P_{raw,i} - P_{fan,i},$$

  where P'_i is the adjusted RTU power, $P_{raw,i}$ is the power for point *i*, and $P_{fan,i}$ is power corresponding to the fractional fan speed of point *i*.
- The remaining steps (shown in the flow chart on slide 14) are the same as for RTUs with constant-speed fans described earlier.

SMDS Algorithms for Operational Faults

Compressor Short Cycling Fault

SMDS Algorithms for **Detecting Operational Faults**

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- Two conditions are evaluated to detect short cycling faults:
  - A compressor “on” cycle shorter than $t_{on\text{-}limit}$ (default set to 4 minutes)
  - A compressor “off” cycle shorter than $t_{off\text{-}limit}$ (default set to 3 minutes), which is measured as the time between the compressor turning “off” and the next time it turns on.
- The conditions for short cycling are evaluated once daily at the end of the day with the number of short cycling violations counted.
- A short-cycling fault alarm is only reported if the number of short cycles detected in a day exceeds an adjustable minimum threshold.

Daily Operation Faults

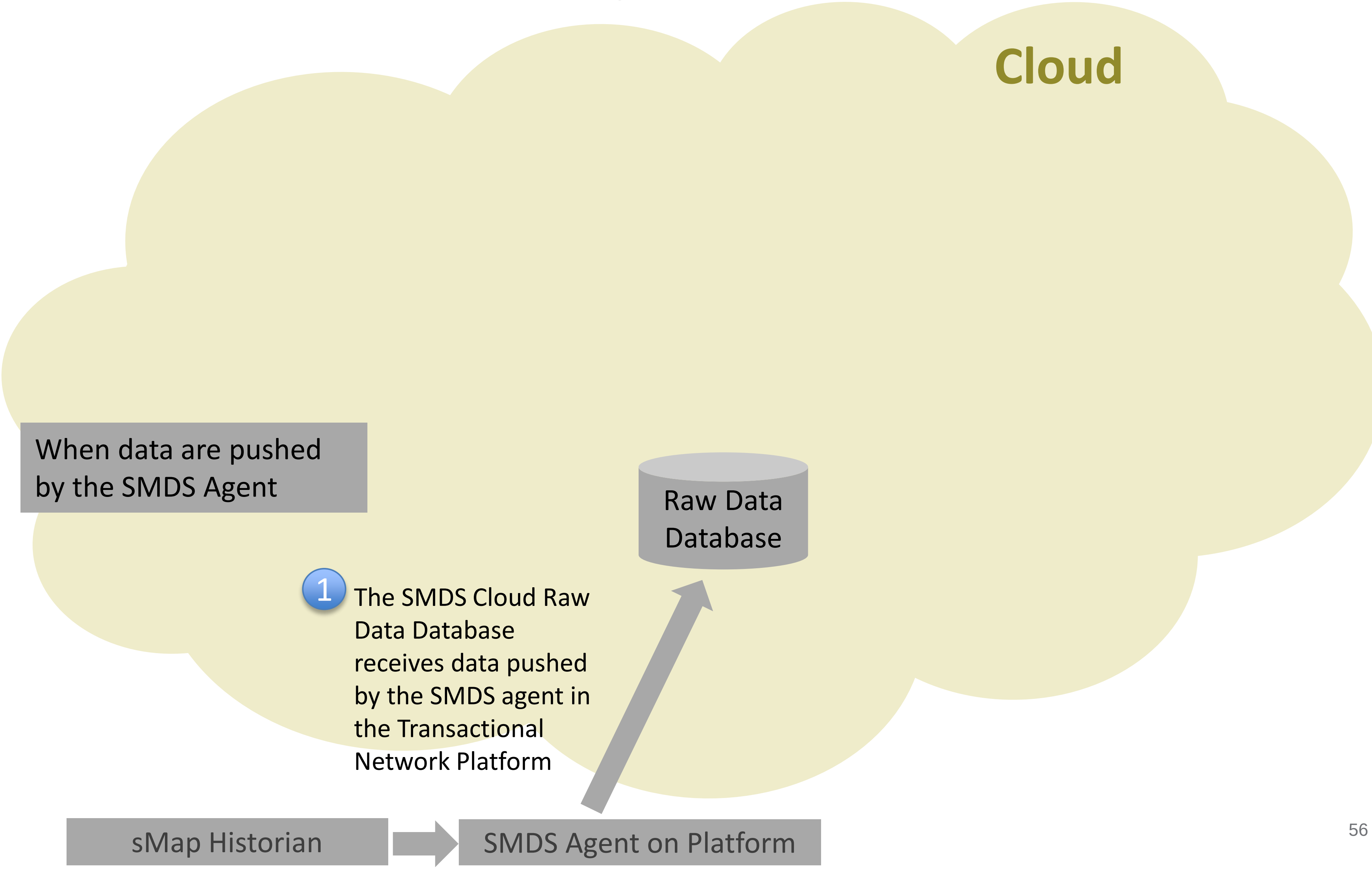
SMDS Algorithms for **Detecting Operational Faults**

- Four additional operational faults are detected by the SMDS:
  - Compressor runs continuously for 24 hours during the day
  - RTU (compressor and/or fan) runs continuously for the 24 hours of the day
  - RTU does not turn on during the 24 hours of the day
  - RTU supply fan cycles with the compressor only, not providing ventilation when the compressor is off and the unit is not cooling.
- At the end of each day, an algorithm counts the number of minutes within each hour that the RTU is in each of the following operation states: off, fan-only, or compressor-on.
- The results are used to evaluate which, if any, of the four operational faults occurred.
- An alarm is provided to the user for each of the faults detected.

SMDS Cloud Implementation

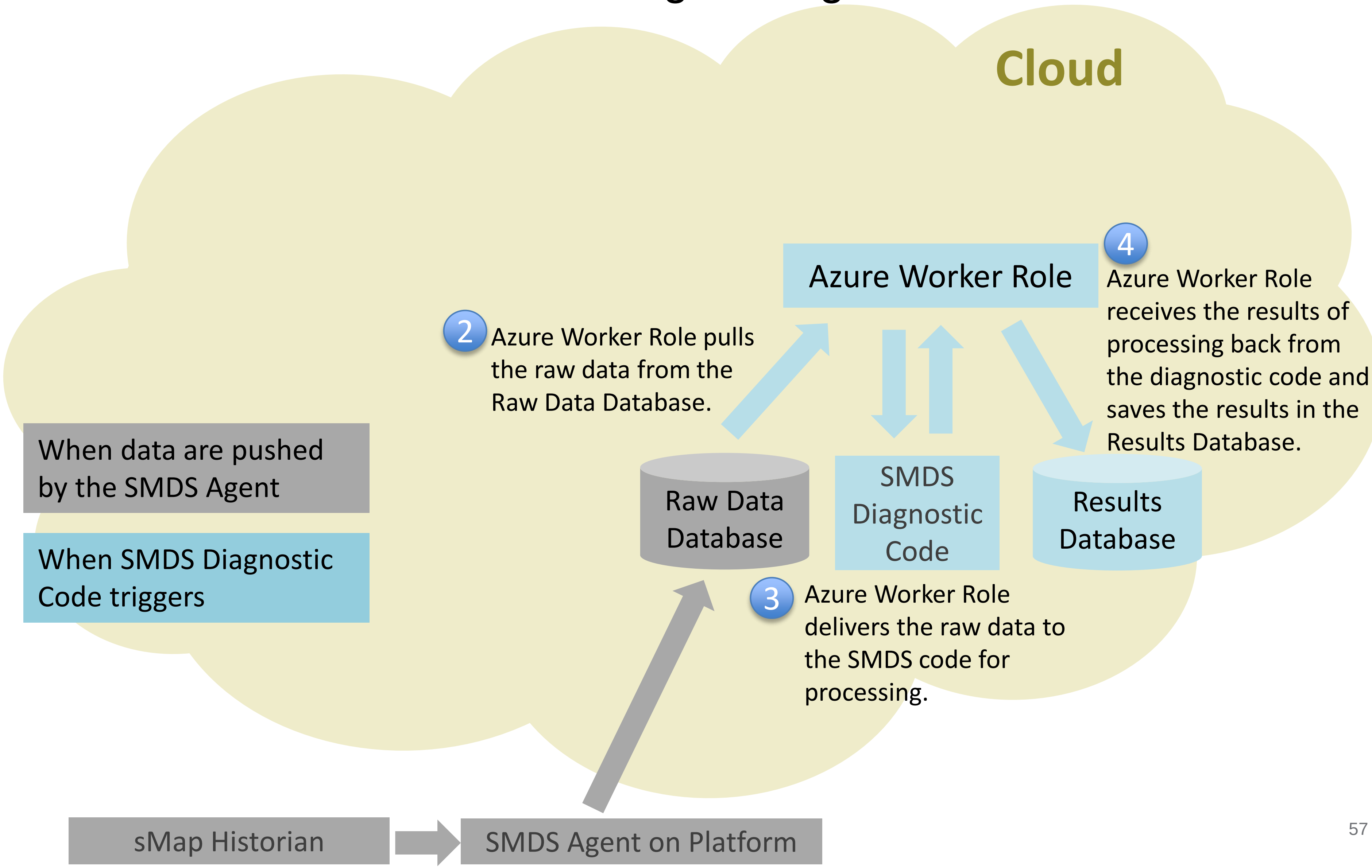
SMDS Cloud Implementation

Overall Structure – Getting the Raw Data



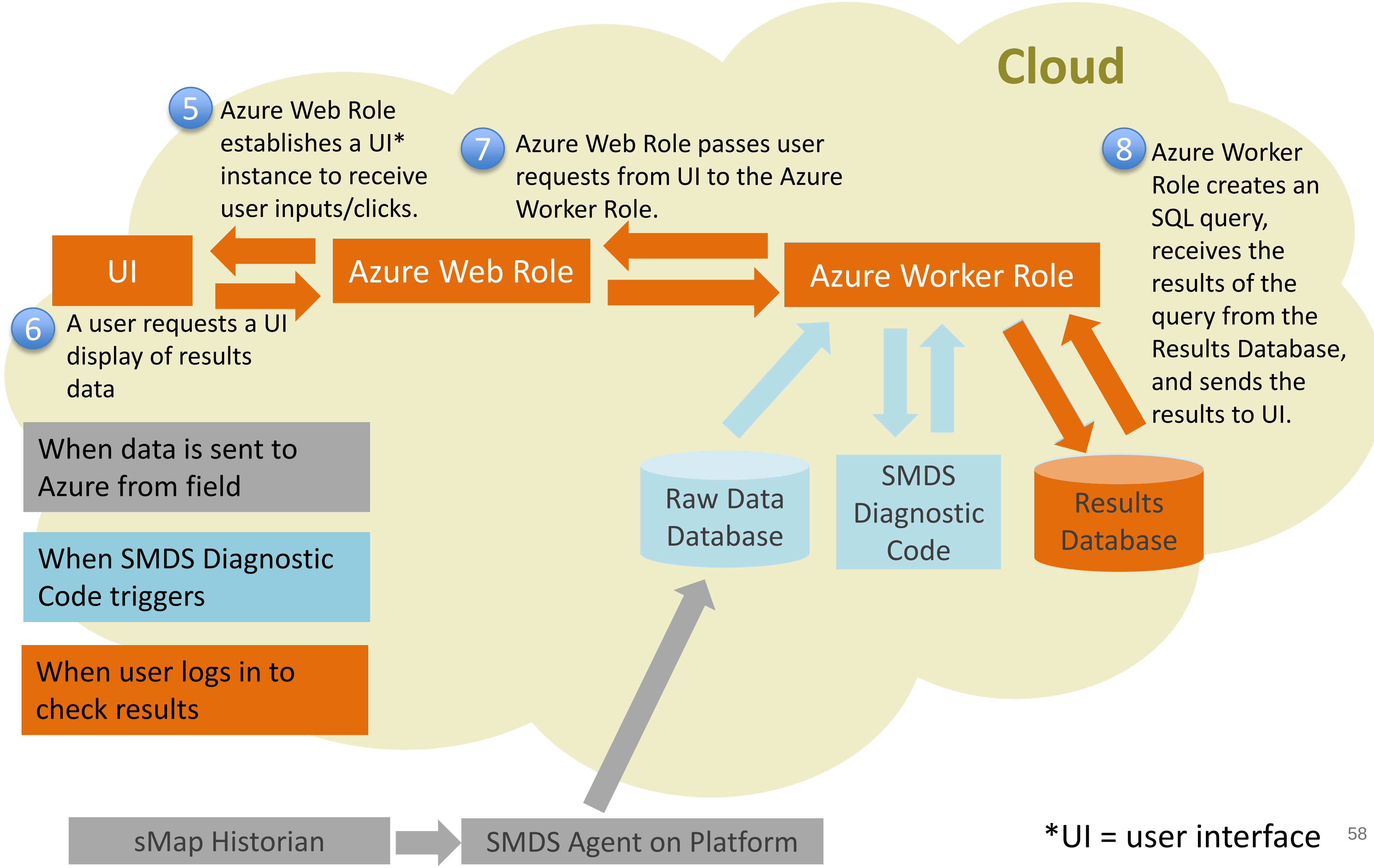
Cloud Implementation

Overall Structure – Executing the Algorithm



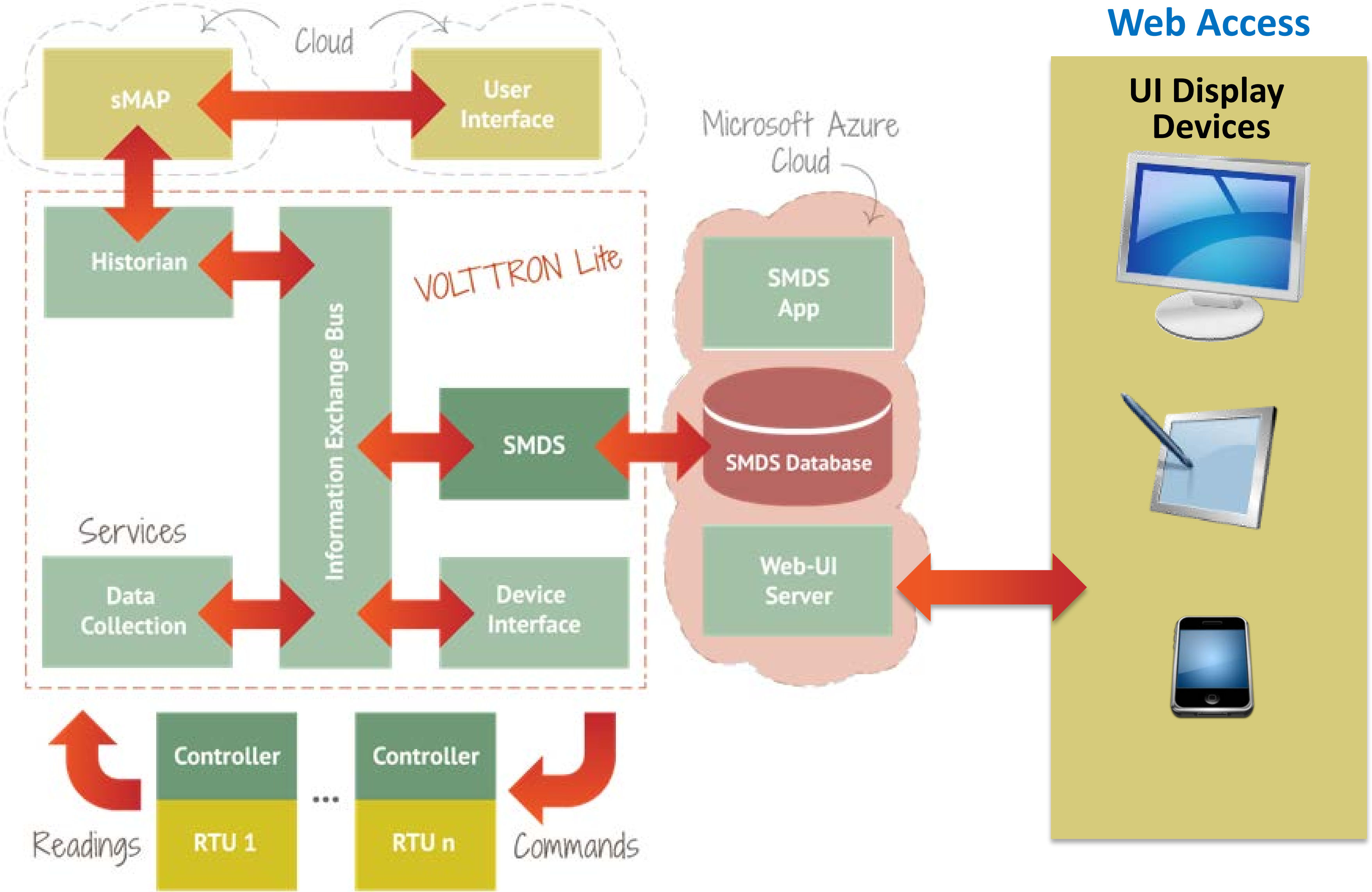
Cloud Implementation

Overall Structure – User Interactions



*UI = user interface

SMDS Cloud Connection to the Transactional Network



SMDS Cloud Execution

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- Operational fault diagnostic processing
  - Daily execution
  - Pull previous 24-hours of raw data from the database
  - Execute the daily operational fault detection algorithm
  - Deliver the daily system operating status results to the results database
  - Results include:
    - compressor short cycling
    - continuous 24/7 compressor operation
    - continuous 24/7 RTU operation
    - RTU never runs
    - Supply fan cycle with the compressor only, not providing ventilation when cooling is off

SMDS Cloud Execution

- Performance degradation/improvement processing
  - Adjustable processing frequency from daily to weekly—currently set to weekly
  - Adjustable amount of raw data for post-baseline processing—currently set to 30,240 raw 1-minute data points
  - Automatic checking for sufficient data. If not available, the system checks again at the next scheduled processing.
  - Results are stored in the Results Database.
  - Results include detection of:
    - Refrigerant-side performance degradation (or improvement)
    - Energy and cost impacts of the degradation (or improvement)
    - Operation schedule changes

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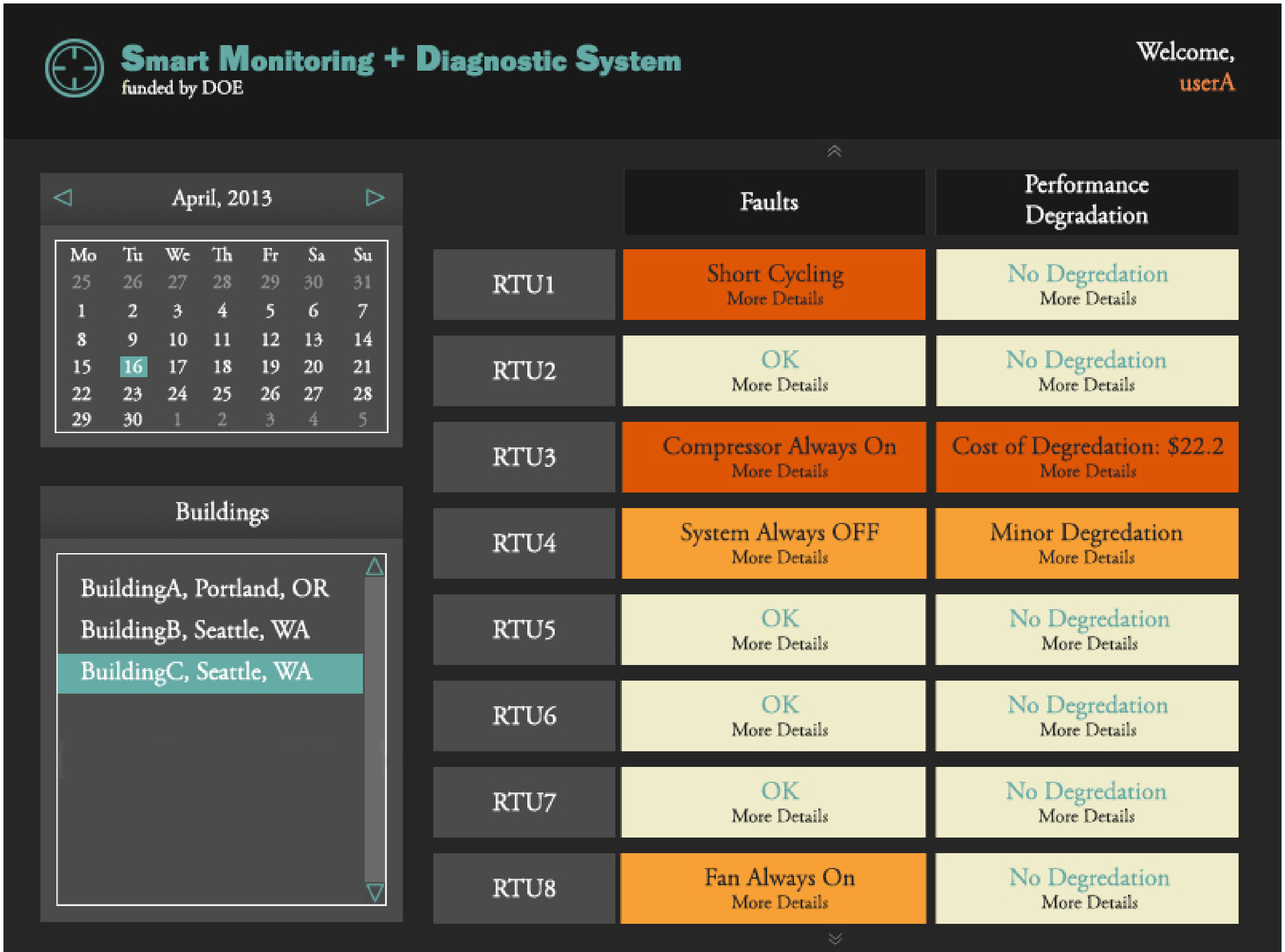
SMDS in the Microsoft Azure Cloud

End User Interface – Operational Faults Summary



SMDS in the Microsoft Azure Cloud

End User UI – Individual Fault Details

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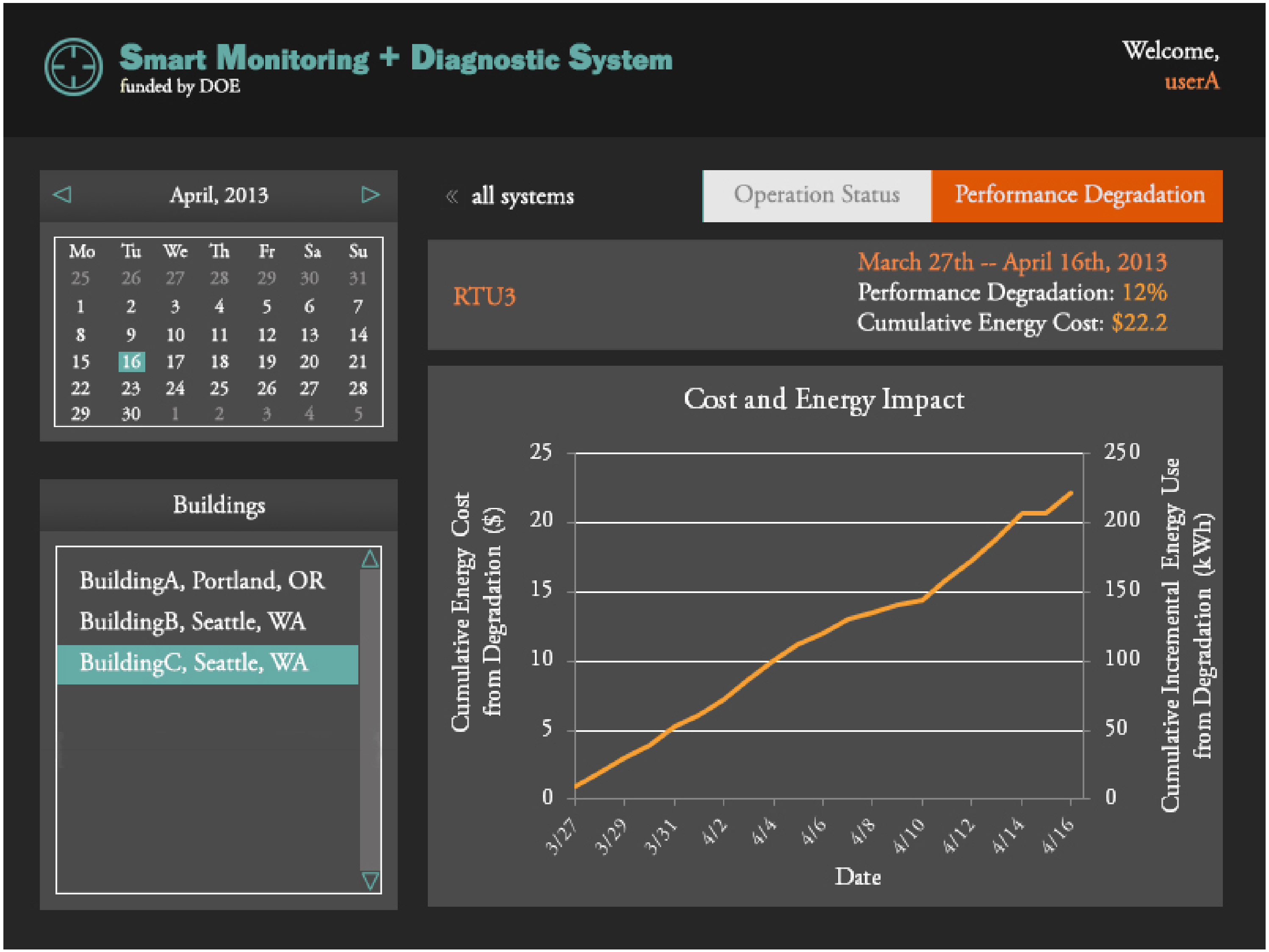
SMDS in the Microsoft Azure Cloud

End User UI – Performance Degradation & Impacts Summary



Performance and Results

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Building	Units	Faults	Occurrence	Data Period
LBNL	RTU 1	System Always Off Fan Cycles with Compressor Short Cycling	2 days 32 days 14 days	8/20-10/1
LBNL	RTU 2	System Always Off Fan Cycles with Compressor Short Cycling	5 days 28 days 22 days	8/21-10/1
LBNL	RTU 3	System Always Off Fan Cycles with Compressor	5 days 28 days	8/21-10/1
LBNL	RTU 4	System Always Off Fan Cycles with Compressor Short Cycling	3 days 30 days 1 day	8/21-10/1
LBNL	RTU 5	System Always Off Fan Cycles with Compressor	134 days 74 days	12/21 – 10/1
LBNL	RTU 6	System Always Off Fan Cycles with Compressor	7 days 26 days	8/21-10/1
LBNL	RTU7	Fan Cycles with Compressor Short Cycling	27 days 20 days	8/21 – 11/4

Performance and Results

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Building	Units	Faults	Occurrence	Data Period
TWT	RTU 1	System Always Off Fan Cycles with Compressor	11 days 7 days	9/8-10/1
TWT	RTU 2			N/A
TWT	RTU 3	System Always Off Fan Cycles with Compressor	11 days 7 days	9/8-10/1
TWT	RTU 4	System Always Off Fan Cycles with Compressor	13 days 7 days	9/8-10/1