Getting Setpoints Under Control: Advancing the Conversation with ASHRAE Standard 195 and Controllable Air Flow Minimums

Jeff Stein and Pat Wendler, Taylor Engineers
S. Michael Daukoru and Mark Alatorre, Pacific Gas & Electric

ABSTRACT

Air flow minimum setpoints for variable-air-volume (VAV) boxes have significant impacts on energy use and comfort. Lower setpoints generally imply energy efficiency. However, setpoints below controllable minimums can result in unstable operation (damper hunting, comfort/noise issues, etc.) or insufficient ventilation. California's Title 24 and ASHRAE 90.1 require minimums not to exceed the ventilation requirements (which can be 10% or lower), but these requirements are often violated by engineers/contractors conservatively implementing 30% or higher minimums. Moreover, past research by ASHRAE and PG&E suggest that accuracy/stability can be maintained down to about 10%. However, reliable data on controllable minimums—which depends not only on box manufacturers but also on controller manufacturers—are not widely available.

To address this industry gap, ASHRAE published Standard 195 (Method of Test for Rating Air Terminal Controls), with the goal of determining controllable minimums for specific combinations of VAV boxes and controllers. Such ASHRAE-rated data could then be published in VAV box catalogs, allow for reliable performance comparisons across different brands of boxes and controllers, and provide engineers/contractors confidence to specify lower, more efficient, controllable minimum flow setpoints. Our project team is currently working with controller manufacturers to test various VAV box-controller combinations. This paper will share results and lessons learned from validating ASHRAE Standard 195 in a laboratory setting and will recommend improvements intended to promote wider adoption of the Standard.

Introduction

Variable air volume (VAV) systems (including terminal unit boxes and controllers) are used in a significant percentage of commercial buildings in North America and around the world. Large office buildings alone account for nearly 17% of total electricity use in the state of California (Barioant et al. 2023), while VAV-related energy use could be up to 17% of total electricity use in commercial buildings nationwide (NREL 2023).

The minimum air flow setpoint of VAV boxes has a huge impact on energy use (Hydeman et al. 2003) and comfort (see Arens et al. 2015[1] and Pang, Piette and Zhou 2017[2]).

---

[1] This field demonstration study modified a single software variable at each thermal zone (the zone minimum airflow) and reported 4 to 19 percent natural gas savings (overall HVAC savings of 5 to 19 percent) across 5 commercial buildings in California.

[2] A simulation study that evaluated the sensitivity of a range of control factors for variable air volume (VAV) systems found that zone minimum flows had by far the largest energy impact when varied between poor vs. good practice.

The lower the setpoint the better. However, if the setpoint is below the controllable minimum then the airflow reading will be inaccurate (potentially resulting in insufficient ventilation) and/or the controls will be unstable resulting in damper hunting, noise, and comfort issues, etc. To avoid these issues, most engineers set the minimum flow rates to the ones recommended by the VAV box manufacturers or even higher. These rates are on the order of 30-50% of the typical design flow. Title 24 does not allow minimums above 20% in most cases, but this requirement is routinely violated by conservative engineers and contractors. Past research on controllable minimums by PG&E (Dickerhoff and Stein 2007) and by ASHRAE (Liu et al. 2012) suggests that accuracy and stability can be maintained down to about 10%.

ASHRAE 90.1 had the same 20% limit as Title 24 but in the 2019 version of 90.1, the 20% has been eliminated and the minimum cannot exceed the ventilation requirement, which can be 10% or lower. One hope of the authors of this addendum is that engineers and contractors will adopt ASHRAE Guideline 36, which recognizes that the ventilation rate will sometimes be below the controllable minimum and therefore cycles the flow setpoint between zero and the controllable minimum to achieve the ventilation rate. This sequence is called TAV (time-averaged ventilation) and has yet to be widely adopted.

Certainly, some engineers will adopt Guideline 36, but we suspect the majority will continue to rely on the available data and set minimums in the 30-50% range. In 2022, Title 24 followed the 90.1 lead and removed the 20% upper limit but we suspect adoption will be spotty. The problem is that reliable, impartial data about the controllable minimum is not available. Again, the main source of information is the VAV box catalogs, which is ironic because the controllable minimum depends largely on the DDC controller, not the box itself, and the controller is supplied by the controls vendor, not the box manufacturer.

To address the lack of reliable, impartial data, ASHRAE published Standard 195-2013 “Method of Test for Rating Air Terminal Controls”. Standard 195 includes a detailed and rigorous test procedure for determining the controllable minimum of a given VAV box with a given controller. The goal is to provide reliable, apples-to-apples data for comparing boxes and controllers. VAV box manufacturers will include this ASHRAE data in their catalogs. Engineers will have confidence in the ASHRAE data and will lower the minimum flow setpoints, accordingly. Another goal is to encourage controller manufacturers to improve their products and reduce the controllable minimum. Right now, there is no real way to compare the performance of controllers from different manufacturers. However, once they are all tested with ASHRAE Standard 195 then the data will be available for all to see.

Unfortunately, Standard 195 has never been used. Controller and box manufacturers are probably not eager to have the true performance of their products exposed. No one wants to be the first to publish their data for fear that others will publish better data. Engineers who have asked for Standard 195 data in their specifications have not received the data because building owners are not willing to fund the testing required to produce the data.

This research project intends to “break the ice” by testing a handful of boxes and controllers from different manufacturers with Standard 195 and publishing impartial data, including manufacturers’ names. Once the ice is broken, manufacturers will have an incentive to publish data and improve their products, box manufacturers will be able to update their catalogs, engineers will be able to specify a Standard 195 controllable minimum and will be able to set lower box minimums, code compliance will improve, and energy will be saved.

Another goal of this research is to validate and improve Standard 195. The Standard was written by volunteers (Jeff Stein was co-chair of the committee) without the benefit of a laboratory to test and confirm that what they had written was reasonable, cost-effective, repeatable, etc. In conducting the testing detailed in this report, we found several flaws in the Standard and recommend changes (highlighted in this paper) to improve accuracy/repeatability and reduce the test burden in terms of time and cost. We intend to update the Standard with our recommended changes for its next periodic republishing and we expect future improvements as the Standard becomes more widely used.

Test Setup

The test setup used consisted of a full-scale duct, 8-inch inlet VAV box, and controller assembly with instruments installed throughout to measure airflow, temperature, pressure, and record other test parameters (see Table 1). VAV controllers and boxes were interchanged throughout the tests, with each controller and box combination constituting a "system under test" (SUT). Airflow was supplied and measured by reference airflow apparatus that included a "Duct Blaster" (for high flows) and a duct leak tester (for low flows) attached to the 8-inch duct. Photos of the test setup are shown in Figure 1.

Table 1. Measured parameters and instrument specifications

Measured parameter	Manufacturer	Model	Range	Accuracy
Airflow (duct leakage)	Kanomax	DALT 6900	2 - 377 CFM	2.5% of reading
Airflow (through SUT)	The Energy Conservatory	Minneapolis Duct Blaster with DG-1000 pressure and flow gauge	10 - 1,150 CFM	3% of reading
Ambient and Airstream Temperature	Burns Engineering	385-1, Platinum RTD	32 - 150°F	±0.1°F
Pressure drop across SUT	Rosemount	3051CD1A22A1A	25 in w.c.	0.025% of range
Flow probe signal from SUT	Air Monitor	VELTRON II	0.1 in w.c.	0.1% of range
	Rosemount	3051CD0A02A1AH2L4	3 in w.c.	0.05% of range
	MKS	AD06A11TRA	10 torr (5.37 in w.c.)	0.05% of reading
Ambient Pressure	Rosemount	3051CA1A22A1AB4	30 psia	0.04% of range
Ambient Relative Humidity	Michell	HS3-S	20 - 80%	±1.1 %RH

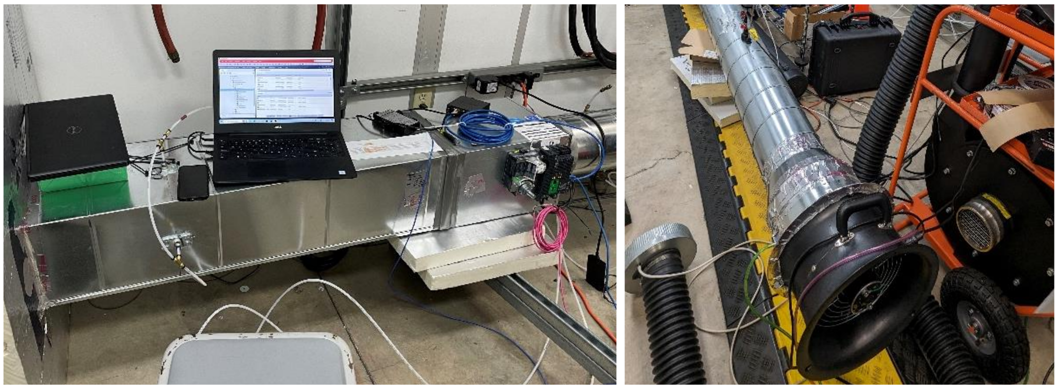

Figure 1. Test setup with installed controller (left) and reference airflow apparatus (right)

Equipment Tested

We installed varying combinations of VAV boxes and controllers from different manufacturers in the setup described above. The box manufacturers used were Price and Nailor while the controller manufacturers were Honeywell, JCI, Schneider, Distech, ALC, and Alerton. Table 2 shows all of the box and controller combinations tested.

Table 2. Controller and box combinations tested

Controller	Box
Honeywell	Nailor
Honeywell	Price
JCI	Nailor
JCI	Price
Schneider	Price
Distech	Price
ALC	Price
Alerton	Price

Discussion

Updates to Standard 195 Rating Methods

Tests were completed using three different methods, hereafter referred to as Method 1, Method 2, and Method 3. Summary descriptions of these methods and summary of the results we obtained with them are presented below.

Method 1. Method 1 is the current Standard 195-2023 method. Method 1 consists of three separate tests: an Accuracy Test, a Zero Drift Test, and a Stability Test. Within the Accuracy

Test, there are 2 subtests, Qmax (accuracy at maximum flow) and Qmin (accuracy at minimum flow). Within the Zero Drift Test, there are 5 subtests, each with a different ambient and airstream temperature requirement. Within the Stability Test, there is only one subtest. Note that Standard 195-2023 requires both a maximum flow Stability Test and minimum flow Stability Test, but we only conducted minimum flow Stability Tests for this study due to instrumentation limitations. The steps and pass/fail criteria of the Method 1 test are summarized below:

- Accuracy Test
    - Qmax
        - Allow the controller to modulate to control to a pre-determined maximum airflow Qmax,
        - Record 30 samples, with collected data including reference airflow, flow probe signal, and pressure across the SUT.
    - Qmin
        - Allow the controller to modulate to control to a pre-determined minimum airflow Qmin,
        - Record 30 samples, with collected data including reference airflow, flow probe signal, and pressure across the SUT.
        - This test should be repeated at multiple selected setpoints until the lowest passing airflow is found.
    - Pass/Fail Criteria
        - Maximum single-point error (reference flow vs. flow setpoint): 20%
        - Maximum average error (reference flow vs. flow setpoint): 10%

- Zero Drift Test
    - Determine Qstpt (typically the lowest passing setpoint found in the Accuracy Test)
    - Run 5 subtests. At each subtest, record 30 samples while the controller modulates to maintain Qstpt.
    - After Subtest 2, auto-zero the controller and record the ambient temperature during autozero (Taz) and the airstream temperature during autozero (Tsz)
    - Each subtest has an ambient and airstream temperature requirement, as detailed below:
        - Subtest 1: Ambient and airstream temperature at least 7°F above calibration temperature.
        - Subtest 2: Ambient and airstream temperature at least 7°F below calibration temperature.
        - Subtest 3: Ambient and airstream temperature within 2°F of Taz and Tsz.
        - Subtest 4: Ambient and airstream temperature at least 7°F above Taz and Tsz.
        - Subtest 5: Ambient and airstream temperature at least 7°F below Taz and Tsz.
    - Pass/Fail Criteria
        - Maximum single-point error (reference flow vs. flow setpoint): 30%
        - Maximum average error (reference flow vs. flow setpoint): 15%

- Stability Test
  - Determine Qstpt (typically the lowest passing setpoint found in the Accuracy Test) and ΔSP (typically 0.3” w.c.)
  - Allow the controller to modulate to control to Qstpt.
  - After 10 minutes, gradually decrease the static pressure to half of the starting static pressure.
  - Allow the controller to modulate to control to Qstpt at the new static pressure.
  - After 10 minutes, gradually increase the static pressure to a point two time the starting static pressure.
  - Allow the controller to modulate to control to Qstpt at the new static pressure for another 10 minutes.
  - Pass/Fail Criteria
    - Maximum single-point error (reference flow vs. flow setpoint): 30%
    - Maximum average error (reference flow vs. flow setpoint): 15%

Method 2. After running several Method 1 tests we invented Method 2 to lower testing burden and introduce the ability to isolate the controller error and probe error components from the SUT error. This allows for the minimum flow probe signals for both the unique box-controller combination (SUT) and the controller itself to be determined, as opposed to only the SUT as was the case under Method 1. The test burden was lowered under Method 2 mainly by combining the Accuracy Test and Zero Drift Test into one test and by requiring less samples to be taken at each Accuracy Test setpoint. The steps and pass/fail criteria of the Method 2 test are summarized below:

- Accuracy Test
  - Qmax
    - Allow the controller to modulate to control to a pre-determined maximum airflow Qmax,
    - Record 10 samples, with collected data including reference airflow, flow probe signal, and pressure across the SUT.
  - Qmin
    - Allow the controller to modulate to control to a pre-determined minimum airflow Qmin. Typically the starting Qmin corresponds to a flow probe signal of 0.005”.
    - Record 10 samples, with collected data including reference airflow, flow probe signal, and pressure across the SUT.
    - This test should be repeated at multiple selected setpoints until the lowest passing airflow is found.
  - Pass/Fail Criteria
    - Maximum single-point error (reference flow vs. flow setpoint): 20%
    - Maximum average error (reference flow vs. flow setpoint): 10%
  - For both Qmin and Qmax tests, determine Qstpt-SUT and Qstpt-adj based on the following equations:
    - $Q_{stpt-SUT} = Q_{min/max} = K_{Qmin/max-cal} * \sqrt{P_{vm-target}}$

        - Where K_(Qmin/max-cal) is the K-factor at which the controller was calibrated at the Qmin or Qmax point Subtest 3: Ambient and airstream temperature within 2°F of Taz and Tsz.
        - $Q_{stpt-adj} = K_{obs} * \sqrt{P_{vm-target}}$
        - Where K_{obs} is the K-factor that is determined by the reference ACFM and reference flow probe signal
    - Repeat the Qmax and Qmin steps 4 times plus two tests with the fan off, according to the following sequence:
        - Accuracy SubTest 1.1 (Tcal)
            - Run the test with the ambient temperature at the calibration temperature
        - Accuracy SubTest 1.2 (85°F)
            - Run the test with the ambient temperature at 85°F
        - Accuracy SubTest 2.1 (no fan)
            - Turn off the fan and lower the ambient temperature from 85°F to 65°F over 12 hours.
        - Accuracy SubTest 2.2 (no fan)
            - Turn off the fan and raise the ambient temperature from 65°F to 85°F over 12 hours.
            - Auto-zero the controller (if applicable)
        - Accuracy SubTest 3.1 (85°F)
            - Run the test with the ambient temperature at 85°F
        - Accuracy SubTest 3.2 (Tcal)
            - Run the test with the ambient temperature at the calibration temperature
    - Pass/Fail Criteria
        - Maximum single-point error, SUT (Qref vs. Qstpt-SUT): 30%
        - Maximum average error, SUT (Qref vs. Qstpt-SUT): 15%
        - Maximum single-point error, controller (Qref vs. Qstpt-adj): 20%
        - Maximum average error, controller (Qref vs. Qstpt-adj): 12%

- Stability Test
    - The Stability Test method is unchanged from Method 1, except for the requirement to determine Qstpt-SUT and Qsptp-adj and calculate their respective errors.
    - The Pass/Fail criteria is the same as the one used in the Accuracy Test.

Method 3. Method 3 was developed to further lower the testing burden from Method 2 and provide more relevant test results. The test burden was lowered under Method 3 mainly by eliminating the need for Accuracy Tests 2.1 – 3.2 from Method 2. Each individual Accuracy Test also has more predictable timing and is often faster to run as the fan is manually adjusted to meet each setpoint throughout the test with the damper fully open, as opposed to having the controller modulate to maintain a pre-determined setpoint. This method allows for data to be gathered across a broad range of setpoints, as opposed to individual discreetly selected setpoints. Also under this method, since there is no setpoint that the controller is trying to control to, the SUT and controller errors are calculated by comparing the reference flow and the adjusted reference flow to the controller flow instead of the setpoint. This allows for a true controller-only result to be obtained for the minimum flow probe signal. Running the Accuracy Test in this way also isolates the accuracy performance of the controller from its control stability as the modulating damper is no longer a factor to be considered that may impact the results. The steps and pass/fail criteria of the Method 3 test are summarized below:

- Accuracy Test
  - Qmax
    - With the damper fixed 100% open, adjust the fan speed to attain a pre-determined Qmax.
    - Record 5 samples, with collected data including reference airflow, controller airflow, flow probe signal, and pressure across the SUT.
  - Qmin
    - With the damper fixed 100% open, adjust the fan speed to attain a reference flow probe signal of 0.1”
    - Record 5 samples, with collected data including reference airflow, controller airflow, flow probe signal, and pressure across the SUT.
    - Repeat the above two steps with the fan speed adjusted to attain each of the following flow probe signals:
      - 0.05”, 0.025”, 0.013”, 0.008”, 0.005”, 0.004”, 0.003”, 0.002”
  - For both Qmin and Qmax tests, determine Q-adj based on the following equation:
    - $Q_{adj} = K_{Qmin/max-cal} * \sqrt{P_{vm-target}}$
  - Repeat the Qmax and Qmin steps 2-3 times according to the following sequence:
    - Accuracy Test 1 (Tcal)
      - Run the test with the ambient temperature at the calibration temperature
    - Accuracy Test 2 (85°F)
      - Run the test with the ambient temperature at 85°F
    - Auto-zero the controller (if applicable)
    - Accuracy Test 3 (85°F)
      - Run the test with the ambient temperature at 85°F
  - Pass/Fail Criteria
    - Maximum single-point error, SUT (Qref vs. Qctrlr): 20%
    - Maximum average error, SUT (Qref vs. Qctrlr): 10%
    - Maximum single-point error, controller (Qadj vs. Qctrlr): 20%
    - Maximum average error, controller (Qadj vs. Qctrlr): 10%

- Stability Test
  - The Stability Test method is unchanged from Method 2
    - Maximum single-point error, SUT (Qref vs. Qstpt-SUT): 30%
    - Maximum average error, SUT (Qref vs. Qstpt-SUT): 10%
    - Maximum single-point error, controller (Qref vs. Qstpt-adj): 30%
    - Maximum average error, controller (Qref vs. Qstpt-adj): 10%

Summary of Controllable Minimums

A useful way to describe the controllable minimum for an SUT or for a controller is in terms of the lowest flow probe signal (Pvm) that results in the SUT or controller passing all the subtests in a particular Method of Test (MOT). With this lowest passing Pvm a designer can easily calculate the lowest controllable velocity (FPM) and volume flow rate (CFM) from a box manufacturer's published K-factor. Table 1 shows the lowest passing Pvm for the six controllers we tested using the initial Std. 195 method (Method 1), our proposed new method (Method 3) and an interim working version (Method 2). For each of the lowest Pvm for SUTs, Table 1 also shows the corresponding minimum velocity for a typical K-factor (890) and the minimum % flow rate based on a typical VAV box max flow rate (630 CFM).

Table 1. Summary of controllable minimums by controller

Controller	Method (Note 1)	SUT Pvm (in.wg.)	Controller Pvm (in.wg.)	Min. velocity, % of max. flow
Honeywell	1	0.021	-	381 fpm, 21%
JCI (Note 2)	1	0.005	-	186 fpm, 10%
Schneider (Note 3)	1	0.005	-	186 fpm, 10%
Distech	1	0.005	-	186 fpm, 10%
Honeywell	2	0.05	0.05	591 fpm, 32%
Honeywell	3	0.05	0.05	591 fpm, 32%
ALC	3	0.002	0.002	118 fpm, 6%
Alerton	3	0.002	0.002	118 fpm, 6%

Note 1: Method 1 is the current Standard 195 method. Method 3 is our new proposed new MOT. Method 2 was a working version that helped us develop Method 3.

Note 2: JCI passed the Method 1 accuracy test several times at 0.002" but also failed the accuracy test at 0.004". We suspect this is due to the flow deadband issue identified in this project. This controller was not tested below 0.005" for zero drift or stability.

Note 3: Schneider passed Method 1 accuracy tests down to 0.002" but was not tested below 0.005" for zero drift or stability.

Issues Identified with Current Standard and Method of Test

Reducing Test Burden. Method 3 reduces the test burden from Methods 1 and 2 mainly by combining the Accuracy Test and Zero Drift Test into one test and by requiring less samples to be taken at each Accuracy Test setpoint. The test burden is also lowered in the Method 3 Accuracy Test by requiring the fan to be manually adjusted to a prescribed number of setpoints with the damper locked fully open. The Method 1 Accuracy Test has a higher test burden since the controller modulates to maintain a pre-determined setpoint for the duration of the test and must be continually re-tested at different setpoints until the test passes. For example, for the same controller (Honeywell), Method 1 accuracy/zero drift tests amounted to about 40 mins of required test time, while Method 3 tests amounted to only 22.5 mins of test time—a 44% reduction.

Reducing Error Sources. Another impact of Method 3's requirement to lock the damper fully open during the Accuracy Test is that it prevents the ability to game the test by manually adjusting the flow within the controller's flow deadband. The flow deadband is essentially a range of airflows above and below the setpoint that is pre-programmed into the controller to prevent excessive damper movement. If the flow measured by the controller changes from setpoint while staying within this deadband (e.g. +/- 10 CFM from setpoint), the controller will not react to change the damper position. During the Method 1 Accuracy Test, we found that a tester could manually adjust the flow within the deadband such that reference flow could change from a failing value to a passing value without causing the controller to move the damper (and without deviating from any of the written requirements of the standard). Therefore, many (if not all) of the Method 1 Accuracy Tests were passed or failed at least in part by a tester's finesse in manually adjusting the reference flow to a passing value, as opposed to the controller's natural ability to maintain an accurate flow reading. This issue of the test method misrepresenting the performance of the controller in the Accuracy Test is eliminated by Method 3's requirement to lock the damper open, as the flow deadband is no longer a factor subject to gaming by a tester.

The Method 3 Accuracy Test procedure also allows for more useful data collection. Since the test requires the fan to be manually adjusted from a high setpoint to a low setpoint, data can be collected on a broader range of setpoints than is the case for Method 1, which only collects data on discreetly selected setpoints. Also under this method, since there is no setpoint that the controller is trying to control to, the SUT and controller errors are calculated by comparing the reference flow and the adjusted reference flow to the controller flow instead of the setpoint. This allows for a true controller-only result to be obtained for the minimum flow probe signal. Running the Accuracy Test in this way also isolates the accuracy performance of the controller from its control stability as the modulating damper is no longer a factor to be considered that may impact the results.

Additional Research Question #1: Are Standard 195 Tests Repeatable?

Figure 2 shows the controller errors for Method 3 Accuracy Tests 1 and 2 (ran at the calibration temperature and 85°F, respectively) for all box-controller combinations with repeated tests and retests thereof. Comparing all tests ran on the same controllers (indicated by same-colored lines), we can see that controller errors seldom vary by more than 5% across all tests for the same flow probe signal. This indicates that the Method 3 Accuracy Tests are repeatable. Of particular importance are the Alerton tests, for which both a Price and Nailor box were used. Since the controller error calculation is intended to isolate the impact of the controller from the box, we would expect that the controller error results be similar when compared across tests that used the same controller on different boxes. Figure 2 also shows that the Alerton test ran on the Nailor box differs by less than 5% from any given Alerton test ran on a Price box at the same temperature and flow probe signal. This suggests that not only is the Accuracy Test method repeatable under Method 3, but the controller-only error calculation introduced by Method 3 is also repeatable.

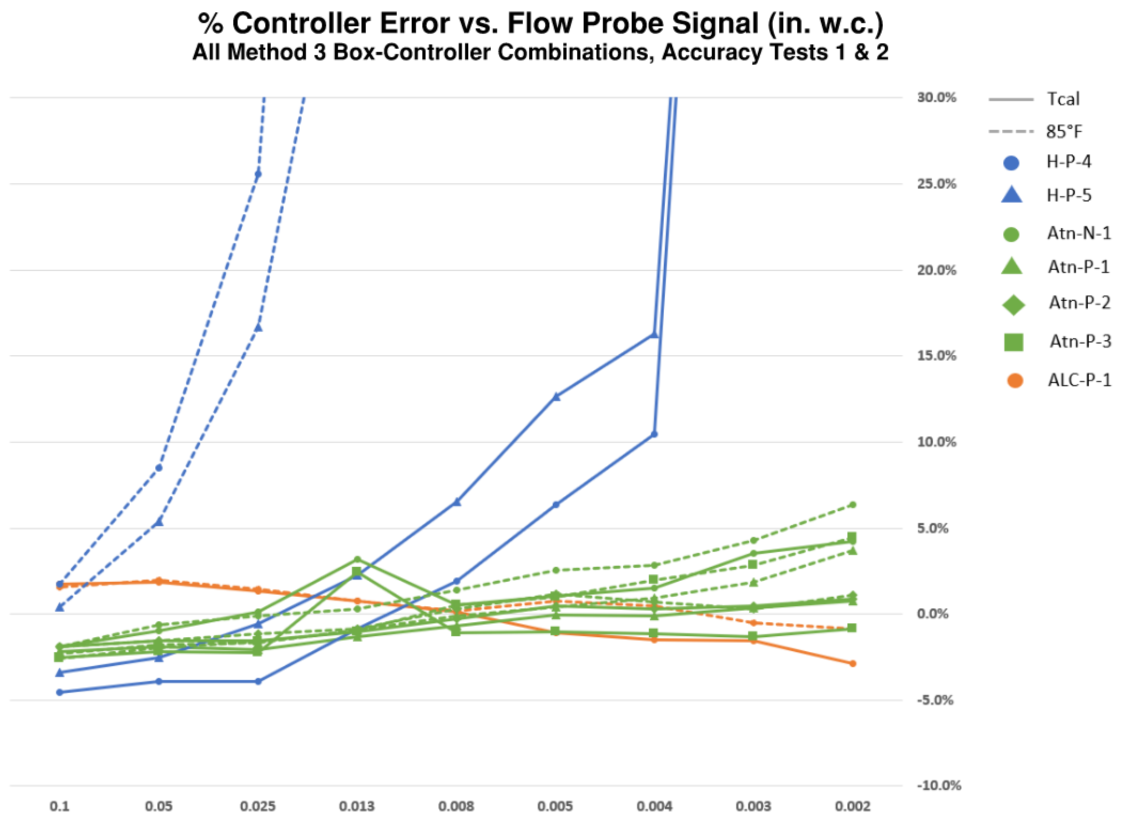

Figure 2. Controller error for all Method 3 accuracy tests

The controller errors for the Method 3 Alerton Stability Tests are similarly plotted in Figure 3. This graph shows that the errors for the Alerton tests varied more widely for the Stability Tests than they did for the Accuracy Tests, despite all Stability Tests being run at the same flow probe target (0.002"). This difference in errors across the Stability Tests is due to the tester's ability to manually adjust the reference flow within the controller's flow deadband while keeping the controller from changing the damper position. The wide range of errors we see in the Stability Tests is therefore a reflection of the wide range of flows the tester could have chosen to allow the test to pass, as opposed to the controller's ability to repeat the same control responses under repeated changes in static pressure of the same magnitude. The test method can therefore be considered repeatable in the sense that passing results can be repeated for the same flow setpoint. However, since the test depends on the tester repeatedly selecting passing flows within the controller's flow deadband, the repeatability of the test may not accurately reflect the controller's natural performance stability. This limitation of the test method should be addressed in forthcoming updates to the Standard.

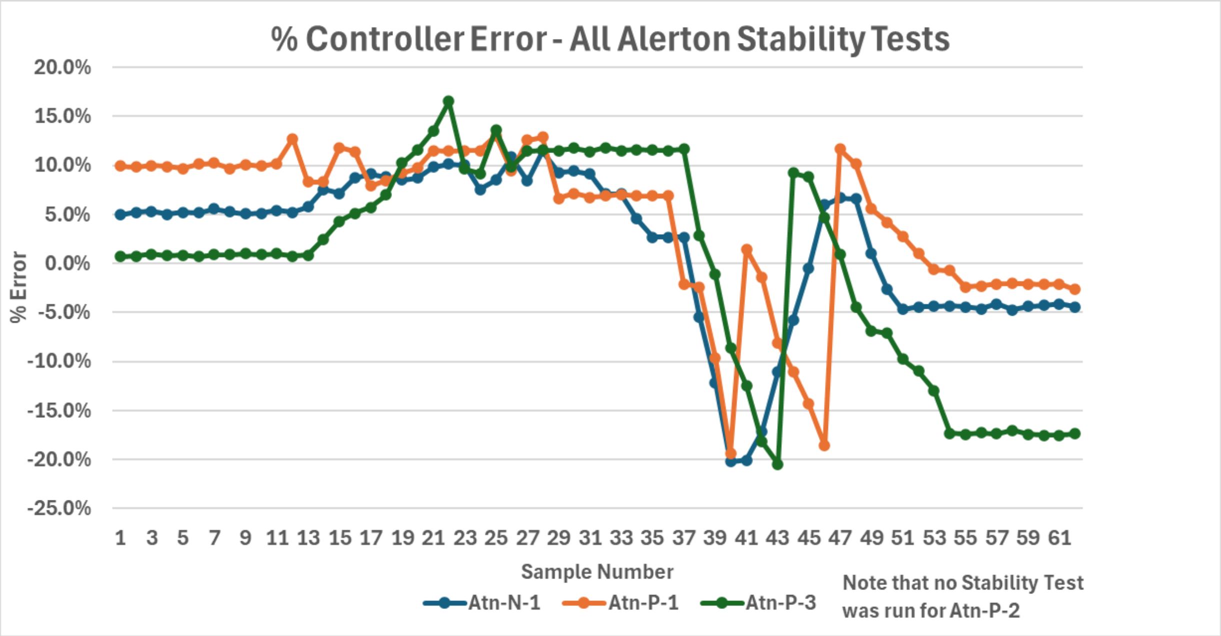

Figure 3. Controller error for Alerton stability tests with Method 3

Additional Research Question #2: Are Standard 195 Tests Results Reasonable?

The method we developed to separate the controller error and flow probe error from the total SUT error yielded the expected result of SUT error being equal to the sum of controller and probe error. Figure 4 shows the SUT error to be equal to the sum of controller and probe errors for a typical accuracy test.

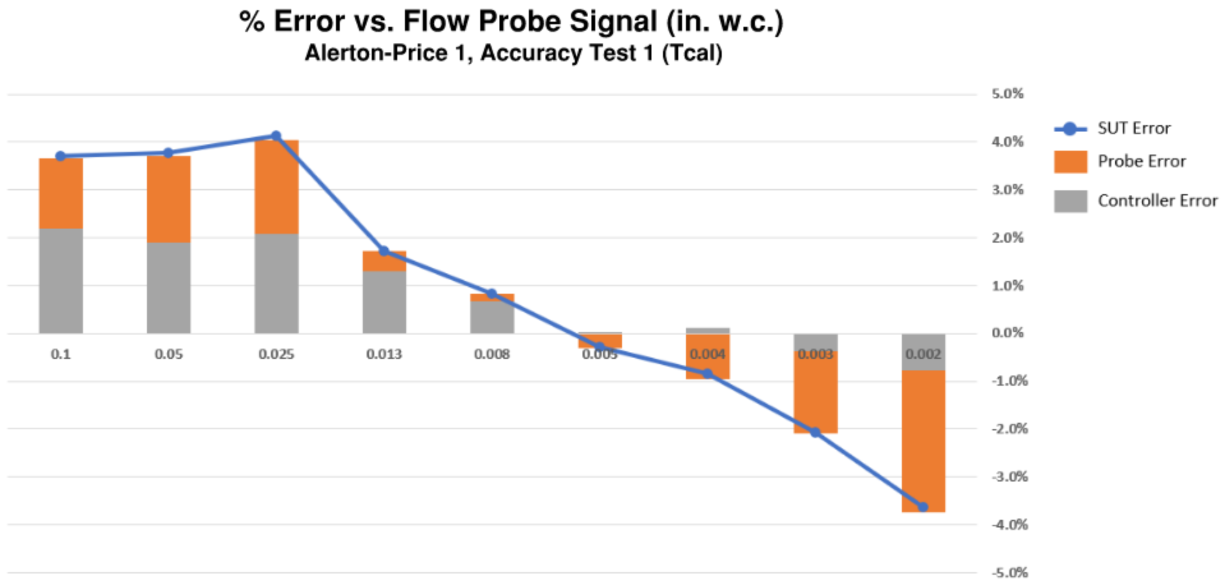

Figure 4. Alerton-Price accuracy test results illustrating disaggregated error components

Additional Research Question #3: Are Standard 195 Accuracy and Tolerance Requirements Sufficiently Strict?

Uncertainty analysis was performed using standard techniques (1) to characterize the overall uncertainty associated with each laboratory test result and (2) to assess the adequacy of instrument accuracy and test tolerance requirements for each rating test in the latest proposed Standard 195 revision (i.e., Method 3). Uncertainty in the reported test results from each type of rating in Standard 195 arises from two primary sources: systematic (bias) uncertainty and random (precision) uncertainty sources. These uncertainty sources themselves include (but are not limited to) the following:

- Uncertainty in the reference airflow rate (Qref) measurement
- Uncertainty in the reference flow probe signal (Pvm,ref) measurement
- Uncertainty in controller velocity pressure measurement
- Uncertainty in airflow properties due barometric pressure, air temperature, relative humidity, and duct area

Out of 60 accuracy rating results assessed across a variety of terminal unit and controller combinations, none was found to be indeterminate (i.e., “conditional pass” or “conditional fail” or having a true SUT or controller-only error less than or greater than a test tolerance condition). Similarly, out of 12 stability rating results, none were found to be indeterminate. Based on these findings, neither the proposed test tolerance conditions nor the proposed instrumentation accuracy requirements appear to be unreasonably strict for the accuracy rating or the stability rating.

Conclusions

As part of this research, we developed a way to distinguish between flow probe error and controller error. We found that the flow probes of the two boxes we tested (Price and Nailor) are indeed stable and accurate even at very low flows, but so are most controllers and that the magnitude of the flow probe error is similar to the magnitude of the controller error for most controllers. Therefore, we developed a new methodology for rating the controller separately from the SUT. We also identified additional improvements to Standard 195 that we addressed with our newly modified method of test including:

- Reducing the overall testing burden by reducing the number of samples recorded during steady state and streamlining the separate accuracy and zero-drift tests into a single test.
- Eliminating a way to game the Std. 195 rating (see Table 1, Note 2) by fixing the damper full open during the accuracy test. In the Std. 195 accuracy test the controller modulates the damper to achieve the target airflow setpoint, with the reference airflow sensor determining how closely the controller holds the setpoint. But if the controller has a wide deadband within which it will not move the damper, then the tester can tweak the fan speed to get the reference airflow closer to setpoint without triggering the controller to move the damper.

- Introducing a way to gather more useful data on the performance of the controllers by running the accuracy tests across a broad range of flow probe signals, instead of individually selected setpoints.

We found that the results of the accuracy tests we ran under the new method of test were repeatable, logical, and fairly represented the accuracy performance of each controller we tested. We also found that our method for separating the controller error and probe error out of the SUT error was validated, as the SUT error was equal to the sum of the controller error and probe error for nearly all flow points tested. However, we also found that the method we used to run stability tests was subject to the same potential to be gamed as was discussed for the accuracy tests above. As such, the stability test results presented in this paper are a reflection of a test method that relies on the tester to manually select the right flow within the flow deadband, as opposed to a reflection of the controller's stability performance alone. Future testing and Standard improvements should seek to improve this aspect of the stability rating test.

This research should help improve Standard 195 and facilitate widespread use of Standard 195 (the authors plan to propose requiring 195 testing in ASHRAE 90.1 and Title 24). This will help give designers and contractors the confidence they need to specify and implement low minimums and thus capture the huge energy savings potential identified by Arens, Pang, and others.

References

Arens, E., H. Zhang, T. Hoyt, S. Kaam, J. Goins, F. Bauman, Y. Zhai, et al. 2015. "RP-1515 -- Thermal and Air Quality Acceptability in Buildings That Reduce Energy by Reducing Minimum Airflow from Overhead Diffusers." ASHRAE. 2015. www.techstreet.com/standards/rp-1515-thermal-and-air-quality-acceptability-in-buildings-that-reduce-energy-by-reducing-minimum-airflow-from-overhead-diffusers?product_id=1892759.

ASHRAE Guideline 36-2021 -- High-Performance Sequences of Operation for HVAC Systems. 2021. Peachtree Corners, GA: ASHRAE. www.techstreet.com/ashrae/standards/guideline-36-2021-high-performance-sequences-of-operation-for-hvac-systems?product_id=2229690.

ASHRAE 90.1-2019 (I-P Edition) -- Energy Standard for Buildings except Low-Rise Residential Buildings. 2019. Atlanta, GA: ASHRAE. www.techstreet.com/ashrae/standards/ashrae-90-1-2019-i-p?product_id=2088527.

ASHRAE Standard 195-2013 Method of Test for Rating Air Terminal Unit Controls. 2013. Atlanta, GA: ANSI/ASHRAE. webstore.ansi.org/standards/ashrae/ansiashraestandard1952013.

Barioant, S., D. Mort, T. Alereza, and D. Dohrmann. 2023. "2022 California Commercial End-Use Survey (CEUS): Final Report." CEC (California Energy Commission). www.energy.ca.gov/publications/2023/2022-california-commercial-end-use-survey-ceus-final-report.

Dickerhoff, D.J., and J. Stein. 2007. “Stability and Accuracy of VAV Terminal Units at Low Flow | Building Technology and Urban Systems.” Lawrence Berkeley National Laboratory. buildings.lbl.gov/publications/stability-and-accuracy-vav-terminal

Hydeman, M., S. Taylor, J. Stein, and E. Kolderup. 2003. “Advanced Variable Air Volume System Design Guide.” CEC (California Energy Commission). efiling.energy.ca.gov/GetDocument.aspx?tn=46224.CEUS.

Liu, R., J. Wen, A. Regnier, X. Zhou, and C. Klaassen. 2012. “RP-1353 -- Stability and Accuracy of VAV Box Control at Low Flows.” ASHRAE. 2012. www.techstreet.com/standards/rp-1353-stability-and-accuracy-of-vav-box-control-at-low-flows?product_id=1834011.

NREL (National Renewable Energy Laboratory). 2023. *ComStock data viewer* (online). EUSS ComStock National 2018 Release 2 2023. comstock.nrel.gov/.

Pang, X., Piette, M. A., and Zhou, N. 2017. *Characterizing variations in variable air volume system controls.* Energy and Buildings, 166-175

State of California. 2019. “Title 24 - Building Energy Efficiency Standards.” CEC (California Energy Commission). 2019. www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards.