Best Practices for Field Measurements of the Performance of Installed HVAC Systems

Summary

This document provides simple test protocols and procedures to support an HVAC system performance assessment process. It can be effectively utilized by HVAC and EM&V professionals in the field to measure and score the performance of installed HVAC systems.

Finalized: December 13th, 2017

Use of this document

Following the field measurement guidance in this Best Practices white paper will minimize measurement uncertainty and provide a consistent set of measurements across a range of practitioners. The uncertainty in the final results can be calculated from the measurement errors to test the statistical significance of measured performance

It is based on an official WHPA Work Product of December 13th, 2017 titled "Test Protocols and Procedures to Support HVAC System Performance Assessment". This Work Product was developed by the Field Data Specifications Working Group (CQI-FDS WG) which reports to the WHPA Commercial Quality Installation Committee.

This document, and also the WHPA Work Product, may be used in part or whole at no charge. Attribution to the Western HVAC Performance Alliance is requested.

Introduction

In 2015 a WHPA Commercial Installation Field Data Specification Working Group (FDS WG) was formed. This Working Group is associated with the WHPA Commercial Quality Installation (CQI) Committee. The purpose of the Working Group was to write a field specification offering guidance on data collection elements required when measuring the performance of an installed HVAC system in the field.

Previously completed products of this cross-cutting Working Group and the CQI Committee (available on the WHPA website) that are associated with these System Performance Calculation Procedures include:

- CQI Standardized Field Data Specification for Commercial HVAC Installation detailing the data points required to be collected.
- A Commercial Maintenance and a Residential Installation version of this specification have been drafted and are pending approval from other WHPA Committees.
- CQI Definition of an Efficient Commercial HVAC Installation.

The CQI Committee goals for 2017 included an expanded role for the FDS WG including:

- Standardized procedures for system performance calculations
- Best practices for field measurements of quantities required by the performance measurement calculations.

Work Product

This document provides a compilation of best practices for field measurements of quantities required by the performance measurement calculations. It is a companion document to the Calculations Work Paper, which was adopted by the WHPA Executive Committee at the same meeting, December 13, 2017.

The field measurements addressed in this White Paper are limited to single zone, constant air volume HVAC systems. The measurements are in support of calculations that address full-load cooling performance only. All equipment is assumed to be operating at full air volume and full cooling output during the test with economizer operating at minimum fresh air setting. Consistent with the Calculations Work Paper, the measurements support the calculation of the following metrics:

#1 – Equipment Delivered Capacity
#2 – System Delivered Capacity
#3 – Equipment Measured Efficiency
#4 – System Measured Efficiency

The equations for these metrics are repeated below:

#1 – Equipment Delivered Capacity

$$\boldsymbol{q_{equip} = \dot{m}_{ex}(h_{ent} - h_{ex}) + \dot{m}_{oa}(h_{oa} - h_{ent})} \quad \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(1)}$$

Where:
q_{equip} = equipment delivered capacity (Btu/hr)
$\dot{m}_{oa}$ = mass flow rate of outside air entering equipment (lb/hr)
$\dot{m}_{ent}$ = mass flow rate of return duct air entering equipment (lb/hr)
h_{oa} = enthalpy of outside air entering equipment (Btu/lb)
h_{ent} = enthalpy of return air entering equipment (Btu/lb)
h_{ex} = enthalpy of supply air leaving equipment (Btu/lb)

#2 – System Delivered Capacity

$$\boldsymbol{q_{system} = \dot{m}_{s}(h_{r} - h_{s}) + \dot{m}_{oa} \times (h_{oa} - h_{ent})} \quad \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(2)}$$

Where:
q_{system} = system delivered capacity (Btu/hr)

m_s = mass flow rate of the supply air entering the zone
h_r = enthalpy of the zone air entering the return grill
h_s = enthalpy of the supply air entering the zone

#3 – Equipment Measured Efficiency

$$\mathbf{EER_{equip} = q_{equip} / W_{equip}} \quad \text{.......} \quad \mathbf{(3)}$$

Where:
EER_{equip} = equipment field measured efficiency (Btu/hr-W)
W_{equip} = unit measured input watts

#4 – System Measured Efficiency

$$\mathbf{EER_{system} = q_{system} / W_{equip}} \quad \text{.......} \quad \mathbf{(4)}$$

Where:
EER_{system} = system field measured efficiency (Btu/hr-W)
W_{equip} = unit measured input watts

The Equipment Delivered Capacity and Efficiency are calculated from the following measurements:

- OA entering flow rate (cfm)
- Supply air flow rate (cfm)
- Supply air dry bulb and wet bulb temperature (or RH)
- OA dry bulb and wet bulb temperature (or RH)
- Return air dry bulb and wet bulb temperature (or RH)
- Unit true electric power (kW)

The System Delivered Capacity and Efficiency are calculated from the following measurements:

- OA entering flow rate (cfm)
- Supply air flow rate delivered to the zone (cfm)
- Supply air dry bulb and wet bulb temperature (or RH) measured at the supply registers
- Return air dry bulb and wet bulb temperature (or RH) measured at the return grills
- OA dry bulb and wet bulb temperature (or RH) measured at the unit
- Unit true electric power (kW)

The best practices described in this White Paper come from the test-and-balance industry and are intended to be compliant with ASHRAE Standard 111-2008—Measurement, Testing, Adjusting and Balancing of Building HVAC Systems—and Proposed ASHRAE Standard 221P—Test Method to Field-Measure and Score the Performance of an Installed Unitary HVAC System. Accurate interpretation of measurements often requires the comparison of multiple readings and comparisons to equipment specifications. Practice, judgment, and skill are critical including the on-going education and training to execute accurate readings and interpret the performance of a system.

1. BEST PRACTICES FOR TEMPERATURE AND HUMIDITY MEASUREMENTS

1.1 Basic Instrument Specifications

When selecting good quality instrumentation, there is a tradeoff in terms of cost and accuracy. Field data instruments must be accurate, affordable, and rugged enough to be used in the field on a regular basis. The suggested accuracy specifications for air temperature and humidity instrumentation is summarized below:

- Temperature: Minimum accuracy of ±1°F, a minimum resolution of 0.1°F and a minimum temperature range of 20 to 180 degrees F.
- Relative humidity: Minimum accuracy for relative humidity is ±2.5%RH, with a minimum humidity range of 5% to 95% relative humidity.
- Each is to be calibrated according to NIST Standards within the past 12 months.

1.2 Probe Placement

1.2.1 Equipment

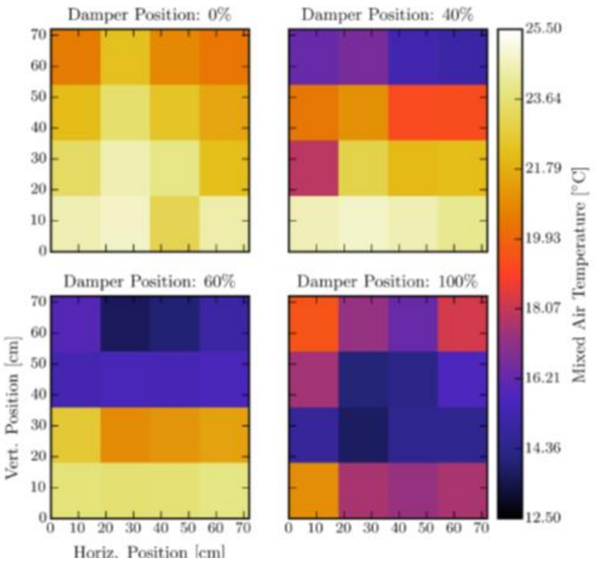
- Measure equipment supply air temperatures out of line of sight of coils, heat strips, or heat exchangers that are energized. Place probe as close to the center of the duct as possible.
- Temperatures shall be taken and recorded to the nearest tenth of a degree.
- The ambient outdoor temperatures at the outdoor air intake should be taken under shaded conditions and reflect the air temperatures entering the outdoor air intake.
- Surroundings also make a difference. There must be a clear area around the unit or stratification and recirculation of the outside air may occur.
- Return air temperatures should be taken within the return air duct at a point where the air enters the equipment at a point where the return air temperature is not affected by the temperature of the outside air entering the system.
- If an energy management control system (EMCS) data is used to make the temperature measurements, verify the locations and the accuracy of the sensors used to record the data. Sensor accuracy should conform to the specifications above.

1.2.2 System

- Make supply temperature and humidity measurements through a minimum of three supply registers.
- Make return temperature and humidity measurements through a minimum of two return grilles.
- Select registers and grilles located near the halfway point between the equipment and the most distant registers and grilles in the system. Make measurements on different main trunks as applicable.
- When testing registers and grilles, each register and grille has openings between the louvers allowing access directly into the airstream by inserting the probe through the louvers. When access into the airstream is not accessible, test ports should be installed into the system providing access into the airstream where the specified temperature tests shall be taken. Do not take temperatures at the face of the register as room air entrainment will affect the reading.

1.2.3 Mixed Air Temperature

Rooftop unit mixing boxes are small and do not do an effective job of mixing the air entering the coil. Data from lab tests taken at the University of Nebraska showed that economizer position has a strong influence on the amount of mixing, as shown below:



The implications of the mixing problems include:

- Air-side stratification – non-uniform temperature and flowrate across the face of the coil
- Refrigerant-side stratification – refrigerant circuits “see” different air temperatures
- Non-uniform exit superheat

Single point temperature measurement of entering wet bulb temperature (EWB) measurement is likely to be inaccurate. Multipoint measurements or an averaging probe can be used to address temperature stratification, but flowrate stratification remains an issue.

1.2.4 Measurement Timing

When a system is set to full cooling in the field, conditions will continually change. Therefore, we need to be mindful that the temperature and humidity conditions will change over the course of the test. Individual measurements recorded sequentially may not work because, by the time the last measurement is taken, the first measurement has changed. We therefore require strategies where we can make multiple and simultaneous measurements using an array of sensors or data loggers. This allows us to obtain comparable values that are recorded at the same time.

Wireless temperature and humidity probes offered by several manufacturers should be used to make simultaneous readings and report directly to mobile devices. An example of a wireless system is shown below:

Portable data loggers that are time synchronized and deployed around the system can also be used to make time series temperature and humidity measurements. The loggers are downloaded at the conclusion of the test, and data taken at the same point in time are used in the calculations. An example of a portable datalogger is shown below:

Maximum Rate of Temperature Change: In order to achieve a near steady state test, the rate of temperature change should be not more than 0.5 F (.25 C) degrees in 60 seconds. The Rate of Temperature Change is defined as the absolute value of the difference between two temperature readings taken 60 seconds apart.

2. BEST PRACTICES FOR STATIC PRESSURE MEASUREMENTS

2.1 Manometer Specifications

- Digital manometer requirements include a minimum accuracy of ±3%, a minimum resolution of 0.01” w.c. (2.5 Pa) and a minimum range of 0” to 10” w.c. (0 to 2,500 Pa).

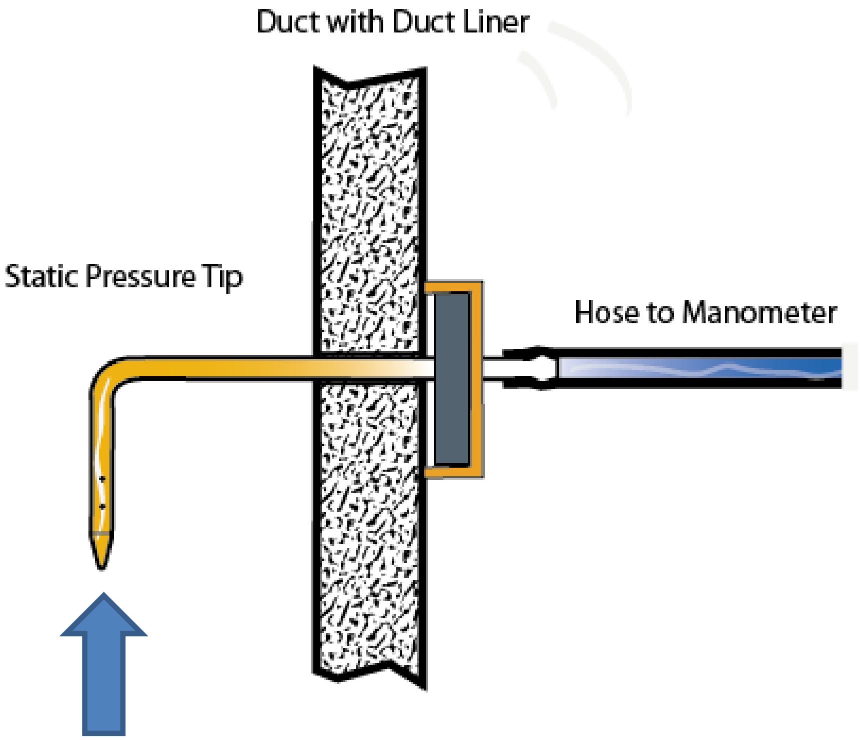
Each instrument is to be calibrated according to NIST Standards within the past 12 months.

- Calibrate instruments annually

An example of a digital manometer is shown below:

2.2 Probe Placement

Placement of a duct static pressure probe is illustrated below:



Best practices for static pressure measurements include:

- Face point of static pressure probe directly into airstream, perpendicular to airflow.
- Move probe to find minimum reading.
- Technician must be trained to identify correct test locations and avoid turbulence.

2.2.1 Equipment Entering Static Pressure

- On units with economizer or outside air intakes, measure equipment entering static at face of filter, downstream from economizer and return dampers.
- On units without economizer or outside air intakes, measure equipment entering static at threshold of unit to curb adapter or duct.

2.2.2 Equipment Exiting Static Pressure

- Measure equipment exiting static at threshold of unit to curb adapter or duct. Ideally, place probe 2 duct diameters downstream of the nearest bend or obstruction.
- Take extra caution when measuring units with electric heat strips, ensure instrument cannot contact element

3. BEST PRACTICES FOR ELECTRIC POWER MEASUREMENTS

3.1 Specifications

- Use true electric power meter not volts, amps, and assumed power factor.
- Power meter requirements include a minimum accuracy of ±3%, a minimum resolution of 10 watts. Minimum range shall be 0-600 Volts and 0-100 Amps. Each electrical power meter is to be calibrated according to NIST Standards within the past 12 months.

3.2 Single Phase Power Measurement (115-120 Volt Systems)

- Set true RMS, auto calculating power meter to read AC Watts.
- Insert the black probe to the meter’s common (COM) port and the red probe in the port to the right of the common port.
- Place the black probe on an exposed common wire or to ground.
- Place the red probe on an exposed and energized incoming bus, lug, or wire marked L1.
- Place the current clamp of the power meter onto the L1 conductor.
- Measure and record the operating wattage displayed on the electrical multi-meter.

3.3 Single Phase Power Measurement (208-230 Volt Systems)

- Set the true RMS auto calculating power meter to read “AC” and “Watts.”
- Insert the black probe to the meter’s common (COM) port and the red probe in the port to the right of the common port.
- Place black probe to the exposed and energized incoming L1 lug or terminal.
- Verify the measured voltage is within the required voltage of the equipment.
- Place red probe to the exposed and energized incoming line 2 lug or terminal.
- Place the power meter clamp onto the L1 and L2 conductors while following the specific steps of the particular meter to complete the wattage calculation.
- Measure and record the system watts displayed on the power meter.

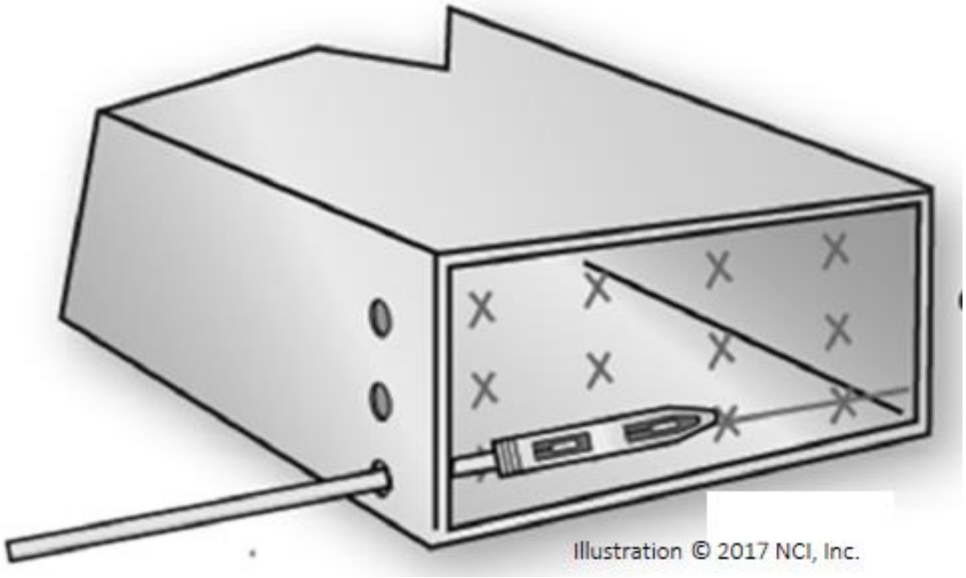
3.4 Three-Phase Power

- When taking power measurements on a three-phase piece of equipment, a three-phase watt meter should be used. Making and summing individual single-phase measurements takes too long and the readings may not be comparable.
- Set the true RMS, auto calculating, 3-phase power meter to read AC Watts. Insert all the probes into the meter.
- Connect all power meter probes to each of the L1, L2, L3, and ground terminals.
- Place the current clamp onto the L1, L2, and L3 conductors while following the proper steps of the particular meter to complete the wattage calculations.
- Measure and record the power displayed on the power meter in Watts.

4. AIR FLOW MEASUREMENTS

Several methods can be used to make air flow measurements at the equipment:
- Digital Anemometers
- TrueFlow Plates
- Indirect Method Using Fan Tables

Digital Anemometers are velocity measurements devices that capture and record the speed of air when placed into an airstream. Each is programmable to accept the dimensions of the airstream and converts a series of velocity readings to volume such as cfm (L/s). Two types of anemometers are generally used: (1) a thermal (hot wire) anemometer or (2) a rotating vane anemometer. Anemometer measurements use a velocity traverse principle. Holes are drilled into the duct at predetermined locations using the equal-distance method or the log-Tchebycheff method. Velocity is recorded at each of those points, and a traverse-specific calculation is used to derive the average velocity and determine the CFM. An example of an anemometer traverse is shown below: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TrueFlow Plates are portable airflow measurement stations that are placed in a filter rack in place of the filter. The plate has an array of static and velocity pressure ports to give an average velocity through the plate. The TrueFLow plate reads out to a dedicated micro manometer with imbedded calculations to directly measure CFM. For larger systems, a series of plates is used to measure total system airflow.

Indirect Method Using Fan Performance. The basic concept is measuring external static pressure on equipment and the RPM of the fan and looking up the air flow based on manufacturer's fan performance data. Often tables are presented for external static pressure without any other elements inside the unit itself that provides additional pressure drop and need to be adjusted for accessories that add additional pressure drop.

Air flow measurements at the zone are generally made using a commercial flow balancing hood. A velocity traverse can be used in applications where a balancing hood cannot be used.

4.1 Equipment Accuracy Specifications

- Anemometer: +/- 5% of reading
- TrueFlow Plate: +/- 7% of reading
- Flow Balancing Hood: Rated accuracy +/- 3% +/- 7 cfm

4.2 Outdoor Air

Technique depends on outdoor conditions. Calm conditions can use vane anemometer traverse across the outdoor air inlet face. Windy conditions use traverse across the outdoor air hood. An example of a vane anemometer traverse is shown below:

An example of a traverse inside the outdoor air hood is shown below:

- Use a smoke pencil to check for turbulence or recirculation in the outdoor air hood
- Make several sets of measurements to determine measurement repeatability.
- With the traverse methods, as outside air fraction gets smaller and smaller, you get to the lower limit of the instrument and the air flow may not be measurable.
- If adequate space is not available to perform a proper traverse, the temperature ratio method can be used as an alternative. Note the issues with making mixed air temperature measurements above. The temperature ratio method can be used only if the outside temperature is at least 20° above or below the return air temperature.

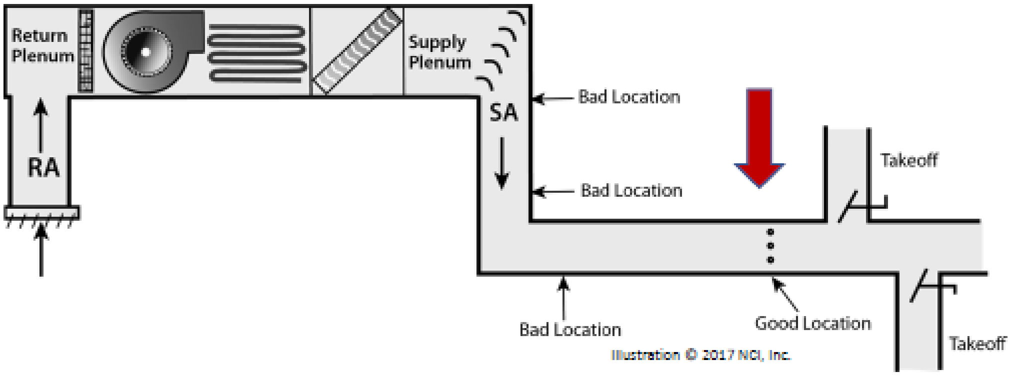
4.3 Equipment Supply Air

Best practices for equipment supply air flow rate measurements are described below:

4.3.1 Anemometer Traverse

- Measurement must be taken at a qualifying measurement plane in the supply trunk duct. See ASHRAE Standard 111 for guidance on selecting a measurement plane.

An example of an acceptable measurement plane for an anemometer traverse is shown below:



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- Make measurements on the main trunk if possible. If not possible, make measurements on each of the main trunk branches and then add up the branches.

4.3.2 TrueFlow Plates

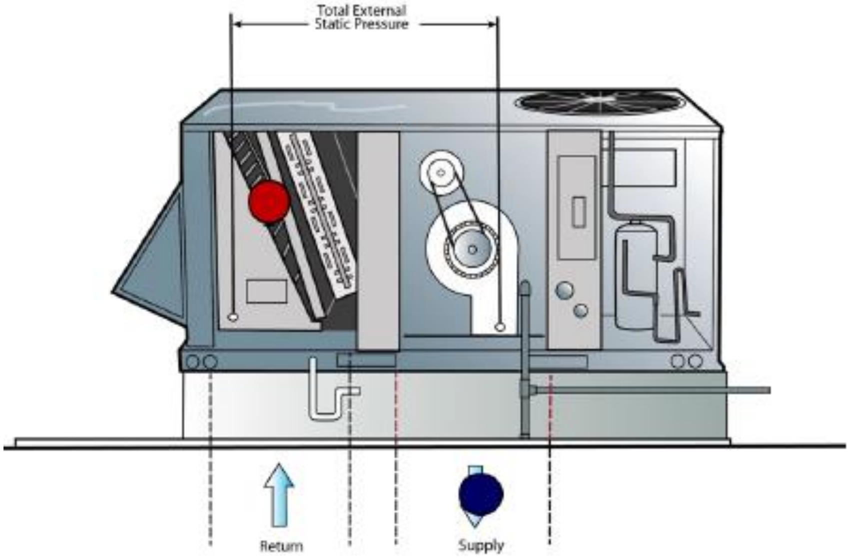
An example of the application of a set of TrueFlow plates in a commercial rooftop unit is shown below:

Best practices for the use of TrueFlow plates include:

- Install one plate per filter.
- Watch for gaps around the plates and adjust the plate seals to eliminate air bypassing the plates.
- Close the unit door and route the pressure tubes to minimize leakage while not crimping the tubes.
- Make static pressure correction as directed by the manufacturer.
- The device reads out in CFM per plate. Sum the readings across each installed plate.

4.3.3 Fan Table Lookup

- Measure inlet and outlet static pressure rise. The pressure measurements will be taken entering and leaving fan or entering and leaving the unit depending on manufacturer's data. Be sure to adjust for accessories as needed. An example of external static pressure measurement locations is shown below:



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- Measure fan rpm using a digital tachometer. Note, unit doors should be closed to establish the correct static pressure difference across the fan before making the RPM measurements.
- Lookup flow on unit fan table or fan curve. Recommend using the fan curve rather than the fan table. The advantage in using the fan curve is that you can follow the curve versus doing a linear interpolation from the table values. If motor is close to fully loaded, you can also use fan amps to verify the air flow estimate. Tests should be made on a clean coil and with new filters. Fan tables assume both wet and dry airflow. Verify the condition of the coil and the assumptions used in the fan performance data.

4.4 Supply Air at the Zone

- Use air balance hood device to measure airflow into supply registers that are accessible and within range of the hood. Set up hood to read in actual volumetric airflow.
- Only commercial grade, digital, back pressure compensating balancing hoods should be used.
- The skirt at the top of the hood needs to be the right size and length to capture all the airflow of the register directed evenly over the manifold. Make sure there is a tight seal where hood meets the register.

An example of a commercial flow balancing hood is shown below:

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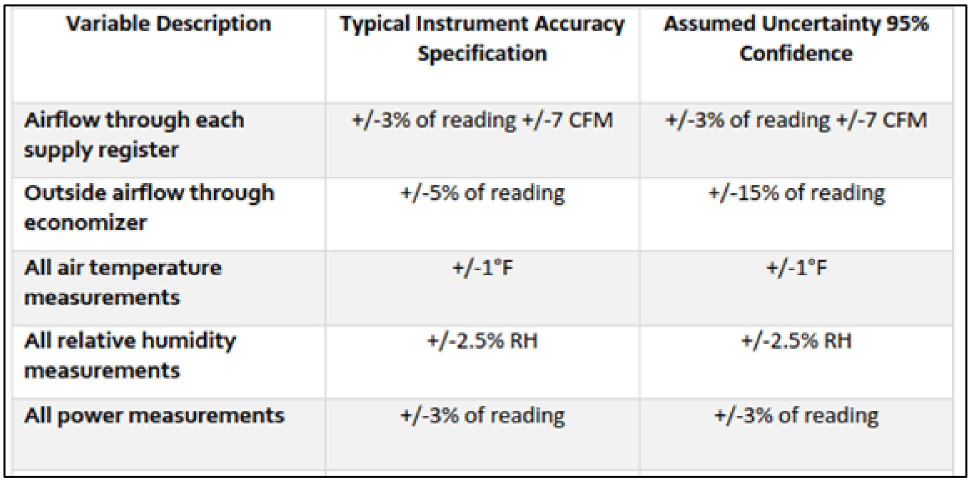
- Supply registers inaccessible to an air balancing hood should be traversed. When the traverse location is within a duct, traverse test ports should be installed in an acceptable test location per ASHRAE Standard 111.

5. UNCERTAINTY SPECIFICATIONS AND ASSUMPTIONS

Uncertainty should be considered in all measurements, and the uncertainty in the measured quantities should be determined from the individual measurement uncertainty using a propagation of error calculation. See ASHRAE Guideline 14 for more information.

For example, 127 performance tests on live HVAC systems in the field were conducted following the methods described in this White Paper and in ASHRAE Standard 221P. Monte Carlo simulations were used to estimate the uncertainty of the measured quantities from the uncertainty in the individual measurements. The measurement uncertainty assumptions were as follows:



Variable Description	Typical Instrument Accuracy Specification	Assumed Uncertainty 95% Confidence
Airflow through each supply register	+/-3% of reading +/-7 CFM	+/-3% of reading +/-7 CFM
Outside airflow through economizer	+/-5% of reading	+/-15% of reading
All air temperature measurements	+/-1°F	+/-1°F
All relative humidity measurements	+/-2.5% RH	+/-2.5% RH
All power measurements	+/-3% of reading	+/-3% of reading

The Average Field-Measured System Efficiency was 6.5 EER ±.76 EER at a 90% confidence level. From this set of data, the uncertainty of the test-in and test-out measurements were as follows:

- Test-In: 5.9 ± 0.7 EER
- Test-Out: 7.9 ± 0.9 EER

The differences were statistically significant at 90% confidence, indicating that the measurements are precise