.

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A Simplified Field Diagnostics Protocol for Envelope and Duct Leakage in Manufactured Homes

slipstream

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COMMON ACRONYMS

ACH: air changes per hour

ACH50: air changes per hour at 50 Pascals pressure

AH: air handler

cfm: cubic feet per minute

CFM50: cubic feet per minute at 50 Pascals pressure

DOE: United States Department of Energy

EPA: United States Environment Protection Agency

FSEC: University of Central Florida – Florida Solar Energy Center

HUD: United States Department of Housing and Urban Development

IECC: International Energy Conservation Code

IQR: interquartile range

MH: manufactured home

mph: miles per hour

NEEM: Northwest Energy-Efficiency Manufactured Housing Program™

NEW: Northwest Energy Works

POS: positive pressure system (for ventilation)

TEC: The Energy Conservatory

ZERH: Zero Energy Ready Home

SUMMARY

Manufactured housing is subject to federal U.S. Department of Housing and Urban Development (HUD) code, which does not require envelope or standardized duct leakage testing. Errors in the home-siting process—along with occasional damage during transport—can lead to envelope and duct-leakage issues that go undetected unless they are severe enough to trigger a customer complaint due to moisture issues, poor comfort, or high energy bills. These problems could be mitigated if home installers or inspectors had a simple way to test for significant envelope or duct leakage at the completion of the siting process.

This report describes the evaluation of a simplified protocol for assessing envelope and duct leakage intended for home installers and inspectors. The protocol is designed to be quick and easy to implement using low-cost, easy-to-carry equipment, and would require minimal training–especially if implemented as a smartphone app in the future. The protocol uses existing home exhaust fans (bath, kitchen range hood, whole-house exhaust, etc.) to depressurize the home and assess envelope leakage based on the level of depressurization. Duct leakage is assessed similarly by measuring the level of home depressurization during air handler operation. If exhaust flow levels associated with the assessment are also measured, the protocol can produce quantitative estimates of leakage and measurements of ventilation fan air flow rates. The protocol is meant to help installers and inspectors easily flag serious envelope and duct leakage issues in the field that could otherwise lead to discomfort and performance issues that result in callbacks or even health hazards.

The protocol was evaluated against standard blower-door and duct-pressurization testing with an automated set-up at an unoccupied lab home in Florida that allowed for repeated measurement under a variety of exhaust-flow, duct-leakage, and wind conditions. It was also field evaluated in 35 additional homes in the Midwest, Southeast, and Northwest, selected based on project partner locations.

The automated measurement in Florida showed that with sufficient exhaust flow and reasonably calm conditions, the protocol did a good job of estimating envelope and duct leakage on average, however low exhaust fan flows combined with windy conditions resulted in estimates with more uncertainty and that were downwardly biased.

The field evaluation showed a strong difference between Northwest homes—where there is a well-established program to provide technical assistance on building practices and incentivize energy efficient new manufactured housing—and those in the other two regions. Homes built in the Northwest region generally had tighter envelopes and duct systems. They also had higher available exhaust flow for the protocol due to widespread use of whole-house exhaust fans to meet HUD ventilation requirements, which is different from typical industry practice in other regions of the country that use a passive duct to the furnace return. These two factors combined to produce protocol estimates of envelope leakage that were in good alignment with blower-door testing.

In contrast, the homes in the other two regions (Midwest and Southeast) had leakier envelopes and low exhaust fan flow rates. The protocol consequently produced envelope leakage estimates for these homes with less reliable results when compared to blower-door values.

Duct leakage estimates are inherently more variable than envelope leakage estimates using the protocol, because assessing duct leakage requires an additional house-to-outside pressure measurement. This additional measurement affords more opportunity for wind variation to affect the calculated result. The ability to assess duct leakage is also contingent on having a reasonably tight envelope so that depressurization effects can be measured.

The data from the study was used to develop a stochastic model of variability in results under different wind and exhaust-flow conditions. The results suggest that the protocol appears to be most suitable for efficient new homes that are expected to have tight envelopes (<4 ACH50) and that have 100 to 200 cfm of total existing exhaust-fan capacity. To be useful in conventionally constructed manufactured homes with leakier envelopes and less existing exhaust-fan capacity, supplementary exhaust flow during evaluation would be needed in most cases.

The protocol is highly amenable to being coded into an easy-to-use smartphone app, preferably connected to a digital manometer to automate the measurement and calculation process. A gauge-connected app could also dynamically assess wind effects on pressure measurements and adjust the measurement period as needed to reduce assessment uncertainty.

Further development of the protocol should include better characterization of how wind affects assessment variability in a wider variety of efficient new homes, and development and evaluation of a field app for implementing the protocol. For implementing the protocol in typical existing manufactured housing, a means of providing supplementary exhaust during assessment would need to be developed.

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THE NEED FOR MH FIELD EVALUATION

While some way of ventilating indoor spaces is vital for the comfort and health of occupants, unintended infiltration of outdoor air into homes is a long-standing area of concern. In hot-humid climates, infiltration can lead to high indoor humidity and serious indoor moisture issues. In heating climates, it can lead to excessively dry homes in the winter, poor indoor comfort, and mold where moist indoor air exfiltrates into cold building cavities. In all climates with non-trivial space heating and cooling needs, excess infiltration increases energy costs.

Similarly, leakage from forced-air duct systems creates energy-cost, comfort, and health concerns. Supply duct leakage imposes a direct penalty on system efficiency when air that has just been heated or cooled is dumped outdoors. Duct leaks can also lead to rooms that are underconditioned and thus uncomfortable. And duct leakage indirectly increases the air exchange rate of the home, leading to the same problems as leaks in the building envelope.

For site-built homes, these concerns have led to the increasing adoption of state energy codes with envelope and duct leakage testing requirements. The International Energy Conservation Code (IECC) is a model code that is widely referenced for adoption at the state level in the U.S. Mandatory leakage testing was first introduced into the 2015 version of the IECC. As of June 2022, 31 states had residential energy codes based on IECC 2015 or later—though some have amendments that eliminate the testing requirements (DOE 2023). However, these are not applicable for manufactured homes.

Manufactured housing is subject to federal building standards, which do <u>not</u> currently require envelope tightness testing and provide a duct leakage testing protocol that is not practical as a function check in the production process.[1] In addition, neither the federal ENERGY STAR® program nor the new Zero Energy Ready Home (ZERH) pilot require routine envelope or duct leakage testing for new manufactured homes—though the latter does call for factory duct-leakage testing of 10 percent of a factory's ZERH-certified homes (EPA/DOE 2023a, 2023b). These standards and program guidelines could change in the future.

The cost of testing relative to the price of the home is likely a factor here. The $250 to $500 cost for standard leakage testing likely looms larger in the highly price-conscious manufactured housing market than it does in the site-built market.[2]

Routine factory testing for duct leakage is performed by some plants in the Pacific Northwest, where Northwest Energy-Efficient Manufactured Housing Program™ (NEEM) has long

[1] Manufactured Home Construction and Safety Standards – 24 CFR §3280.715(4)

[2] In 2021, the average sales price for new single-wide manufactured home in the U.S. was about $73,000 and that for a double-wide home was $132,000. This is 67 to 82 percent below the overall median sales price of $397,000 for new single-family homes in the same year (Census 2023a, 2023b). Note that the former excludes siting and lot costs while the latter includes the value of the improved lot.

encouraged quality and energy-efficient construction of manufactured homes. Even so, half of all new manufactured homes are multi-section models that are only joined together and sealed when the home is at its final destination. Errors in the siting process—along with occasional road damage during transport—can lead to envelope and duct-leakage issues that go undetected unless they are severe enough to trigger a customer complaint due to poor comfort or high energy bills.

These kinds of problems could be mitigated if home installers or inspectors had a simple way to evaluate significant envelope or duct leakage at the completion of the siting process. To be widely adopted, the ideal assessment protocol would be quick and easy to implement using low-cost, easy-to-carry equipment, and require minimal training. The trade-off for meeting these ease-of-implementation objectives would likely mean reduced accuracy relative to current blower-door and duct-pressurization protocols that are designed to yield accurate and repeatable results. But if widespread field assessment using current techniques is a non-starter for the manufactured-housing industry, then it is arguably preferable to have a more widely used but less-accurate evaluation protocol that catches egregious problems than it is to have no assessment at all.

There are options for how the protocol could be adopted by the manufactured home industry:

1. Manufacturers and retailers could use the protocol to support field QA/QC and provide feedback to home installers and setup crews.
2. Programs requiring field leakage evaluation could allow the protocol in place of more robust and more labor and equipment intensive testing.
3. Codes and standards could require performing the protocol on a percentage of homes.
4. New construction manufactured-home programs could require the protocol on a percentage of homes.

The remainder of this document describes the development and assessment of a simplified protocol for field evaluation of envelope and duct leakage in manufactured homes designed to meet these objectives.

DEVELOPING A SIMPLIFIED PROTOCOL

The protocol described here is based on a technique developed by Brady Peeks (Northwest Energy Works (NEW)) and Bobby Parks (Healthy Homes of Louisiana) when evaluating homes for quality-control or complaint-resolution purposes. The protocol is a quick way to assess whether it is worth the time and effort to conduct standard blower-door and duct pressurization testing on homes. They found that if a home with all doors and windows closed became noticeably depressurized relative to the outdoors when all exhaust fans were turned on, it was unlikely that blower-door testing would reveal major envelope leakage. In effect, the exhaust fans in the home act like a miniature built-in blower door. When the fans are turned on, a tight home will show a noticeable decrease in house pressure because there are few avenues for outdoor air to enter the home to replace the air pulled out by the fans. On the other hand, a leaky home will show little or no pressure response because it is easy for the air removed by the fans to be replaced by outdoor air through the many penetrations in the envelope.

Similarly, duct leakage can be quickly assessed by observing the depressurization effect when the main air handler is operated. If the ducts are substantially tight in a home with ≤ 4ACH50, there should be little change in the house-to-outside pressure when the air handler is operated, and the air handler simply circulates air throughout the home. However, if the duct system leaks to the outdoors, then it will act like an exhaust fan and the house will become depressurized relative to the outdoors.

Note that this effect relies on a unique aspect of manufactured home duct systems: they typically only have ducts for delivering supply-air to rooms and no return ductwork in unconditioned space. Any duct-system leaks will thus be on the supply side of the system and will tend to depressurize the home. This contrasts with the much trickier situation found with site-built homes where both supply and return ducts are present, and where leaks on one side of the system may be offset by leaks on the other side, resulting in a home with a leaky duct system that nonetheless shows little pressure response when the air handler is operated.

EQUIPMENT

The full protocol requires two pieces of equipment: a single-channel digital manometer (for example The Energy Conservatory (TEC)’s DG-8) and a calibrated exhaust flow box (for example the TEC exhaust fan flow meter), as shown in Figure 1. The required equipment costs about $800, takes up minimal space, and is easy to carry into the home. As described in more detail below, it is also possible to implement a more qualitative version of the protocol using only the manometer.

Figure 1. Example single-channel digital manometer (TEC DG-8) and calibrated exhaust flow box (TEC exhaust fan flow meter). Images courtesy of TEC.

PROTOCOL

The complete protocol involves three key steps that can generally be accomplished in 15 minutes or less:

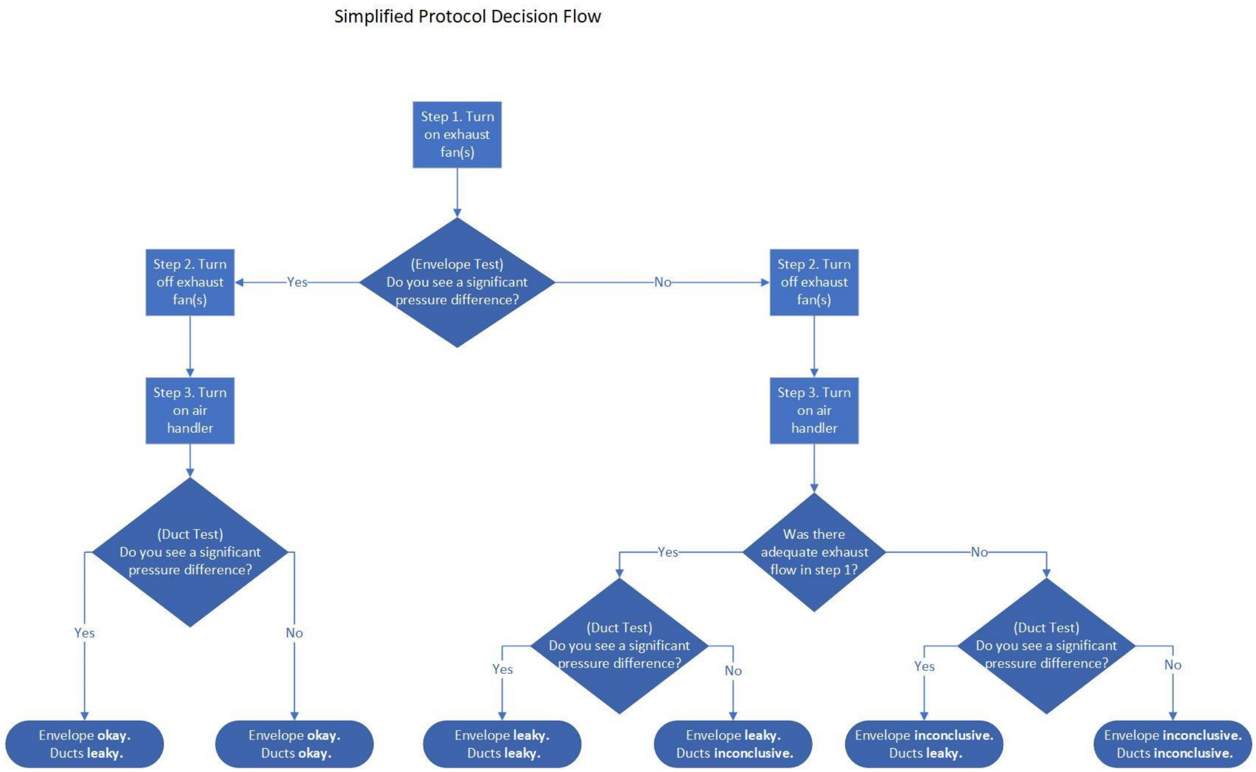
1. With the home closed and all fans in the house turned off, measure the baseline house pressure with reference to the outside (house-to-outside pressure) with the digital manometer.

2. Turn on factory-installed exhaust fans (for example, bath fans) that can be readily measured with the exhaust-fan flow meter. Measure the flow for each fan. Measure the house-to-outside pressure difference with the fans operating. The difference between this pressure and the baseline reading is the net house depressurization induced by the total flow of the operating fans.

3. Turn off the exhaust fans and turn on the main air handler. Remeasure the house-to-outside pressure difference. The difference between this pressure and the baseline reading is the net depressurization induced by supply duct leaks to the outside.

A variant of the protocol is to skip the exhaust-fan flow measurements in Step 2 and qualitatively assess leakage solely based on the observed house depressurization levels in Steps 2 and 3. With reasonable exhaust flow, a tight home should show a noticeable depressurization response in Step 2 and a home with significant duct leakage should induce a noticeable house depressurization when the air handler is operated in Step 3. The flow chart in Figure 2 can be used to decide whether significant envelope or duct leakage issues may be present. Note that questions about what level of depressurization constitutes "significant" and how much exhaust flow is needed to be "adequate" will be addressed later in this report.

Figure 2. Flow chart for qualitative implementation of the Simplified Protocol.



CALCULATIONS

When exhaust flow in Step 2 is measured, it is possible to translate the house-depressurization and exhaust-flow measurements into estimates of the magnitude of envelope and duct leakage rates using the general relationship between airflow and differential pressure:

$$Q = CP^n \tag{1}$$

where,

> Q is the rate of airflow through cracks in the envelope or duct system in cubic feet per minute (cfm);
>
> C is a house-specific constant that relates to the total leakage area;
>
> P is the net (baseline-adjusted) house-to-outside pressure difference, in pascals (Pa); and,
>
> n is a house-specific flow exponent that relates to the nature of the leakage pathways, and that usually falls between 0.60 and 0.70 for blower-tested measurement of envelope leakage.

Step 2 of the protocol provides a measurement of how much depressurization (*P*) is induced in the home from the measured total exhaust-fan flow (*Q*). Using Equation 1 above with an assumed exponent of 0.65, envelope leakage at the standard 50 Pascals of depressurization can be estimated as follows:

$$Q_{env,50} = Q_{exh}(50/P_{exh,adj})^{0.65} \tag{2}$$

where,

> $Q_{env,50}$ is the protocol-estimated envelope leakage (cfm) at 50 Pascals, often abbreviated simply as CFM50, and frequently expressed alternatively in terms of air-changes per hour at 50 Pascals (ACH50) using the known conditioned volume of the home;
>
> Q_{exh} is the measured total exhaust-fan flow (cfm) from the protocol;
>
> $P_{exh,adj}$ is the baseline-adjusted house-to-outside depressurization during exhaust-fan operation; and,
>
> 0.65 is the assumed flow exponent for the house.

Estimating duct leakage from the measurements is somewhat more complicated because, while duct leaks act as passive envelope leaks during the exhaust assessment in Step 2, they effectively become exhaust-flow pathways when the air handler is operated in Step 3. This means that the total leakage area of the home changes between the two measurements, which complicates the analysis.[3] A simple two-zone model involving the home interior and a duct system—along with some key assumptions—operating duct leakage can be calculated from the protocol measurements as follows:[4]

$$Q_{ducts,operating} = \frac{Q_{exh}}{\left(\frac{P_{exh,adj}}{P_{AH,adj}}\right)^{0.65} + \left(\frac{P_{exh,adj}}{25}\right)^{0.60}} \qquad (3)$$

where,

> $Q_{ducts,\ operating}$ is the estimated duct leakage to outside (cfm) when the main air handler (AH) is operated;
>
> $P_{AH,adj}$ is the baseline-adjusted house-to-outside depressurization (Pa) when the AH is operated;
>
> 0.60 is the assumed flow exponent for duct leaks,
>
> 25 is the assumed average duct-system operating pressure (Pa) at the duct leaks; and,
>
> Q_{exh}, $P_{exh,adj}$ and the assumed envelope flow exponent of 0.65 are per Equation 2 above.

Note that duct leakage estimates from the protocol reflect actual operating leakage to outside. This is qualitatively different than duct leakage measured with standard duct pressurization testing, which involves temporarily sealing the duct system grilles and return intake and pressurizing it uniformly to a standard level of 25 Pascals with a calibrated test fan.[5] This makes it difficult to compare the protocol to standard duct-pressurization testing. The DeltaQ method (Walker et al. 2001) uses a series of blower-door tests with and without air-handler operation to measure operating leakage, like the Simplified Protocol described here. Though the DeltaQ test is much less commonly used for field testing, a comparison of duct-pressurization and DeltaQ estimates for homes in a recent Minnesota manufactured-housing characterization

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[3] This analysis does not consider the reverse effect where exhaust fans may act as passive air leaks when the air-handler is operated and duct leaks are present. Exhaust fans typically (but not always) have dampers intended to mitigate the reverse flow of air.

[4] The Project Team is indebted to Collin Olson of The Energy Conservatory for working out this relationship, which is described in more detail in Appendix E.

[5] The team initially considered adjusting the protocol results to leakage at 25 Pascals (CFM25) by also measuring the average duct-system pressure during air handler operation. But this proved difficult, because duct system operating pressure is highly variable across the duct system and establishing an average system in the field is difficult. Moreover, the correct pressure for accurate adjustment to CFM25 would be the flow-averaged pressure at leakage sites, which is generally unknown.

study suggests that operating duct leakage to outdoors is typically about 30 percent less than measurements obtained from duct pressurization. (Pigg et al. 2016).

ADDITIONAL CONSIDERATIONS

If measuring exhaust flows with the protocol, the user can verify if ventilation systems are meeting federal HUD code as well. Federal HUD code for manufactured homes requires installed ventilation capacity at least 50 cfm for whole house ventilation and kitchen range hood mechanical ventilation capable of exhausting 100 cfm outside the home.[6]

An idea floated during refinement of the Simplified Protocol was to operate the home's range hood in the background throughout all three steps of the protocol. Used in this way, the range hood does not contribute to the total measured exhaust flow in Step 2 of the protocol: instead, it acts to depressurize the house throughout the assessment. The reasons for this are twofold. First, while it might seem logical to include the range hood in the exhaust devices operated during Step 2 of the protocol, in practice it is difficult to fit an exhaust-flow meter on most range hoods without considerable effort for creating and mounting a mask to ensure that all range-hood flow passes through the meter. Also, the measured flow through the face of the range hood might not accurately represent the actual exhausted flow due to leakage in the body of the range hood and venting system. Second, because the induced pressures from exhaust flow and air-handler operation are small, it was thought that placing the home under additional depressurization throughout the assessment might help reduce variability in the face of changing wind conditions. The protocol for the research study therefore included assessing with and without background range-hood operation.

Finally, while not part of the core Simplified Protocol goal of assessing envelope and duct leakage, proof-of-concept evaluation suggested that the exhaust-flow meter needed for the protocol could also be diagnostically useful for measuring supply airflow at individual registers. The ability to quickly measure airflow at individual registers to ensure that they reasonably match design values could add another useful quality-control element to the protocol. Doing so, however, requires using the meter to measure supply—instead of exhaust—airflow, effectively running air through the meter in the opposite direction that it was designed for. The research therefore also looked at the accuracy of using the meter in this manner.

EVALUATING THE PROTOCOL

After initial proof-of-concept evaluation in two homes, the project team performed two main research activities to assess the protocol: (a) a semi-controlled evaluation of the protocol with repeated measurements under varied exhaust-flow, duct leakage and wind conditions at the FSEC Manufactured Housing Laboratory (MH Lab) home in Florida using a special automated setup; and, (b) field evaluation of the protocol in a variety of homes in the Pacific Northwest,

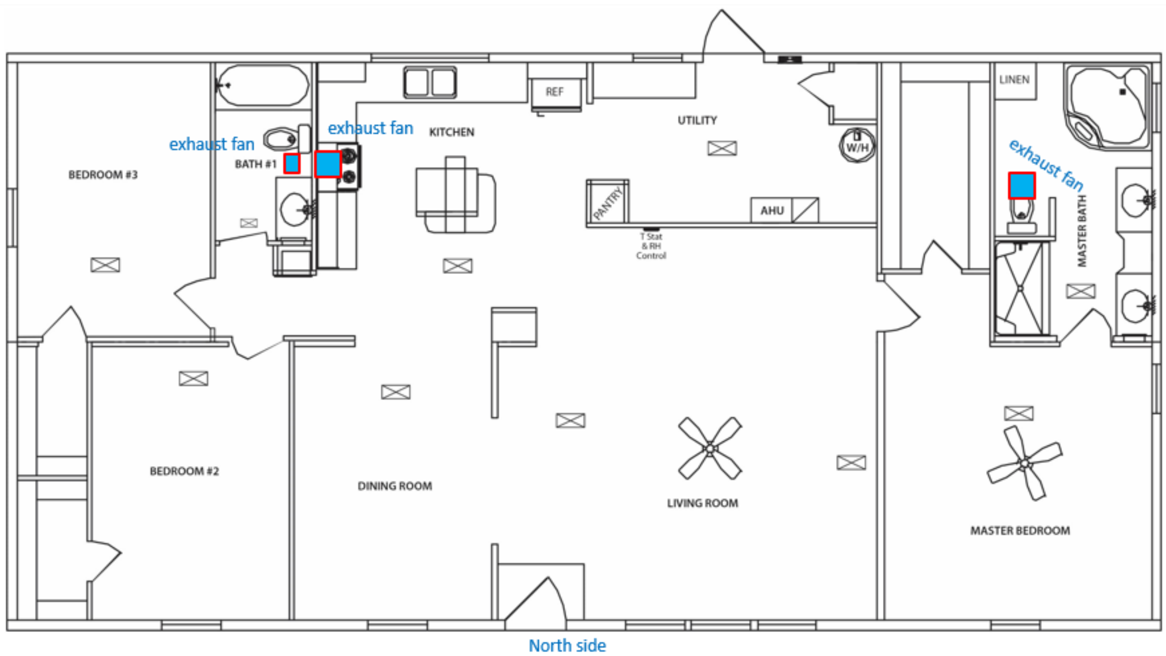
[6] Manufactured Home Construction and Safety Standards – 24 CFR §3280.103(b) and (c)

the Southeast and the Midwest. Both activities compared Simplified Protocol estimates of envelope and duct leakage to more traditional methods. The field evaluation also looked at the accuracy of supply register airflow measurements made using the exhaust-fan flow meter.

AUTOMATED EVALUATION AT THE FSEC MH LAB HOME

The project team used the University of Central Florida – Florida Solar Energy Center (FSEC) MH Lab home to repeatedly run the protocol under various conditions using an automated setup. The MH Lab home is a double-wide manufactured home built in 2001 to meet the ENERGY STAR® home standards at the time.[7] It is a 1,620 square foot (14,400 ft^3) manufactured home with three bedrooms and two bathrooms (Figure 3). For research purposes, the home is configured with multiple duct systems to allow the selection of either an attic or floor-mounted central supply duct system. As is typically the case for manufactured homes, there are no return ducts: the air handler unit is in a utility room and pulls air directly from the home's interior.

Figure 3. Floor plan for the FSEC MH Lab.



[7] See http://www.fsec.ucf.edu/en/about/facilities/mhl.htm

Configuration and Data Collection

To evaluate the Simplified Protocol repeatedly under semi-controlled conditions, FSEC project team members used an existing automation scheduler to repeatedly turn fans on and off while tracking house-to-outside (and other) pressures under three sequential operating conditions:

Condition 1: Baseline (no fans operating)
Condition 2: Exhaust-only operation
Condition 3: Air-Handler-only operation

Each operating condition lasted for 100 seconds, with the data for each complete cycle through the three conditions (300 seconds in total) comprising an "assessment" for the purposes of analysis.[8] Throughout the evaluation, an Energy Conservatory 8-channel APT manometer and TecLog software were used to record the house-to-outside pressure difference once per second, with the APT auto re-zeroing itself once a minute. Four different outdoor pressure references were measured simultaneously on the north, south, east, and west locations approximately one foot above the ground within about one foot of the exterior wall.

Exhaust-fan only operation in Condition 2 above was implemented in two ways. In early implementation, the kitchen range hood was configured to turn on and off under automation control and serve as the exhaust device for the protocol. An Energy Conservatory Exhaust Fan Flow Meter was affixed to a mask on the inlet face of the range hood, and the pressure difference across the flow meter was logged by the APT and used to track the actual flow through the range hood.

Runs were implemented in this manner in May and November 2022 with the range hood at both its low- and high-speed settings. But the airflow limitations of the range hood led to changing the approach in January 2023 to using a calibrated duct pressurization fan to simulate exhaust flows from 25 to 300 cfm. After this change, the range hood was repurposed to operate continuously every other hour to evaluate whether operating the range hood in the background improved assessment reliability. Evaluating under this configuration occurred between January and March 2023.

To ensure a known and controllable airflow under Condition 3 above, air handler operation under this condition was simulated throughout by using a duct-pressurization fan mounted at the return face of the actual air handler. The fan was set to produce approximately 750 cfm of flow, which is appropriate for the duct system in the lab and is typical of air handlers in manufactured homes. Flow through the fan was monitored throughout by tracking the fan

[8] To avoid issues with the lag effects of fans ramping up and down, only data for a 30-second period within each 100-second operation window was used, selected to avoid times when the APT auto-zeroed. This period was further reduced during data reduction to a single 5, 10, 20 or 30-second subperiods to examine the effect of the averaging period on the results. Most of the results here make use of the 5-second sub-period averages, which reflect the most likely situation for protocol field implementation.

pressure on one channel of the APT.

Automated evaluation of the Protocol was implemented in this manner for both the ceiling and floor duct systems at the MH Lab home. Each duct system was assessed in its normal condition and with artificially added leakage (holes added to the ducts) for various exhaust flow levels and background range-hood conditions.[9] Altogether 7,375 assessments of the protocol were conducted (Table 1).

As a point of comparison for the protocol estimates, a series of blower door, duct pressurization and DeltaQ tests was run for each duct configuration. Results of these tests (Appendix B) show the home has envelope leakage of 6.3 to 7.5 ACH50 under depressurization and duct leakage to outside of 2.8 to 10.3 cfm/100ft^2 floor area, depending on the duct configuration involved during testing.

Table 1. Number of automated Simplified-Protocol assessments, by duct system and configuration, background range-hood operation and exhaust flow level.

Duct System	Duct Leakage Level	Background Range-Hood Operation*	Exhaust Flow Level (cfm)					Total
			25	50-75**	100	200	300	
Ceiling	Normal	Off	137	865	531	184	142	1,859
		On	140	177	248	191	143	899
		Total	**277**	**1,042**	**779**	**375**	**285**	**2,758**
	Added	Off	0	330	144	141	287	902
		On	0	0	144	139	284	567
		Total	**0**	**330**	**288**	**280**	**571**	**1,469**
Floor	Normal	Off	290	138	282	142	140	992
		On	287	132	285	144	143	991
		Total	**577**	**270**	**567**	**286**	**283**	**1,983**
	Added	Off	0	144	299	143	0	586
		On	0	144	297	138	0	579
		Total	**0**	**288**	**596**	**281**	**0**	**1,165**
Total		Off	427	1,477	1,256	610	569	4,339
		On	427	453	974	612	570	3,036
		Total Assessments	**854**	**1,930**	**2,230**	**1,222**	**1,139**	**7,375**

*79% of range-hood-on assessments were conducted at the high-speed setting (~100 cfm); the remainder at lower flow rates
**Assessments occurred at measured flows of 50, 55, 60 and 75 cfm under various runs

[9] For the ceiling system, the added duct leak was introduced in the supply plenum area. For the floor system, the added leak was introduced in one of three trunk ducts, several feet from the down-flow collar.

Understanding the effect of wind on evaluation reliability was an important objective. Windspeed was measured on a one-minute basis from an anemometer located at a height of about 18 feet above ground 75 feet away from the home. Although the evaluation was somewhat at the mercy of the weather, some assessment periods were selected specifically based on forecasted windy conditions. Nonetheless, most assessments occurred when winds were less than 10 mph at the site (Table 2).

Table 2. Distribution of average windspeed during FSEC MH lab automated evaluation.

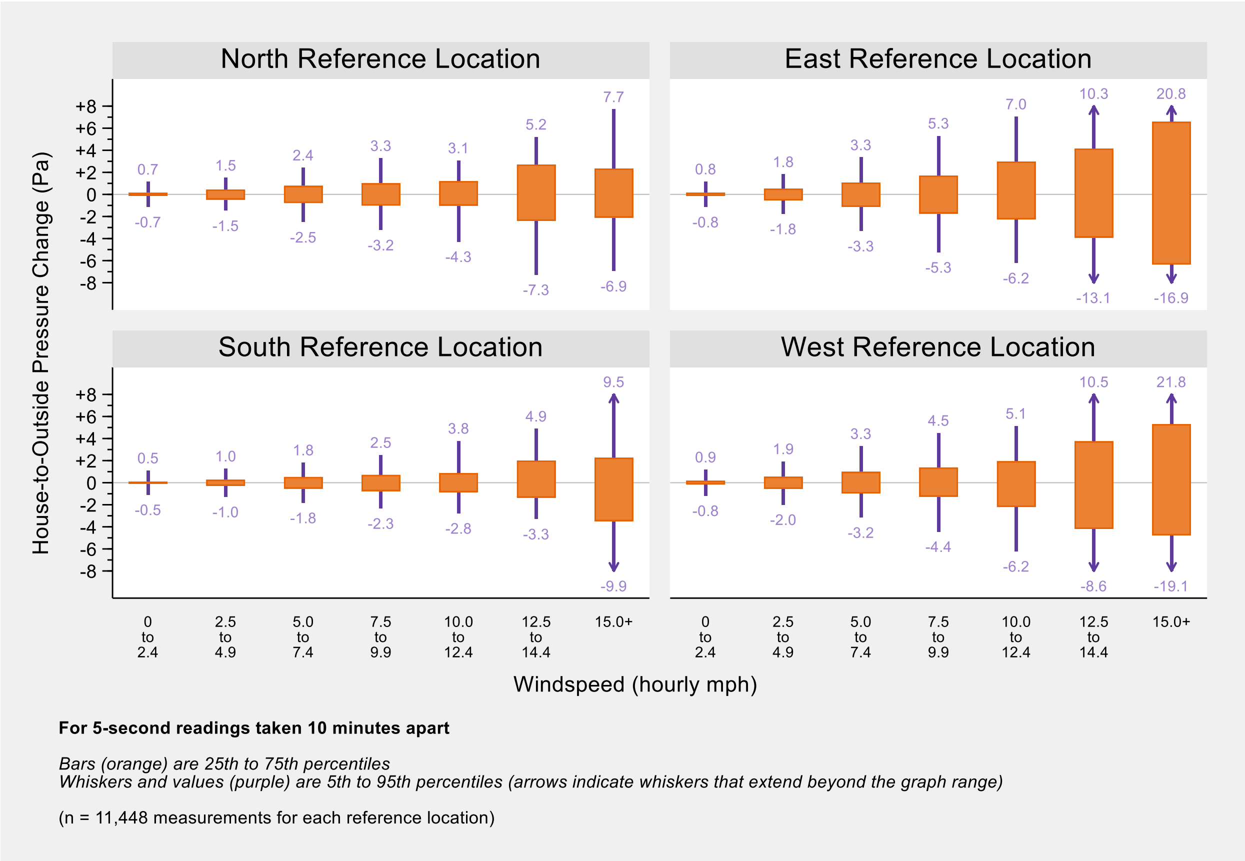
Windspeed (mph)	Number of Assessments	Percent of Assessments
0 to 2.4	2,728	37.0%
2.5 to 4.9	1,973	26.8%
5.0 to 7.4	1,647	22.3%
7.5 to 9.9	768	10.4%
10.0 to 12.4	145	2.0%
12.5 to 14.9	61	0.8%
15.0 to 17.4	28	0.4%
17.5 to 19.9	15	0.2%
20.0 to 22.4	5	0.1%
22.5 to 24.9	5	0.1%
25.0+	0	0.0%
Total	7,375	100.0%

Results for Automated Evaluation of the Protocol

It is helpful to begin the discussion of the FSEC MH lab home evaluation results with an examination of the variability in *baseline* house-to-outside pressures, since the efficacy of the protocol depends on its ability to distinguish small house depressurization effects during exhaust-fan or air-handler operation from moment-to-moment pressure fluctuations due to wind effects. As expected, the background variability in house-to-outside pressure increases with windspeed (Figure 4). Even with light winds, pressure fluctuations of 1 to 2 Pascals are not uncommon, and at windspeeds of 10+ mph, wind noise in pressure measurements can easily exceed several Pascals. Baseline pressures also vary by the location of the outdoor pressure reference: the North and South reference locations—which correspond to the long walls of the home—exhibit somewhat less variability in baseline pressure than the East and West pressure locations. The remainder of the results presented here focus on the results using the North pressure reference location.

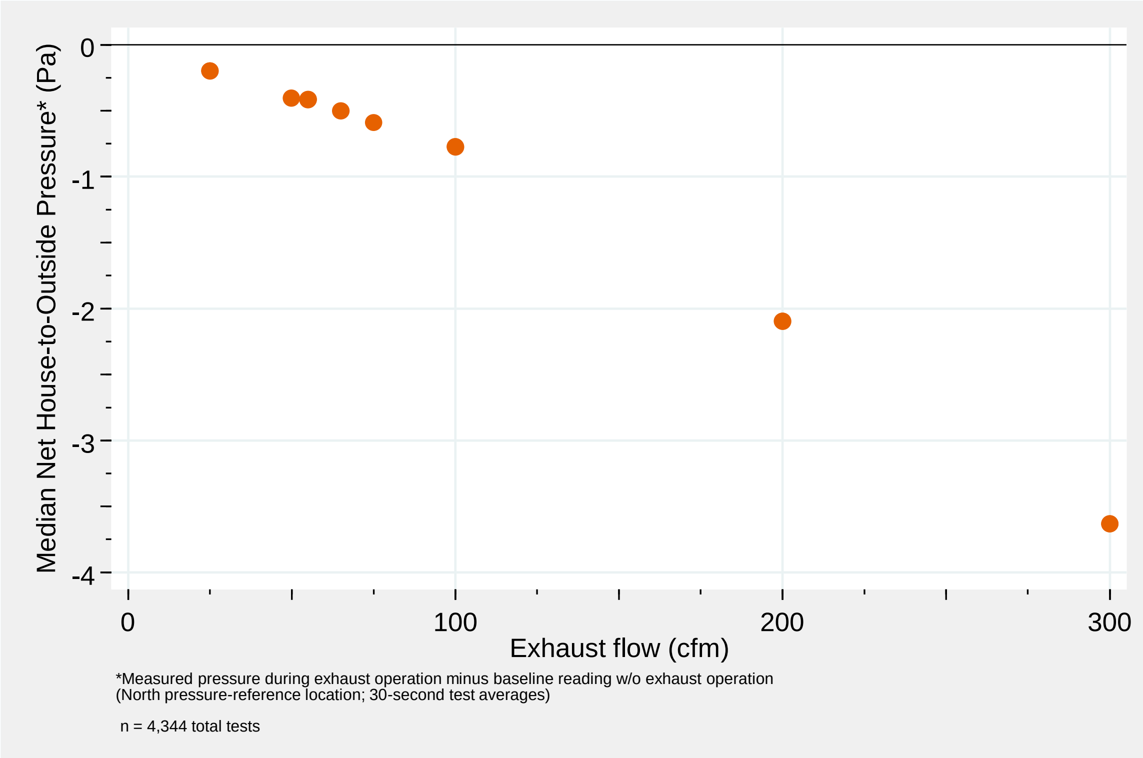
In theory, averaging pressure readings over longer time periods should help reduce the background variability in pressure measurements. As described in more detail in Appendix E, taking 30-second averages of house-to-outside pressure reduces the standard deviation of the measurements by about 40 percent compared to 5-second averages. Most results presented in this report are based on 5-second averages, but in wider application of the protocol, longer averaging periods could be useful in windy conditions.

Figure 4. Distribution of baseline house-to-outside pressure changes at the FSEC MH Lab home for 5-second average readings taken 10 minutes apart, by pressure-tap location and windspeed.



The results in Figure 4 suggest that for the Simplified Protocol measurements to be meaningful for the MH Lab home, the exhaust fans used in the protocol should induce at least several pascals of house-to-outside depressurization so that wind noise does not overwhelm the fan-induced depressurization signal that is at the heart of the protocol. The median depressurization observed at various exhaust-flow levels for the MH Lab home suggests that exhaust flow of several hundred cfm is needed to achieve this (Figure 5). The magnitude of the depressurization effect is directly related to the tightness of the envelope: tighter homes will show a larger pressure response than leaky homes at a given exhaust flow level. At about 7 ACH50, the MH Lab home is towards the leaky end of the ACH50 distribution for new manufactured homes.

Figure 5. Median observed net house depressurization from exhaust flow at different flow levels, FSEC MH Lab home.

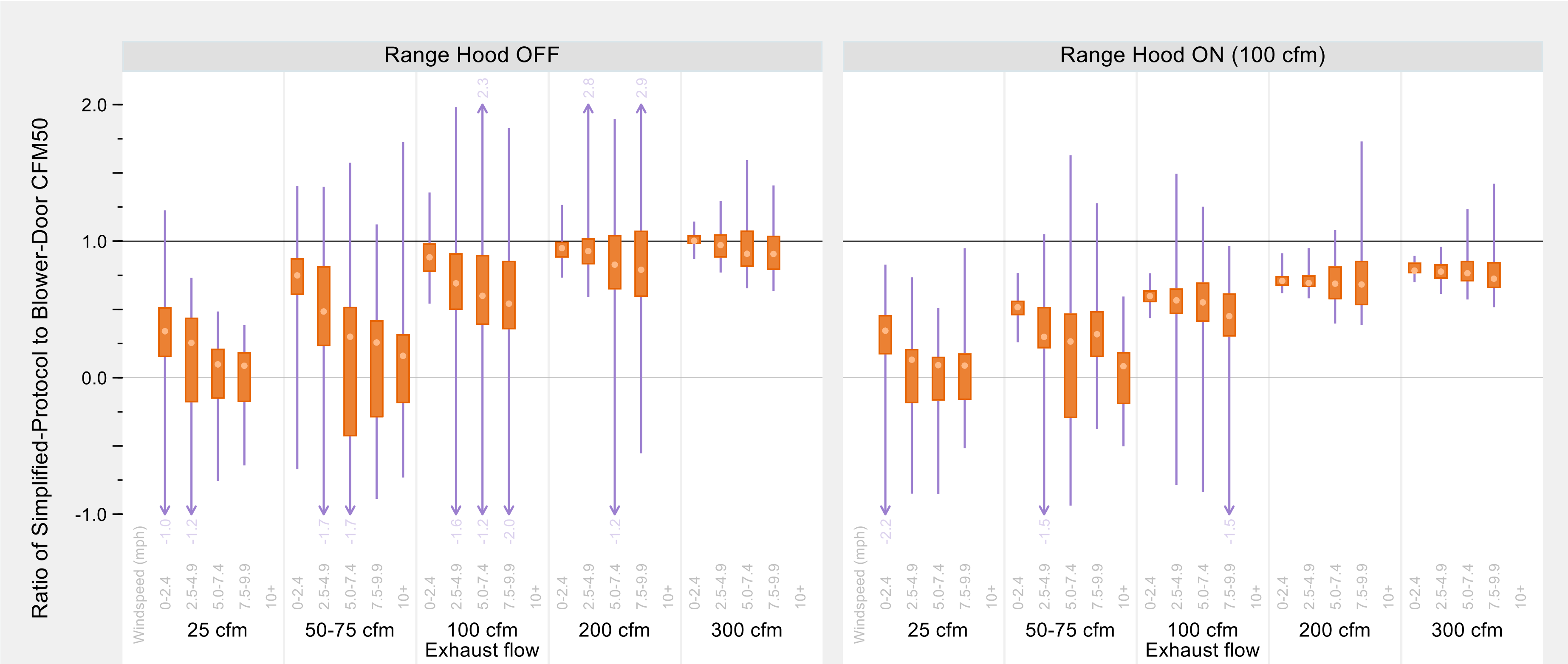


Calculated Envelope Leakage

Figure 6 shows the distribution of protocol-calculated envelope leakage as a function of exhaust flow, wind speed and whether the range hood was operated in the background during evaluation. The results are presented as a ratio of the protocol-calculated leakage to a blower-door leakage measurement, comparing assessments performed under different duct configurations and envelope leakage levels. A ratio of 1.0 indicates that the Simplified Protocol result matches the blower-door value exactly. Note that negative values for envelope leakage are non-sensical, representing scenarios where the baseline-adjusted house-to-outside pressure during exhaust operation indicated pressurization of the home instead of the expected depressurization effect: these are due to spurious wind effects on the measurements.[10]

[10] All results here are based on the North pressure-reference location.

Figure 6. Distribution of the ratio of protocol-calculated envelope leakage to blower-door measurements for the FSEC MH Lab home, for different combinations of exhaust flow level and windspeed during the evaluation, with and without background range-hood operation



Bars (orange) are 25th to 75th percentiles
Dots (light orange) are medians
Whiskers (purple) are 5th to 95th percentiles (arrows with values indicate whiskers that extend beyond the graph range)

Results based on North pressure-reference location. Results omitted if n<30.

The results indicate that exhaust flow of 300 cfm reasonably replicates the blower-door measurements. However, as exhaust flow decreases, the protocol-calculated envelope leakage estimates become both more variable and increasingly biased downward. At 25 cfm of exhaust flow, the protocol tends to produce estimates of envelope leakage that hover around zero under windy conditions.

In addition, comparing the right and left sides of Figure 6 suggests that, while operating the range hood in the background during assessments somewhat reduces assessment variability, it also tends to bias the estimates downward somewhat compared to assessments under similar conditions without range-hood operation.

Regression analysis (see Appendix C) helps separate and quantify these effects.[11] The results confirm a severe downward bias to the Simplified Protocol results for low exhaust flow, which is exacerbated by the presence of wind (Table 3). For example, at 25 cfm of exhaust flow without background range-hood operation, the regression model indicates that the Simplified Protocol produces a median leakage estimate that is 54 percent below blower-door measurements: this bias further declines to 98 percent below in 10-mph winds at that flow level. In contrast, at 300 cfm of exhaust flow, the protocol matches the blower door values (zero bias) when winds are calm but is biased downward in 10-mph winds. However, at this higher exhaust flow level, the bias is only -9 percent. The model further quantifies the bias from background range-hood operation at about -20 percent.

Table 3. Regression estimates of the median bias in Simplified-Protocol estimates of envelope leakage relative to blower-door measured ACH50, by range-hood status and exhaust-flow level at selected windspeeds.

Range Hood Status	**Exhaust Flow Level** (cfm)	**Windspeed (mph)**		
		0	5	10
Off	25	-54%	-76%	-98%
	50-75	-26%	-51%	-77%
	100	-15%	-30%	-45%
	200	-7%	-12%	-18%
	300	0%	-5%	-9%
On (100 cfm)	25	-73%	-95%	-117%
	50-75	-45%	-70%	-96%
	100	-34%	-49%	-64%
	200	-26%	-31%	-37%
	300	-19%	-24%	-28%

[11] See Appendix B for details.

A regression model of the interquartile range (IQR i.e. the magnitude of the orange bars in Figure 6) suggests that windspeed and background operation of the range hood are the two most important factors affecting assessment variability (Table 4). For example, at 300 cfm of exhaust flow with little or no wind and no range-hood operation, the model suggests an IQR of 0.7 ACH50, meaning that half of all assessments under these conditions will fall within that span. Reducing the exhaust flow to 25 cfm, however, increases the IQR to a 2.5 ACH50 span, a more than threefold increase. Similarly, reading across the rows of Table 4 shows how wind increases variability in the calculated envelope leakage. And finally, comparing the lower half of the table to the upper half confirms that operating the range hood in the background (without including it in the measured exhaust flow) tends to reduce assessment variability.

Table 4. Regression estimates of the magnitude of the interquartile range (25th to 75th percentile) of protocol-estimated envelope leakage (ACH50), by range-hood status and exhaust-flow level at selected windspeeds (normalized to envelope leakage of 6.9 ACH50). (See Appendix C.)

Range Hood Status	**Exhaust Flow Level** (cfm)	**Windspeed (mph)** 0	5	10
Off	25	2.5	3.2	4.0
	50-75	2.4	3.2	3.9
	100	1.6	2.4	3.2
	200	1.2	2.0	2.7
	300	0.7	1.5	2.3
On (100 cfm)	25	1.9	2.7	3.5
	50-75	1.8	2.6	3.4
	100	1.0	1.8	2.6
	200	0.6	1.4	2.2
	300	0.2	0.9	1.7

While there are several possible explanations for these results, the effect of wind noise on the pressure measurements appears to be the dominant factor. As described in more detail later, stochastic simulation of the effects of wind noise on the protocol-calculated envelope leakage values reasonably reproduces both the downward bias associated with low exhaust flow and the increasing variability of assessment results under low exhaust flow and increasing wind. The main mechanism appears to be that as the level of exhaust flow decreases, the baseline-adjusted measured depressurization increasingly hovers close to zero. Because this measurement appears in the *denominator* of the envelope-leakage calculation, the calculated envelope leakage becomes destabilized in the direction of increasingly extreme positive and (non-sensical) negative estimates of envelope leakage, which both increases assessment variability and creates a downward bias in the average result.

In wider field implementation of the protocol, non-sensical negative estimates of envelope leakage would be rejected, and the assessment would need to be rerun. As Table 5 shows, the proportion of such assessments increases as exhaust flow decreases and wind increases.

Table 5. Percent of Simplified-Protocol assessments producing a non-sensical negative estimate of envelope leakage due to spurious wind effects, by range-hood operation, assessed exhaust-flow level and windspeed during assessment. (See Appendix C.)

Background range-hood operation	Exhaust flow level (cfm)	Windspeed during assessment (mph)				
		0-2.4	2.5-4.9	5.0-7.4	7.5-9.9	10+
Off	25	24%	27%	45%	47%	--
	50-75	7%	23%	35%	33%	41%
	100	1%	14%	18%	20%	--
	200	1%	2%	8%	7%	--
	300	0%	0%	1%	0%	--
On (100 cfm)	25	22%	37%	42%	36%	--
	50-75	3%	16%	34%	16%	46%
	100	1%	8%	12%	19%	--
	200	0%	0%	3%	4%	--
	300	0%	0%	0%	--	--

Results omitted if n<30 for a given assessment configuration and windspeed category.

While wind effects appear to explain much of the variation in results from the automated evaluation, a different mechanism is likely behind the observed downward bias from range hood operation. Here, the protocol incorrectly assumes that the home is at zero airflow in the baseline measurement, when in fact the background range-hood operation puts it partway up the flow-pressure curve. Adding the exhaust flow on top of the already-operating range hood produces a larger pressure response than would occur if flow was zero in the baseline measurement: this in turn produces an underestimate of leakage when extrapolated upward to 50 Pascals of depressurization.

Calculated Duct Leakage

Interpreting the duct leakage results from the MH Lab evaluation is more complicated both because multiple duct systems and configurations were assessed and because the basis for comparison with alternative measurements is less clear. Duct pressurization leakage values are highly repeatable but produce an artificial measure of duct leakage. DeltaQ measures leakage under actual operating conditions like the Simplified Protocol, but—also like the Protocol—is subject to uncertainty due to wind noise.

Nonetheless, the median leakage for the protocol for assessments with 200+ cfm of exhaust flow, no range-hood operation and calm conditions seems to compare reasonably favorably with these standard leakage-testing protocols (Table 6), especially considering that the DeltaQ values have statistical uncertainty that is on the order of 1 to 6 cfm per 100 ft^2 of conditioned floor area (see Appendix B). The last row of Table 6 is therefore used here as the best estimate of the actual operating duct leakage for each duct configuration.

Table 6. Measured duct leakage to outside (cfm per 100 ft^2 of conditioned floor area), by assessment method, duct system and leakage level.

	Ceiling Ducts		Floor Ducts	
	Normal Leakage	Added Leakage	Normal Leakage	Added Leakage
Duct Pressurization (leakage @25 Pa)*	4.9	8.0	2.8	10.3
DeltaQ (operating leakage)**	2.6	7.4	0.2	7.3
Simplified Protocol (operating leakage) — median*** *Used as best estimate in later analysis*	**3.6**	**6.9**	**2.8**	**7.6**

* Based on assessments conducted on 02/07/22 (Ceiling ducts) and 02/06/23 (Floor ducts) — see Appendix B
**Average of assessments conducted on 02/11/22 and 02/14/23 (Ceiling ducts); 02/03/23 and 03/21/23 (Floor ducts) — see Appendix B
***Based on 30-second average pressure readings for assessments with exhaust-flow of 200+ cfm, no background range-hood operation, and winds<2.5 mph (n = 63 to 165 assessments, depending on duct configuration).

Observed depressurization levels during air-handler operation are small (Table 7), again due to the leaky envelope.

Table 7. Median house depressurization associated with air-handler operation.

Duct System	Leakage Level	Median baseline-adjusted house-to-outside pressure during air-handler operation (Pa)
Ceiling	Normal	-0.36
	Added Leakage	-0.92
Floor	Normal	-0.28
	Added Leakage	-0.99

n = 586 to 1,861, depending on duct configuration.

Figure 7 and Figure 8 show how the Simplified Protocol estimates of duct leakage varied for each duct configuration for different assessed exhaust-flow levels, range-hood operating modes and windspeeds encountered during assessments, and Table 8 and Table 9 summarize regression results regarding assessment bias and variability.[12]

[12] See Appendix B, Models 3 and 4.

As with the envelope leakage estimates, duct leakage tends to be significantly underestimated when exhaust flow is low, especially when wind is also present (Table 8). Unlike the envelope leakage results, however, operating the range hood appears to produce a small *positive* bias of roughly 5 to 15 percent in calculated duct leakage.

Wind is the dominant factor affecting the variability of calculated duct leakage (Table 9), and calculated duct leakage estimates appear to be more sensitive to wind than envelope-leakage estimates. This makes sense given that the duct-leakage calculations are based on three house-to-outside pressure measurements, all of which tend to be small in magnitude and subject to wind-induced variation. This phenomenon also increases the likelihood that the assesment will produce a non-sensical negative estimate of duct leakage due to either the calculated exhaust-fan-induced or the air-handler-induced house-to-outside pressure falsely showing pressurization instead of the expected depressurization (Table 10).

Figure 7. Distribution of calculated operating duct leakage, for the FSEC MH Lab home ceiling duct system at two leakage levels and with and without background range-hood operation, by exhaust flow level and windspeed during assessment.

Bars (orange) are 25th to 75th percentiles
Dots (light orange) are medians
Whiskers (purple) are 5th to 95th percentiles (arrows with values indicate whiskers that extend beyond the graph range)
Dashed Line (green) is the median for tests with exhaust flow of 200+ cfm, no range-hood operation and winds<2.5 mph

*Operating duct leakage to outside per 100 ft^2 of conditioned floor area

Results omitted if n<30

Figure 8. Distribution of calculated operating duct leakage, for the FSEC MH Lab home floor duct system at two leakage levels and with and without background range-hood operation, by exhaust flow level and windspeed during assessment.

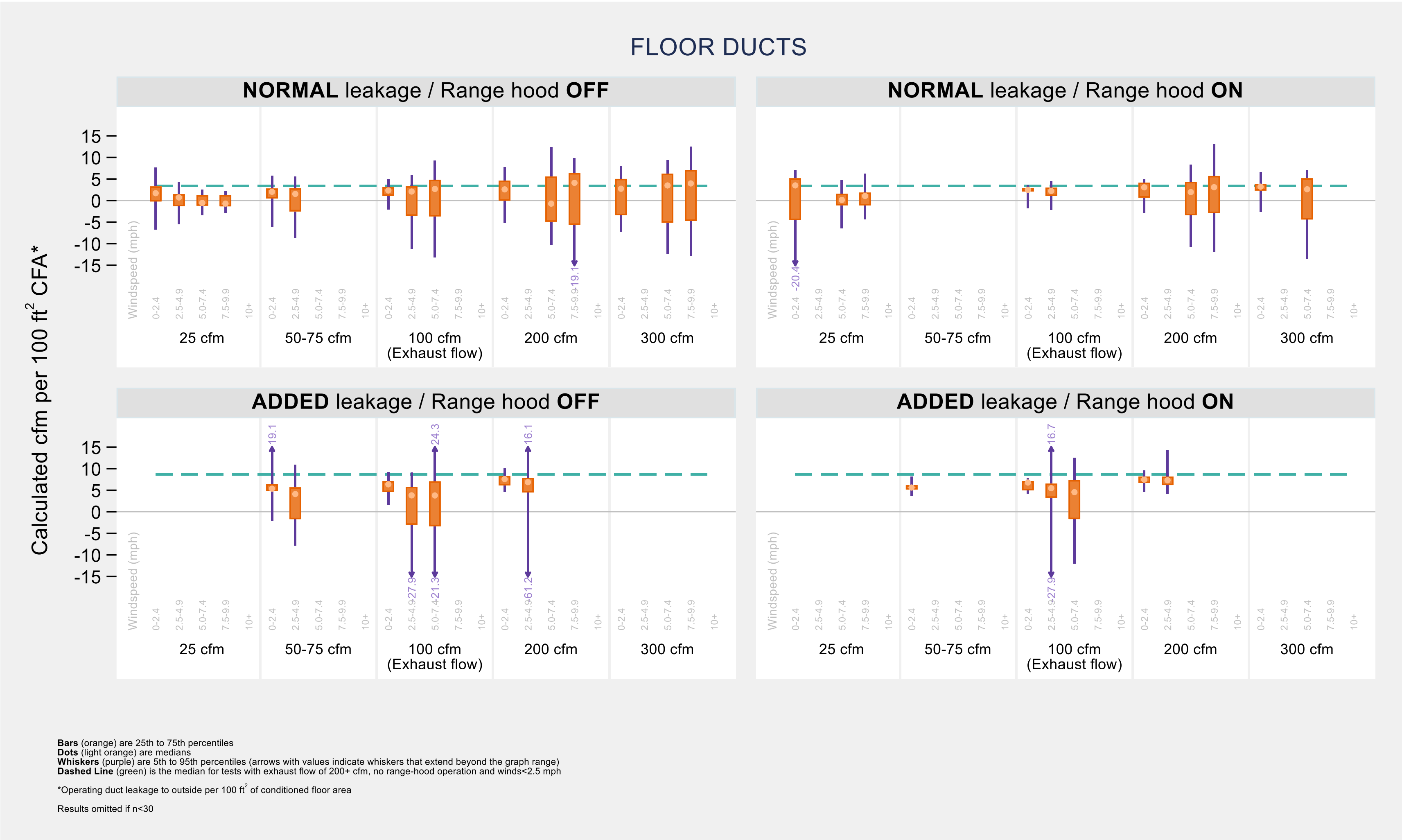


Table 8. Regression estimates of the median bias for protocol-estimated duct leakage to outside relative to best estimates, by range-hood status and exhaust-flow level, at selected windspeeds (see Appendix C).

Range Hood	Exhaust Flow (cfm)	Windspeed (mph)		
		0	5	10
Off	25	-43%	-82%	-121%
	50-75	-14%	-50%	-87%
	100	-17%	-29%	-42%
	200	-1%	-4%	-7%
	300	+5%	+5%	+5%
On (100 cfm)	25	-34%	-73%	-113%
	50-75	-5%	-42%	-78%
	100	-8%	-21%	-33%
	200	+7%	+5%	+2%
	300	+14%	+14%	+13%

Table 9. Regression estimates of the magnitude of the interquartile range (25th to 75th percentiles) of protocol-estimated duct leakage to outside (cfm per 100 ft^2 of floor area), by range-hood status and exhaust-flow level at selected windspeeds (normalized to leakage of 6 cfm/100 ft^2). (See Appendix C.)

Range Hood	Exhaust Flow (cfm)	Windspeed (mph)		
		0	5	10
Off	25	1.4	6.2	11.0
	50-75	2.0	6.8	11.7
	100	2.1	6.9	11.8
	200	2.6	7.5	12.3
	300	2.0	6.8	11.6
On (100 cfm)	25	-0.2	4.7	9.5
	50-75	0.4	5.3	10.1
	100	0.6	5.4	10.2
	200	1.1	5.9	10.8
	300	0.4	5.2	10.1

Table 10. Percent of Simplified-Protocol assessments producing a non-sensical negative estimate of duct leakage due to spurious wind effects, by duct leakage level, range-hood operation, exhaust-flow level and windspeed during assessment.

Duct Leakage Level	Background range-hood operation	Exhaust flow level (cfm)	Windspeed during assessment (mph) 0-2.4	2.5-4.9	5.0-7.4	7.5-9.9	10+
Normal	Off	25	25%	--	--	--	--
		50-75	12%	32%	45%	46%	54%
		100	8%	31%	34%	27%	--
		200	2%	13%	32%	37%	--
		300	3%	14%	22%	--	--
	On (100 cfm)	25	20%	--	--	--	--
		50-75	--	--	44%	16%	60%
		100	2%	13%	18%	24%	--
		200	0%	6%	19%	28%	--
		300	0%	3%	8%	--	--
Added Leakage	Off	25	27%	45%	59%	53%	--
		50-75	13%	37%	41%	--	--
		100	8%	33%	36%	--	--
		200	13%	32%	49%	39%	--
		300	32%	--	39%	40%	--
	On (100 cfm)	25	26%	--	50%	36%	--
		50-75	2%	--	--	--	--
		100	3%	19%	31%	--	--
		200	10%	9%	31%	39%	--
		300	15%	--	37%	--	--

Results omitted if n<30 for a given assessment configuration and windspeed category.

FIELD EVALUATION OF THE SIMPLIFIED PROTOCOL

The Project Team also evaluated the protocol in the field alongside conventional blower-door and duct-leakage testing in three regions of the country, for a total of 36 homes.

Northwest

Twenty-two homes in the Pacific Northwest were evaluated, mostly during quality-control and troubleshooting visits associated with the Northwest Energy-Efficient Manufactured Housing (NEEM) program by team member, Northwest Energy Works (NEW). One Northwest home (ID# NW00) was a triple-wide unit belonging to one of the team members and was subject to initial proof-of-concept evaluation for the protocol. Additionally, two homes (NW20 and NW21) were research homes at the Pacific Northwest National Laboratory.[13]

Southeast

In addition to the MH Lab home described above where additional proof-of-concept evaluation was conducted and where the automated evaluation for repeatability occurred, six homes in the region were evaluated using the protocol. These homes were completely set up, ready to be sold, and assessed by team member, Bobby Parks of Healthy Homes of Louisiana during fall of 2022. The homes presented an opportunity to implement the protocol on typical homes in the Southeast, with the installation crew having no prior knowledge that they were to be evaluated.

Midwest

To obtain data for a sample of homes in the Midwest, Slipstream team members assessed seven homes on the display lot of a Wisconsin manufactured-housing retailer over the course of two days in the fall of 2022.

Overall, some of the homes (NW00, NW20, SE00 and all seven Midwest homes) were assessed multiple times under the protocol, always on the same day and generally under similar wind conditions. All homes received standard multi-point blower-door tests and duct-pressurization tests for comparative purposes. Duct leakage for a few of the homes was also assessed with DeltaQ tests. Appendix D provides more detail about the characteristics and standard test results for the homes.

Field Evaluation Results

The blower-door testing showed that homes assessed in the Northwest had less envelope leakage than homes built in the Midwest and Southeast (Figure 9). Homes in the Northwest averaged 3.9 ACH50 (excluding one home that was deliberately assessed prior to being completely joined and sealed), compared to 5.9 in the Midwest, and 8.0 in the Southeast. Homes in the Northwest also showed lower levels of duct leakage than homes built in the Midwest and Southeast (Figure 10). These differences likely are the result of the strong presence of the NEEM program in the Northwest.

The available exhaust flow for conducting the Simplified Protocol ranged from less than 25 cfm to more than 300 cfm (Figure 11). Most homes had 2 or 3 available exhaust fans that could be readily measured and used in the protocol. Most homes in the Northwest also had dedicated whole-house exhaust fans for meeting HUD ventilation requirements, giving homes in that region significantly more available exhaust capacity than homes in the other two regions, which used furnace-return POS systems for code-required ventilation. Note that only 5 of 77 evaluated

[13] See https://labhomes.pnnl.gov/documents/Lab_Homes_Flier.pdf

bath fan installations (6.5%) met the HUD-code requirement of 50 cfm of exhaust capacity. Measured flows for these ranged from 8 to 130 cfm, with an average of 33 cfm.

In two cases, special effort was made to measure and include the kitchen range hood as part of the total exhaust flow. This generally required using cardboard to mask part of the underside of the hood so that the exhaust-flow meter can capture all flow through the hood. The extra time and effort required for this would be a barrier to including the range hood in the exhaust-flow measurement in general implementation of the protocol and would probably not be done. As with the automated evaluation at the FSEC Lab home, most of the field assessments were run twice: once with the range hood off throughout the assessment, and once with the range hood running in the background throughout the assessment.

Figure 9. Measured envelope leakage from blower-door testing (air changes per hour @ 50 Pa).

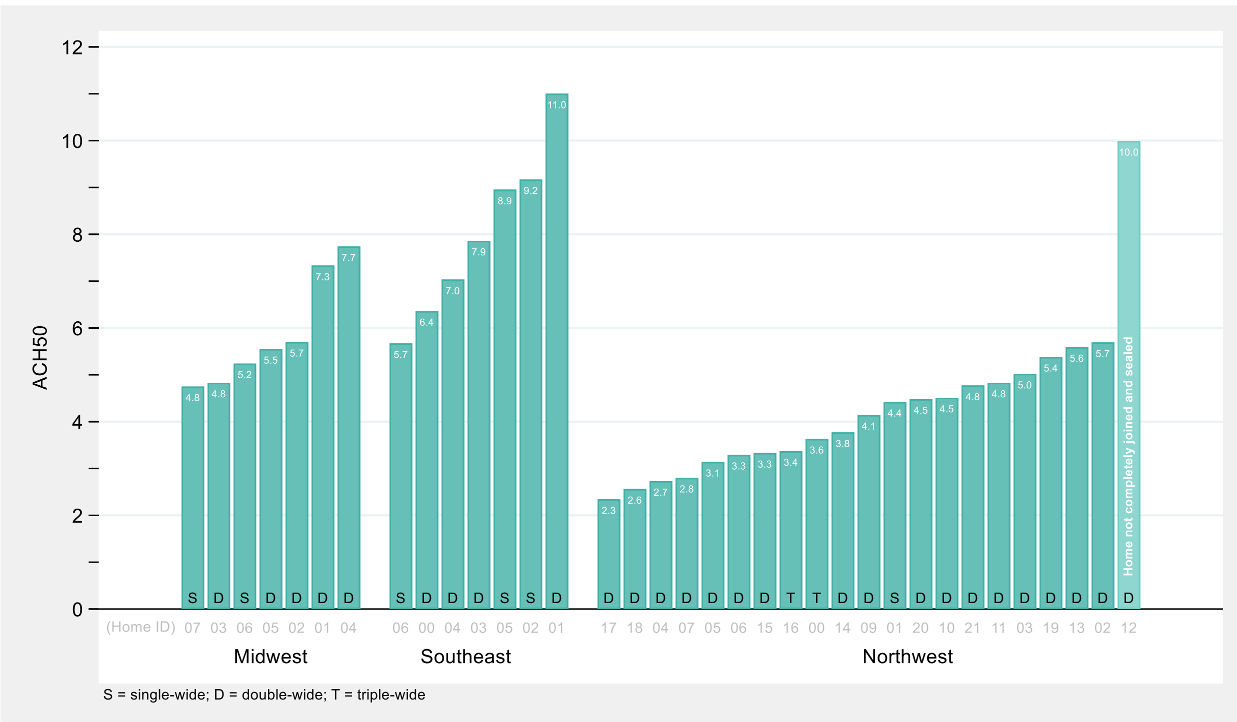
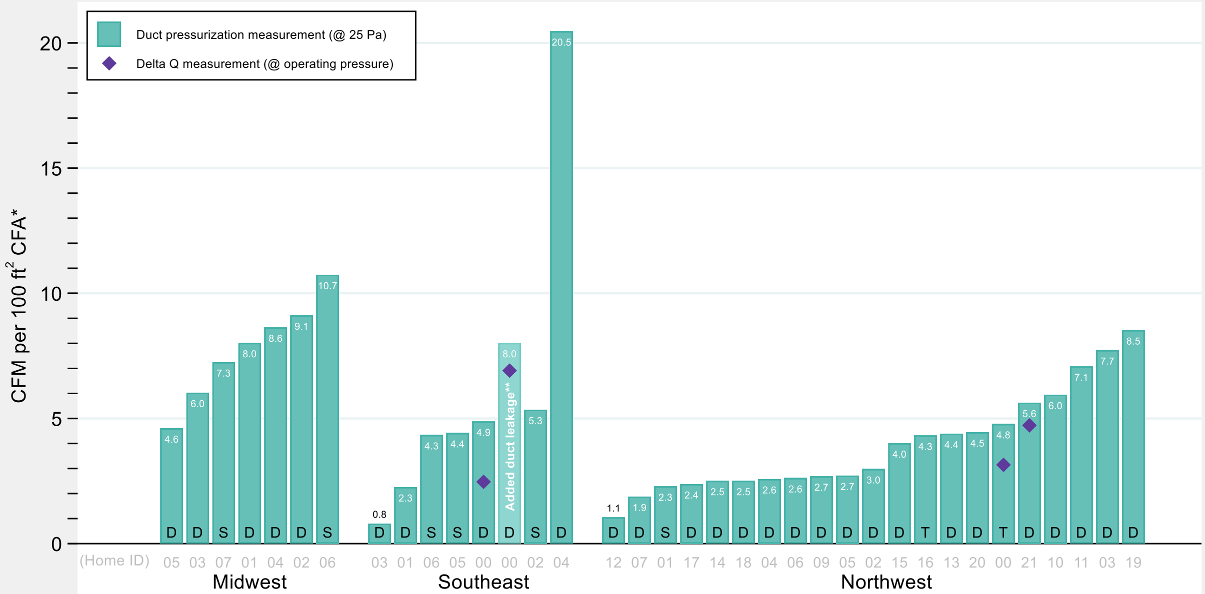


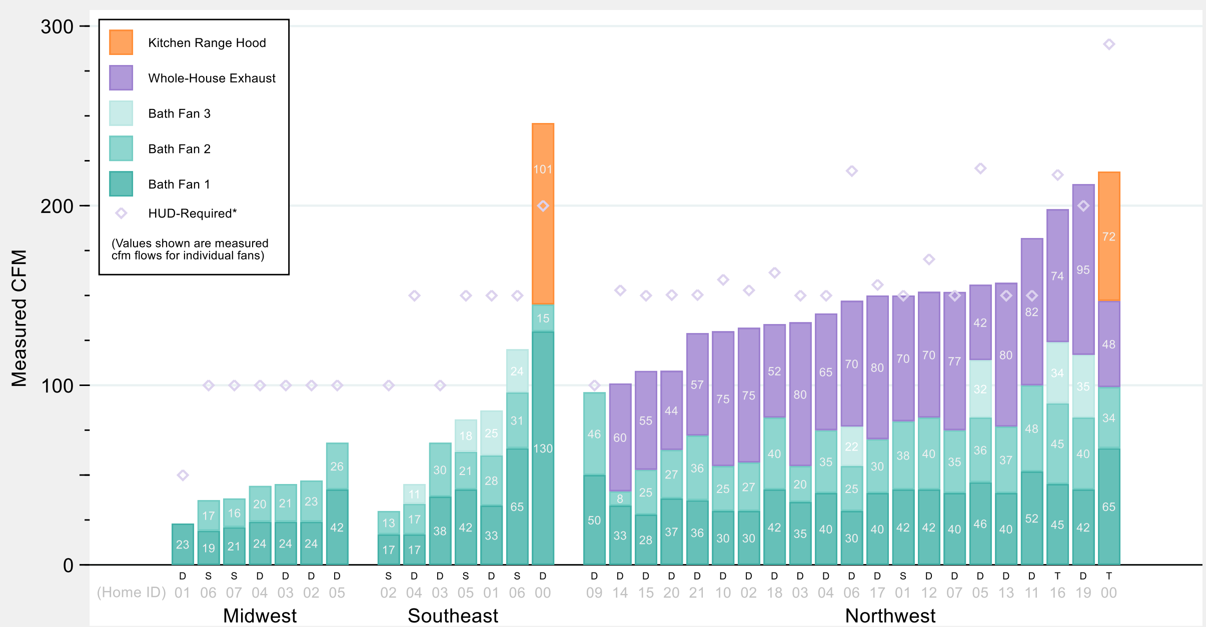
Figure 10. Measured duct leakage to outside from duct pressurization and DeltaQ testing.



S = single-wide; D = double-wide; T = triple-wide

*cfm leakage to outside per 100 ft² of conditioned floor area
**Additional duct leakage deliberately added for experimental purposes

Figure 11. Measured exhaust flow.



S = single-wide; D = double-wide; T = triple-wide

*Total HUD-required flow for measured devices (50 cfm per bath fan, 100 cfm per range hood, 0.035 cfm/ft2 for whole-house ventilation)

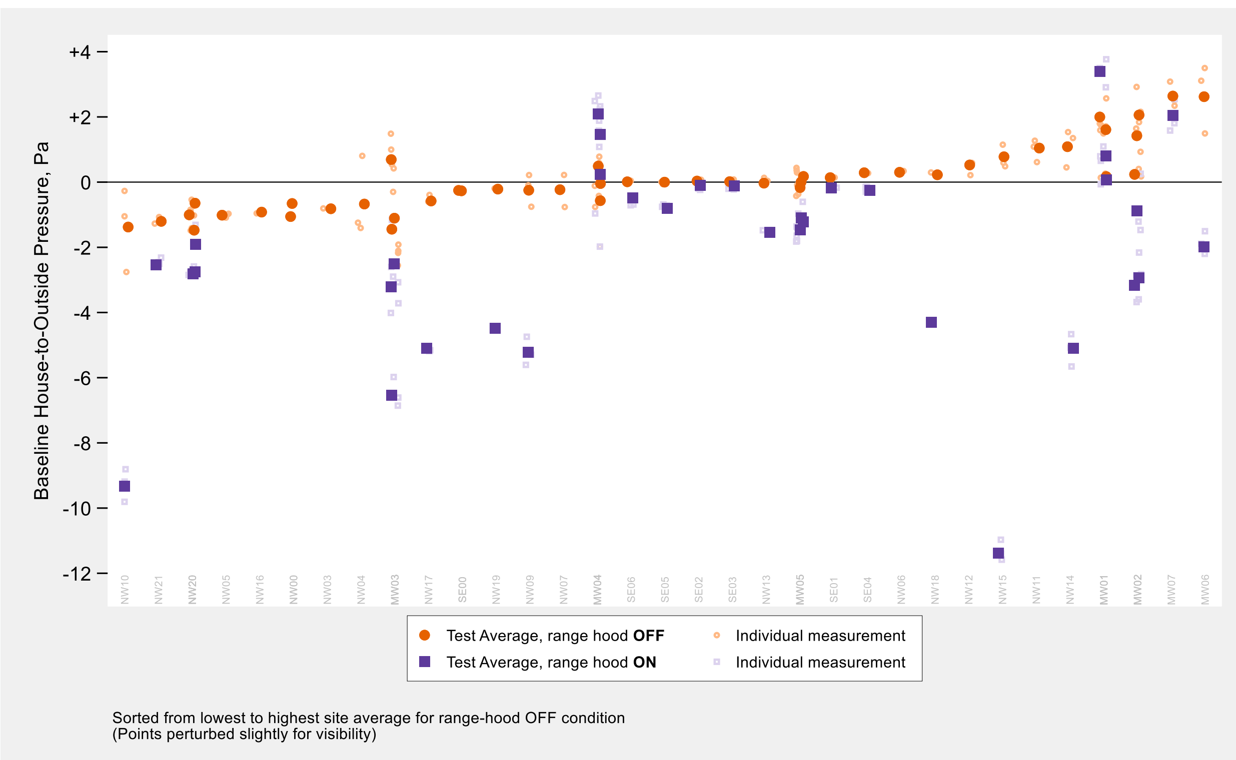
Induced House-to-Outside Pressures

House-to-outside pressures were captured in the field evaluation by manually recording three consecutive house-to-outside pressure readings spaced about 15 seconds apart, then averaging these values.[14] Average baseline house-to-outside pressure ranged from -1.4 to +2.7 Pascals for the assessments that were conducted without the range-hood operating in the background (Figure 12). Running the range-hood added substantial baseline depressurization in some cases.

The net pressurization induced by exhaust operation averaged about 2 Pascals across the field-evaluated homes (Figure 13), but this belies a strong regional difference between the Northwest (~4 Pascals) and the Midwest and Southeast (~1 Pascal), owing to the combination of tighter envelopes and higher available exhaust flow in the Northwest sample.

Measured depressurization associated with air-handler operation was mostly less than 3 Pascals (Figure 14).

Figure 12. Recorded baseline house-to-outside pressure, with and without range hood operation.



[14] It is expected that wider implementation of the protocol would utilize automated capture and averaging of pressures over a 5- to 20-second window, analogous to the data capture for the FSEC MH Lab under automated testing. Analysis of the data from the automated testing suggests that the two approaches will yield similar results in most cases.

Figure 13. Baseline-adjusted house-to-outside pressure during exhaust operation, with associated exhaust flow.

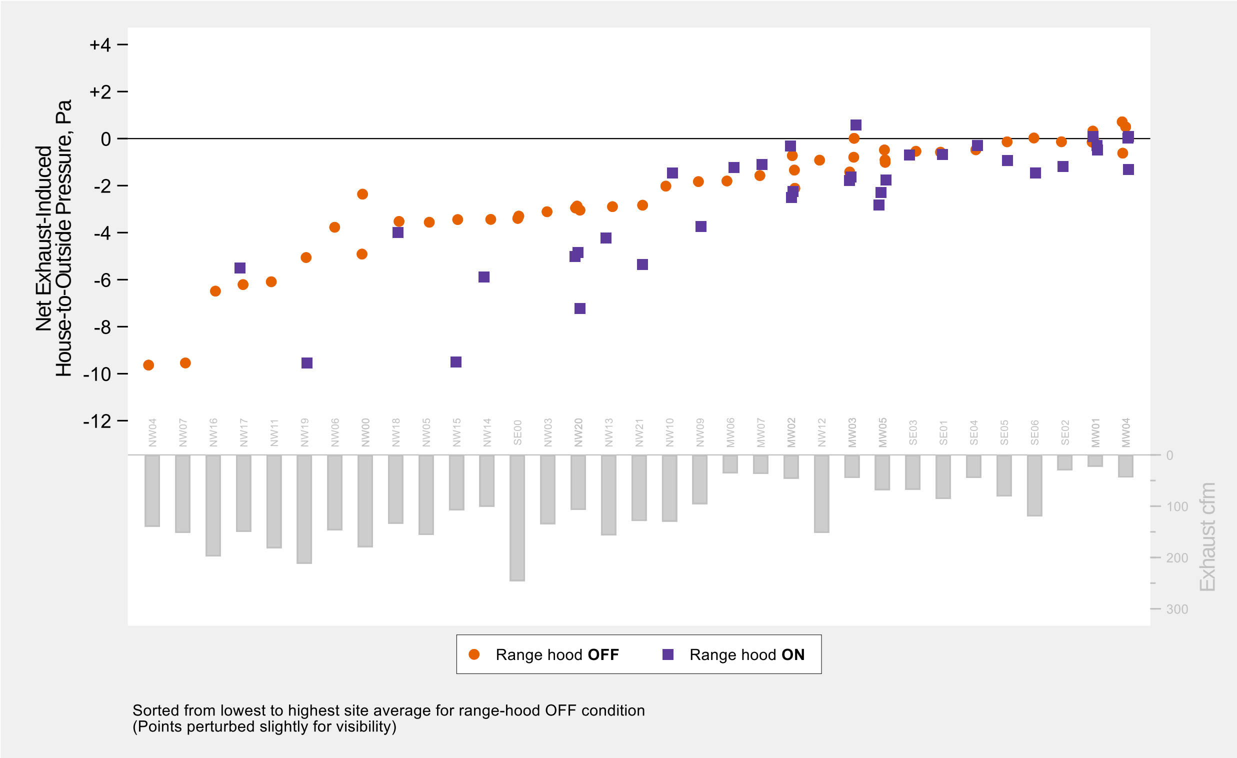
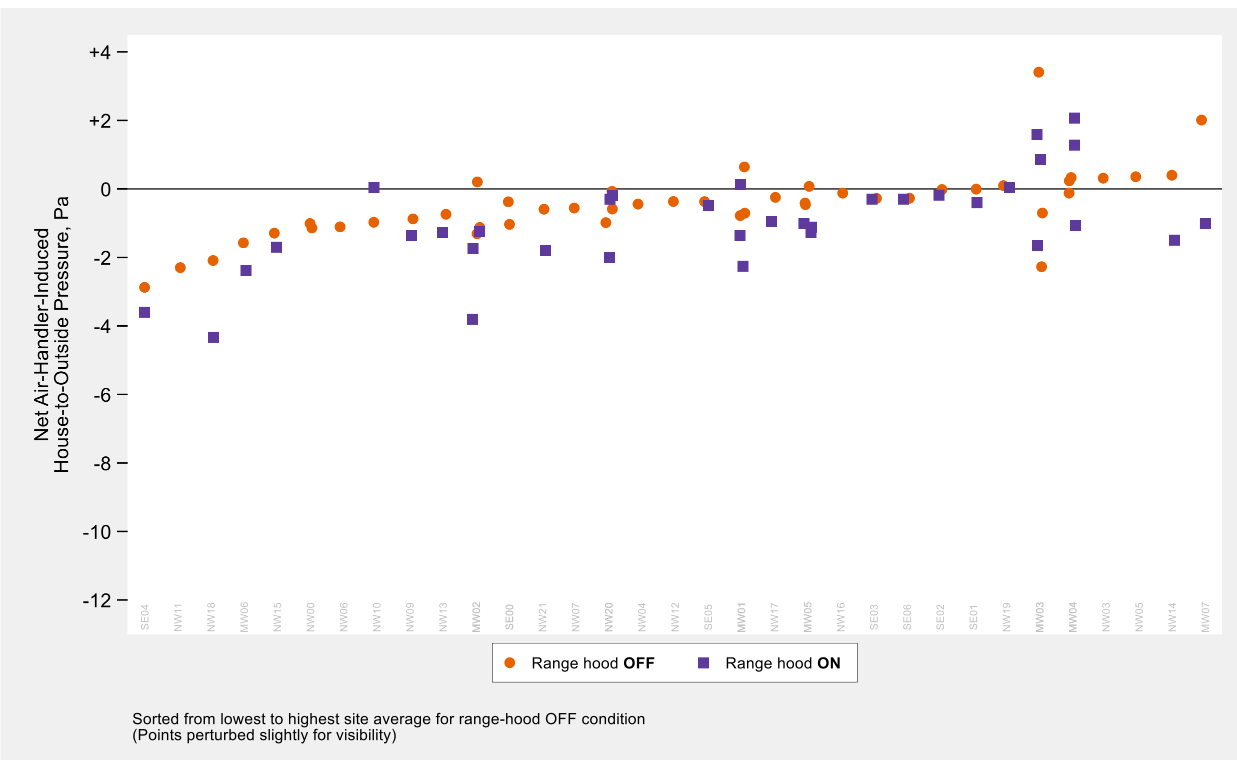


Figure 14. Baseline-adjusted house-to-outside pressure during air-handler operation.

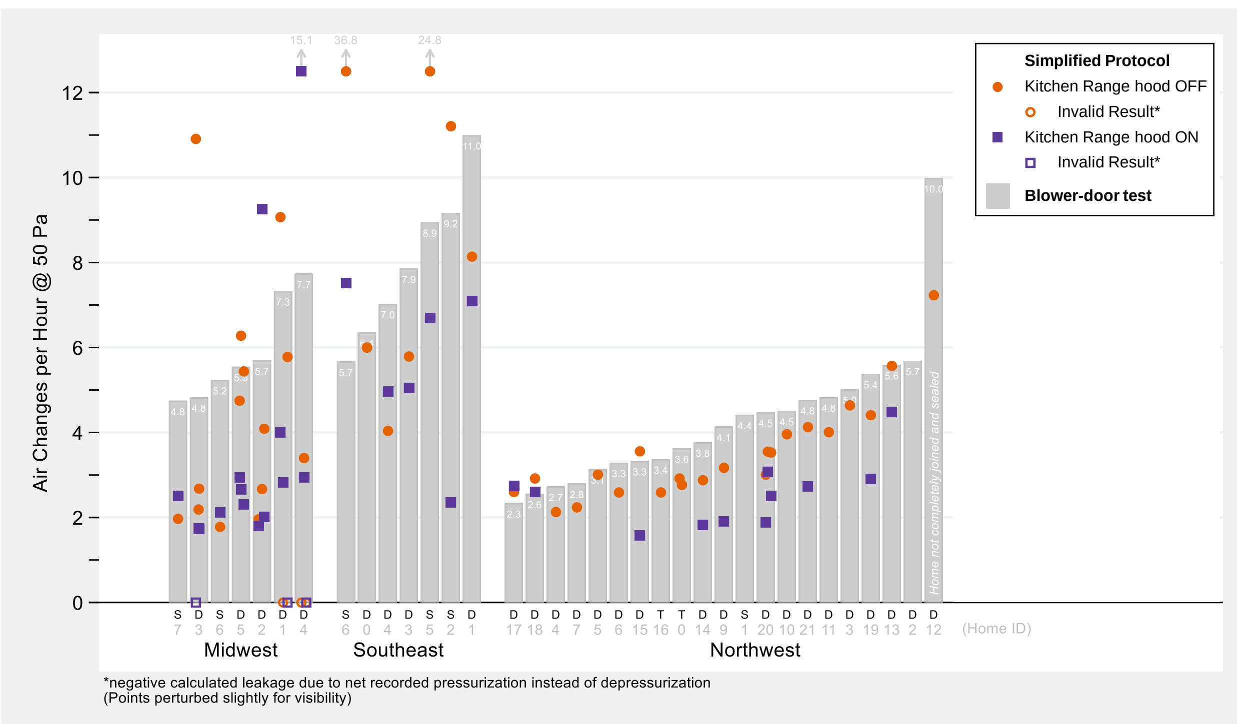


Envelope Leakage Estimates

Figure 15 compares the Simplified Protocol estimates of envelope leakage to the blower-door test results. The results for the Northwest homes generally track with the blower-door values when the range hood was left off for the assessment (orange dots in the figure). Except for one high outlier (NW10) and one low outlier (NW12) among the Northwest homes, the Simplified Protocol produced envelope-leakage estimates that were within 1 ACH50 of the blower-door testing. And although the Simplified Protocol estimate for NW12 (far righthand side of the graph) came in well below the blower-door test result for this home (which was deliberately tested prior to final joining and sealing) it still indicated high envelope leakage that would likely prompt investigation and remediation. Echoing the findings from the FSEC MH Lab home automated evaluation, operating the range hood during evaluation (purple squares) tended to produce envelope-leakage estimates that were low among the Northwest homes.

Results for the Midwest and Southeast homes are much more scattered around the blower-door values. Among the 25 Simplified Protocol assessments conducted in these homes with the range-hood off, only one in five came within 1 ACH50 of the blower-door value and only about half were within 3 ACH50 of the blower-door leakage. This is likely because these homes have higher envelope leakage levels and lower available exhaust flow; these factors combine to produce much smaller exhaust-induced depressurization signals that are more susceptible to the wind noise and bias effects seen in the MH Lab home automated evaluation.

Figure 15. Simplified Protocol estimates of envelope leakage, with blower-door test results.



Duct Leakage Estimates

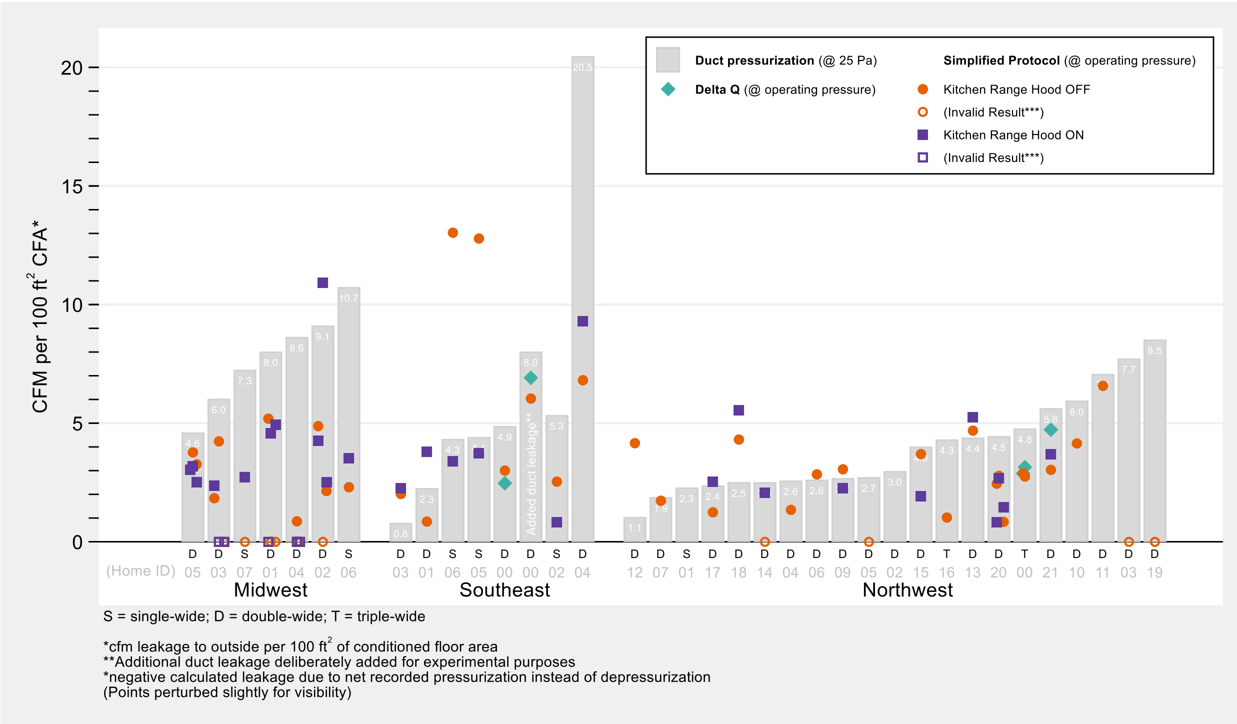
There is considerable scatter in the Simplified Protocol estimates of duct leakage (Figure 16), and interpreting the results is again complicated by the fact that the protocol measures leakage under actual operating conditions which may be different from the leakage measured under duct pressurization testing. Notably, the Simplified Protocol results were reasonably comparable to DeltaQ results for the few homes where the latter testing was performed (SE00, NW00 and NW21).

Nonetheless, as with the MH Lab home repeat evaluation, field evaluation of the Simplified Protocol produced a higher proportion of invalid assessments and outliers for duct leakage compared to its envelope-leakage estimates. This is likely due to the generally small depressurization effect during air handler operation, along with the fact that the duct leakage results are dependent on a reasonable envelope-leakage estimate, which in turn depends on obtaining a measurable depressurization effect under exhaust flow.

In this vein, it is perhaps no surprise—though disappointing—that the home showing more than 20 cfm/100ft^2 of duct leakage under duct pressurization testing (SE04) did not have nearly as dramatic calculated leakage from the Simplified Protocol. While it is possible that the actual operating duct leakage for this home is less than indicated from duct pressurization testing, it is more likely that the Simplified Protocol underestimated leakage due to the combination of a leaky envelope (7 ACH50) and low available exhaust flow (48 cfm). This likely biased the results downward.

Five sites had calculated duct leakage from the protocol that was considerably *higher* than the duct-pressurization results. Four of these sites (MW02, SE06, SE05 and NW12) also showed exhaust-induced depressurization of less than 1 Pascal, which tends to destabilize the duct-leakage calculation.

Figure 16. Simplified Protocol estimates of duct leakage to outside, with duct-pressurization and DeltaQ test results.



Register Flow Measurements

As described previously, the research sought to assess the efficacy of using the exhaust-fan flow meter in reverse for measuring supply register airflow. Prior proof-of-concept evaluation suggested that this was best done by placing the flow meter transverse to the long access of the register with the opening for the meter as far as possible from the register itself (Figure 17). The proof-of-concept evaluation also suggested that adding a small manifold system of tubing with multiple pressure taps to the inside of the meter improved reliability (Figure 18). This setup was used to measure register flow among field-evaluated homes in the Northwest and Midwest and compare them to concurrent measurements with a commercial balometer designed for this type of flow measurement.

Figure 17. Orientation of exhaust-fan flow meter for measuring supply register flow.

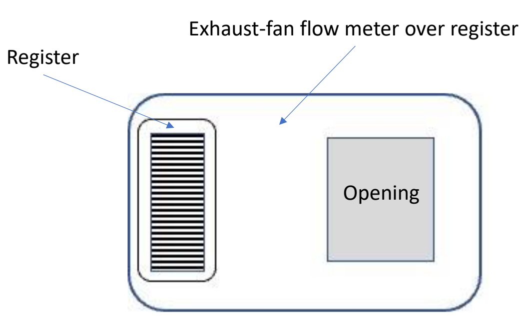


Figure 18. Modification to exhaust-fan flow meter for multiple pressure taps inside the meter.

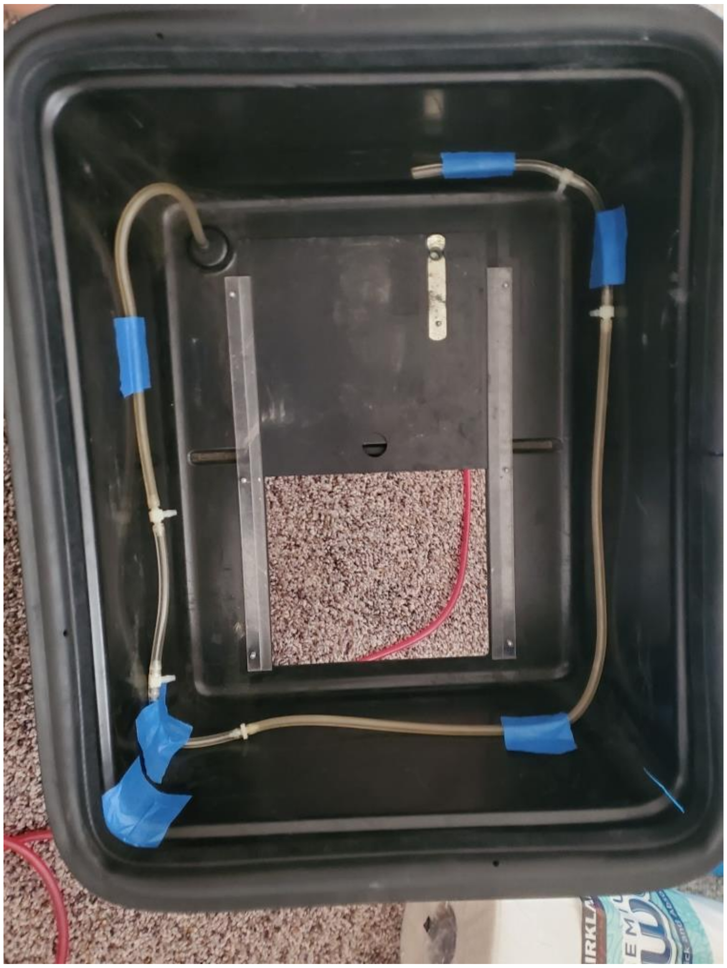
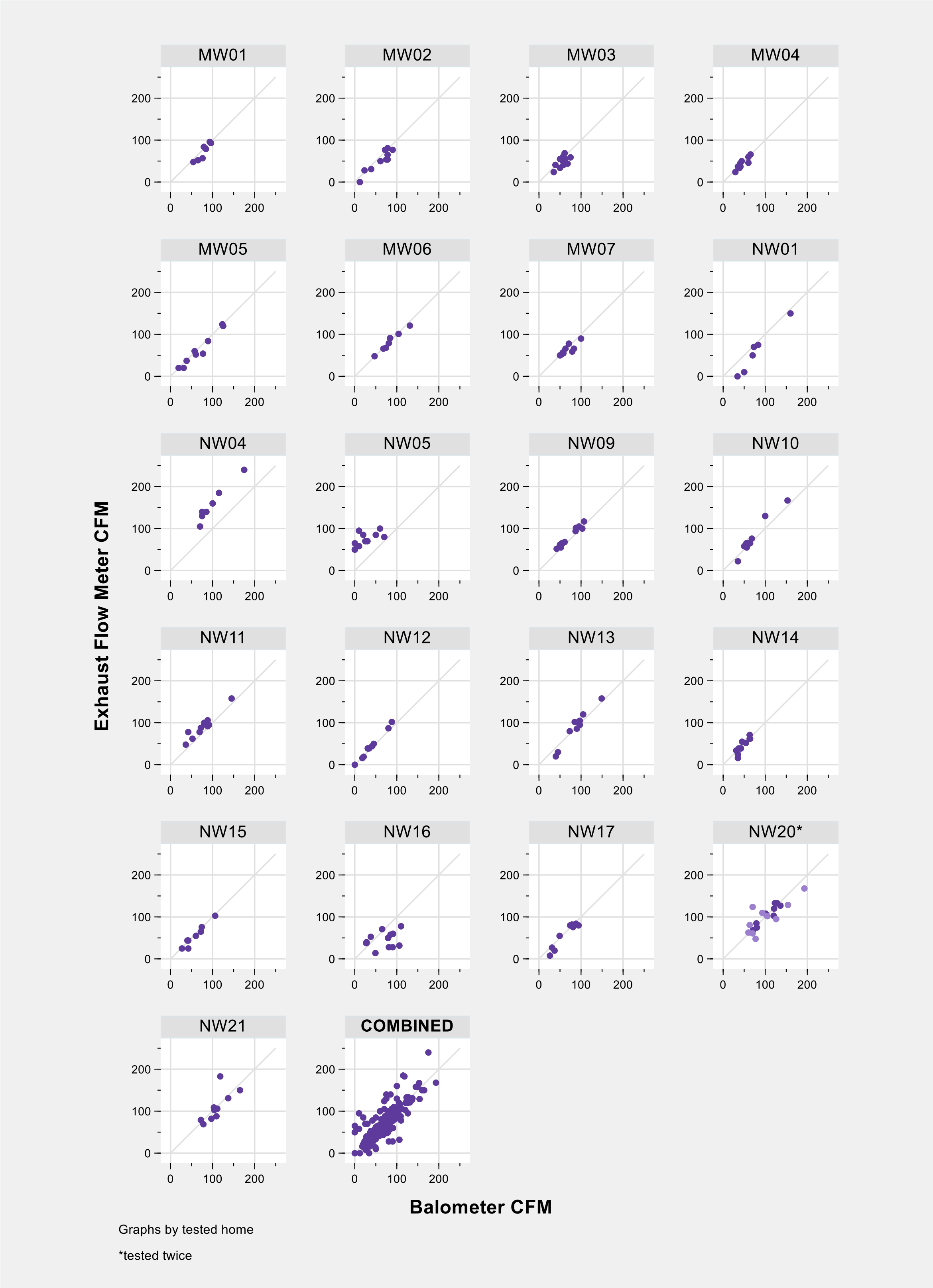


Figure 19 compares the two sets of measurements for 212 registers in 22 homes (one home was measured twice). In general, the flow measured with the exhaust-flow meter compared well with the side-by-side balometer measurement: 60 percent of the measurements agreed to within ±10 cfm and 80 percent to within ±20 cfm. Home NW04 shows signs of some type of systematic error between the two measurements, which could be the result of an incorrect setting on either the exhaust-fan flow meter or the balometer. A few homes (e.g. NW05 and NW16) show noticeably more scatter between the measurements. But overall, the exhaust-fan flow meter used in this way appears to be capable of producing useful measurements of register flow.

Figure 19. Register airflow measured by exhaust-fan flow meter versus measured by balometer, by home.



A STOCHASTIC MODEL OF SIMPLIFIED-PROTOCOL RELIABILITY

To help shed light on the FSEC MH Lab and field-evaluation results—and to better understand the reliability of the protocol under various conditions—a stochastic model of the protocol was developed. The model simulates the effects of random wind noise, flow-exponent uncertainty, and other factors on protocol-calculated estimates of leakage. It was used to develop confidence intervals for protocol estimates and explore how these vary with wind and exhaust flow level. Appendix E describes the model in more detail and provides a series of confidence-interval plots derived from the model.

The calculated confidence intervals from the model can be further distilled down to explore the concept of establishing field pass/fail criteria for envelope and duct leakage. These would likely be set in relative terms (e.g., ACH50 for envelope leakage and percent of system airflow duct leakage) and would then be translated into absolute (cfm) values based on the characteristics of each assessed home.

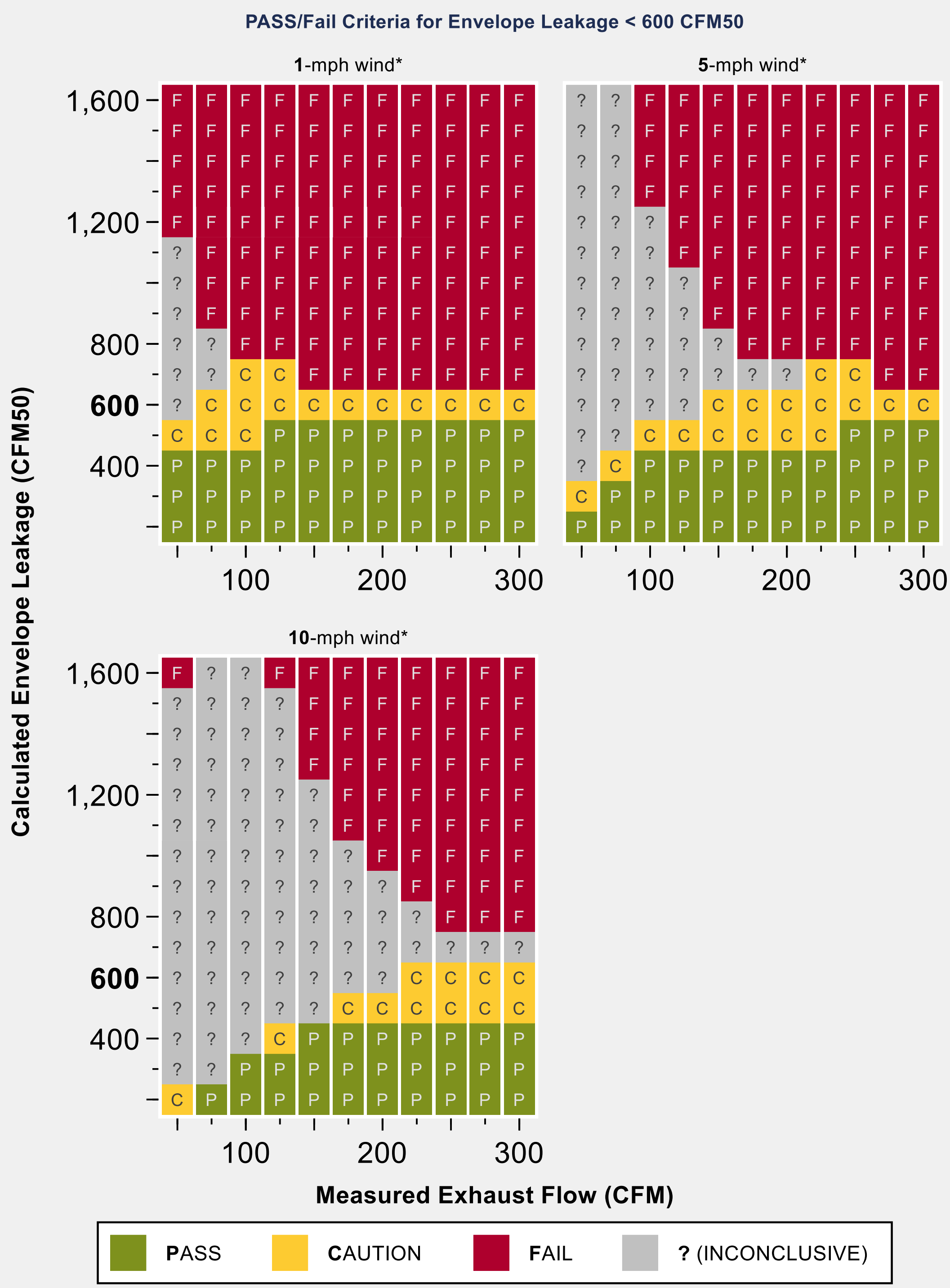
Figure 20 and Figure 21 show hypothetical pass/fail determinations for an envelope leakage threshold of 600 CFM50, which would correspond to 4 ACH50 for a 9,000 ft^3 single-wide home. Figure 20 assumes that exhaust flow is measured during the protocol; Figure 21 assumes that only the rated exhaust flow in the protocol is known. Figure 22 and Figure 23 similarly show pass/fail determinations for a hypothetical duct-leakage threshold of 80 cfm, which would correspond to 10 percent leakage for a home with total system airflow of 800 cfm.

As envisioned here, a given set of measurements and wind conditions results in one of four pass/fail determinations:

- **Pass** — there is 90% confidence that actual leakage is at or below the threshold
- **Caution** — there is 90% confidence that actual leakage is within 150% of the threshold
- **Fail** — there is 90% confidence that actual leakage is more than the threshold
- **Inconclusive** — the 90% confidence interval for leakage extends from below the threshold to more than 150% above the threshold

In general, the pass/fail charts reflect the general principles observed in the empirical data and the stochastic model: confidence in protocol-calculated leakage is lowest when available exhaust flow is low, the building envelope is leaky and winds are high; conversely, confidence is high when exhaust flow is high, the envelope is tight and winds are low.

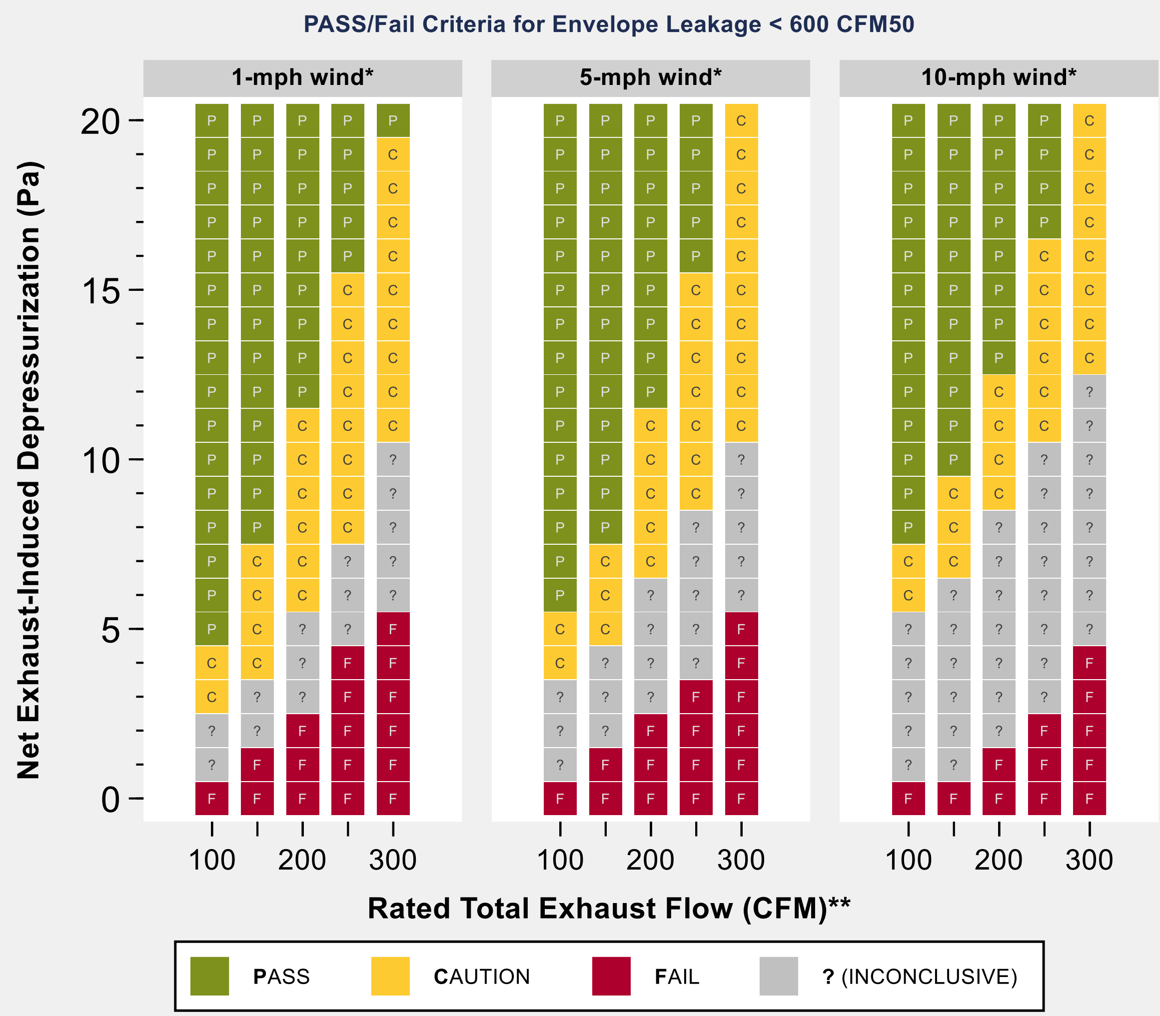
Figure 20. Example pass/fail criteria for **envelope leakage** at or below 600 CFM50, based on protocol-calculated CFM50, measured exhaust flow and stated wind condition.



PASS - 90% confidence that leakage is at or below 600 CFM50
CAUTION - 90% confidence that leakage is at or below 900 CFM50
FAIL - 90% confidence that leakage is greater than 600 CFM50
INCONCLUSIVE - 90% confidence interval extends from below 600 to above 900 CFM50

*Assumes standard deviation of $P_{Baseline}$ (Pa) = 0.1 + 0.25*windspeed (mph)

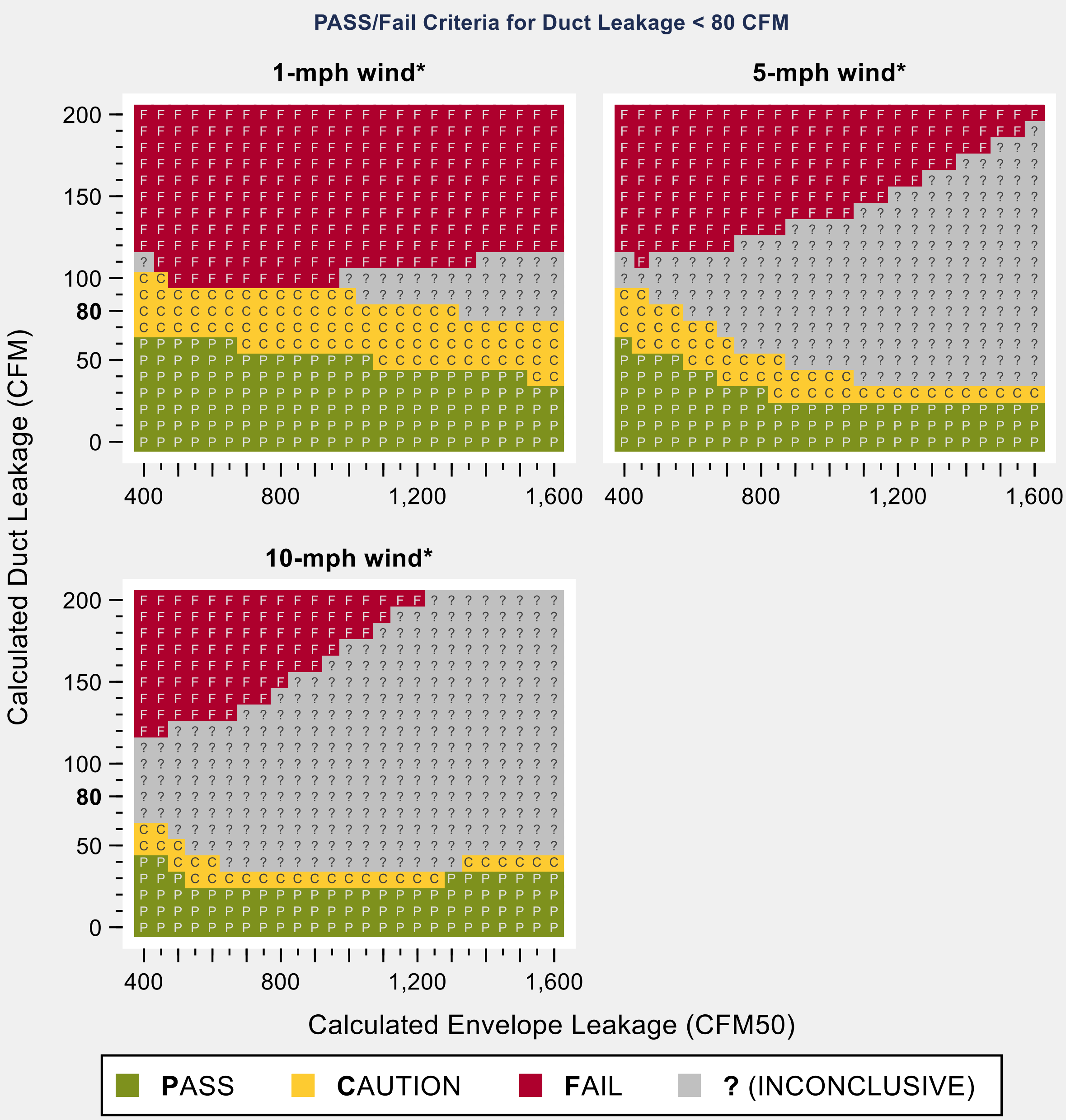
Figure 21. Example pass/fail criteria for **envelope leakage** at or below 600 CFM50, based on observed house depressurization during exhaust operation, rated (but unmeasured) exhaust flow and stated wind condition.



PASS - 90% confidence that leakage is at or below 600 CFM50
CAUTION - 90% confidence that leakage is at or below 900 CFM50
FAIL - 90% confidence that leakage is greater than 600 CFM50
INCONCLUSIVE - 90% confidence interval extends from below 600 to above 900 CFM50

*Assumes standard deviation of $P_{Baseline}$ (Pa) = 0.1 + 0.25*windspeed (mph)
**Assumes that actual flow is 50-100% of rated

Figure 22. Example pass/fail criteria for **duct leakage** at or below 80 CFM, based on protocol-calculated envelope and duct leakage and stated wind condition, for measured exhaust flow of 150 CFM.

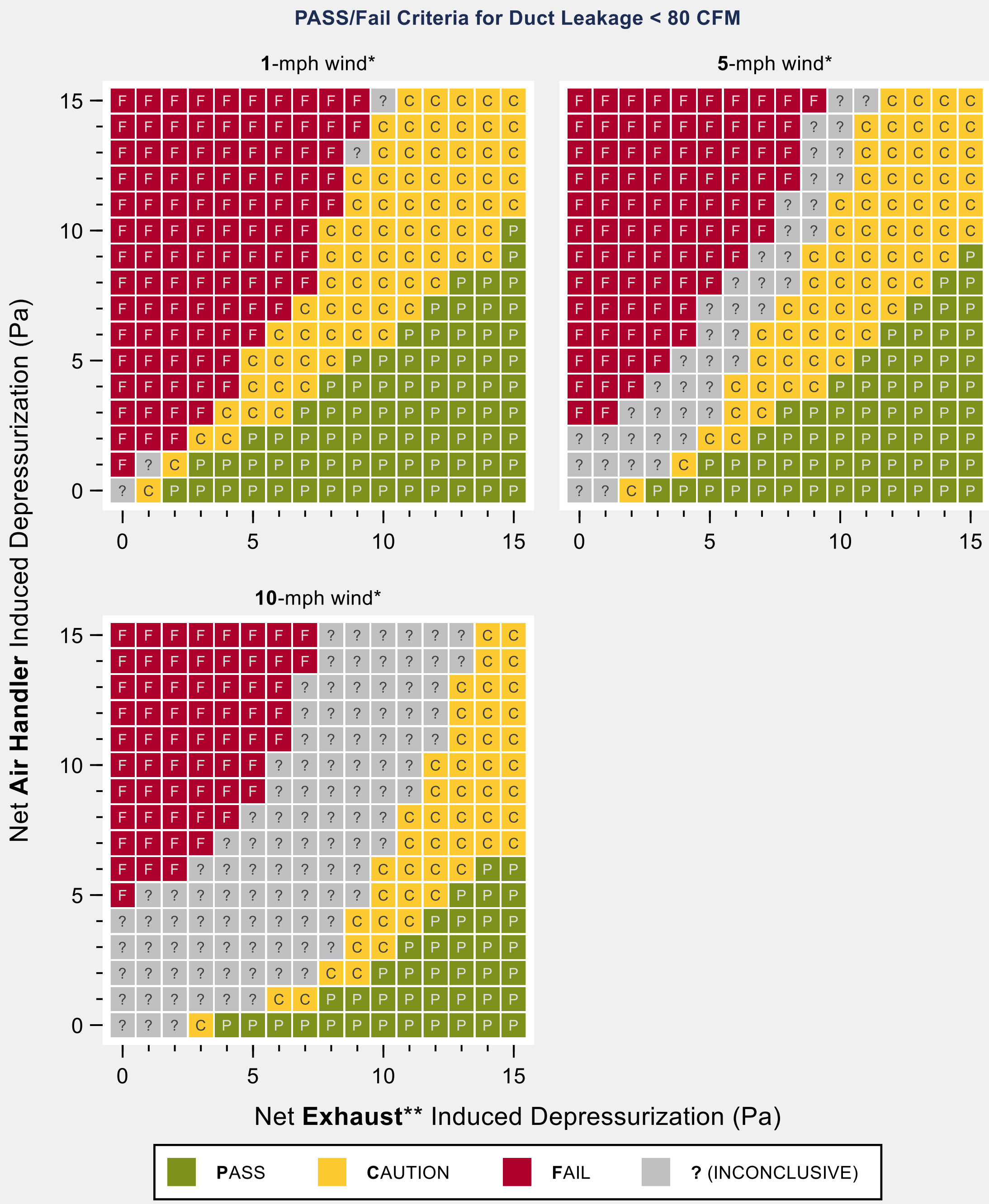


PASS - 90% confidence that duct leakage is at or below 80 CFM
CAUTION - 90% confidence that duct leakage is at or below 120 CFM
FAIL - 90% confidence that duct leakage is greater than 80 CFM
INCONCLUSIVE - 90% confidence interval extends from below 80 to above 120 CFM

Results for exhaust flow of 150 CFM

*Assumes standard deviation of $P_{Baseline}$ = 0.1 + 0.25*windspeed (Pa)

Figure 23. Example pass/fail criteria for duct leakage at or below 80 CFM, based on observed net induced depressurization during exhaust operation and air-handler operation and stated wind condition, for rated (but unmeasured) exhaust flow of 150 CFM.



PASS - 90% confidence that duct leakage is at or below 80 CFM
CAUTION - 90% confidence that duct leakage is at or below 120 CFM
FAIL - 90% confidence that duct leakage is greater than 80 CFM
INCONCLUSIVE - 90% confidence interval extends from below 80 to above 120 CFM

*Assumes standard deviation of $P_{Baseline}$ (Pa) = 0.1 + 0.25*windspeed (mph)
Results for total **rated exhaust flow of 150 CFM. Assumes (unmeasured) actual flow is 50-100% of rated.

CONCLUSIONS

The automated evaluation at the FSEC MH Lab home, the field-evaluated data and the stochastic model developed here all show that the efficacy of the protocol is highly dependent on three factors: (1) the amount of available exhaust flow for assessment; (2) the expected tightness of the building envelope; and (3) winds during assessment. More exhaust flow with a tighter envelope means a larger home depressurization signal that is less subject to wind noise and other confounding effects; conversely, low exhaust flow in a leaky home leads to a small depressurization signal and downwardly biased and highly variable leakage estimates. These effects become magnified with increasing windspeed.

The amount of exhaust flow needed to produce diagnostically useful assessment results depends on the expected envelope leakage for homes being assessed: efficient new homes that are expected to have tight envelopes can get by with less exhaust flow than less-efficient homes where the expected depressurization effect will be less for a given level of exhaust. Table 11 provides suggested levels of exhaust flow needed for typical-sized single- and double-wide homes at various levels of expected envelope tightness and low to moderate winds based on the findings from this project. These exhaust flow levels should produce about 5 Pascals of depressurization during exhaust operation and provide an adequate depressurization "signal" to overcome wind-induced measurement errors in most cases (assuming that the wind effects seen in the FSEC MH Lab home evaluation hold true for other homes—more on this later).

Home size (specifically, the home volume) plays a role in determining the minimum exhaust flow needed for evaluation because the depressurization effect of exhaust or air-handler operation is keyed to absolute envelope leakage (CFM50) not the volume-normalized leakage (ACH50). A large home might need 30 to 50 percent more exhaust flow than shown here.

Table 11. Suggested minimum exhaust flow needed for Simplified Protocol for typical single- and double-wide manufactured homes under low-to-moderate wind conditions.

Home category	**Expected envelope leakage (ACH50)**	**Minimum needed exhaust flow for Simplified-Protocol evaluation (cfm)**	
		Single-wide Home	Double-wide home
New, very tight	<3	75	100
New, tight	3-5	150	200
New, typical	5-8	200	300
Older	>8	400	600
Assumes typical volume of 8,750 and 12,500 ft³ for new single- and double-wide homes, respectively. Assumes 7,500 and 10,500 ft³ for older single- and double-wide homes.			

Taken together with the field-study data on the amount of available exhaust flow in new homes, the above minimums suggest that new very efficient homes that use whole-exhaust systems to meet HUD ventilation requirements are most likely to be amenable to the current vision of the Simplified Protocol. As exemplified in the NEEM program homes in the Northwest sample for this study, such homes are likely to have 100 to 200 cfm of readily available existing exhaust fan capacity, which should allow for verifying envelope and duct tightness for homes with expected air leakage below 3 ACH50 in most cases; homes expected to be between 3 and 5 ACH50 could be evaluated in some cases, depending on home size, available exhaust capacity and wind conditions during evaluation. Anecdotal evidence suggests that the new DOE ZERH pilot will also produce homes with expected envelope tightness and available exhaust flow that will be amenable to the protocol.

At the same time, it appears that the industry currently mostly produces new homes with envelope leakage in the range of 4 to 8 ACH50, and with one to three available exhaust fans producing less than 100 cfm of total exhaust flow. For the Simplified Protocol to work well in these homes, some form of additional exhaust flow is needed beyond bath fans. An obvious candidate is the kitchen range hood, which—when appropriately vented to the outside—can likely produce 75 to 300 cfm of exhaust flow. However, the geometry of range hoods makes measuring their flow a time-consuming process with current measurement equipment. On a related note, the study found that operating the (unmeasured) range hood in the background throughout the assessment is not a particularly effective strategy: it reduces assessment variability, but also introduces significant bias into the results, especially when available exhaust flow is low. The modeling done here suggests that it is still possible to pass/fail tight homes without measuring exhaust flow if the total *rated* exhaust flow is known, albeit with less confidence.

Another possibility for extending the applicability of the protocol to conventional new or even older manufactured homes would be to employ a supplementary fan, with measured airflow, that is carried from home to home to provide the additional needed exhaust capacity. This could be a window-mounted fan or perhaps an in-line booster fan mounted on the clothes dryer venting. Naturally, such a device would need to be considerably lighter, cheaper, and easier to deploy than the standard blower-door and duct pressurization equipment that the Simplified Protocol is intended to replace.

NEXT STEPS

This study suggests that the protocol could find good immediate application for field quality control among efficient new manufactured homes with tight envelopes and whole-house exhaust ventilation. The next logical step is to encode the protocol in a smartphone app to make it user-friendly. The app would be especially useful if it interfaced with a connected digital manometer. Such an app could:

- Provide step-by-step field instructions for implementing the protocol.
- Automatically take pressure readings, and dynamically adjust measurement averaging periods to account for wind noise.
- Internalize protocol calculations and provide immediate pass/fail or quantitative field feedback on evaluation results.
- Automatically upload evaluation results to a cloud data-management system for tracking evaluation results for many homes.

In addition, some additional field research on the protocol would be beneficial.

A key limitation of this study is that the relationship between windspeed and house-to-outside pressure variability is based on the data collected for a single home (the FSEC MH Lab home). The fact that wind-induced noise on pressure measurements varied by a factor of two among the four measurement locations for that home alone suggests that wind effects likely vary not just among homes but also as a function of pressure-hose placement. More research is needed on how wind affects pressure measurements for homes of different tightness levels, and how to optimally locate pressure-measurement hoses to minimize wind effects. Such research would also help refine algorithms for dynamically adjusting the pressure-measurement averaging period associated with a smartphone app.

In addition, more field data from applying the protocol in tight homes that employ whole-house exhaust for ventilation would be helpful. The FSEC MH Lab home and the Midwest and Southeast field-evaluated homes were leakier than ideal for implementing the protocol with existing exhaust ventilation: more data from tight homes with higher available exhaust flow would help confirm the efficacy of the protocol.

Finally, if there is a desire to use the protocol in conventional new homes—or in older manufactured homes—development and evaluation of strategies to temporarily enhance the total available exhaust flow would be needed.

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APPENDIX A —DUCT LEAKAGE CALCULATION

This appendix derives the equation for protocol-calculated duct leakage, accounting for the fact that duct leaks combine with envelope leaks during the exhaust-flow measurement but act as exhaust-flow pathways during air handler operation. The Project Team is grateful to Collin Olson of The Energy Conservatory for the development of this equation.

Consider a simple two-zone model of leakage under exhaust-fan and air-handler operation (

Figure 24). Under exhaust operation, the measured flow through the exhaust fan (Q_{exh}) is balanced by leakage through the envelope (Q_{house}) and through duct leaks (Q_{ducts}), with a protocol-measured induced house-to-outside depressurization (P_{exh}), which is also experienced in the duct system. Under air handler operation, there is no exhaust flow and flow through duct leaks is balanced is made up by flow through envelope leaks. Also, during air handler operation, the duct system is pressurized relative to the outdoors (P_{ducts}) and a house-to-outside (P_{AH}) is induced.. Note that duct leaks may have a different flow exponent (n_{ducts}) than the envelope leaks ($n_{envelope}$), and the envelope and ducts each have, unique leakage-area coefficients (C_{env} and C_{ducts}., respectively).

Thus, for exhaust-fan operation:

$$Q_{exh} = Q_{env} + Q_{ducts} \qquad (A1)$$

Using the standard flow-pressure equation, this becomes:

$$Q_{exh} = C_{env}{P_{exh}}^{n_{env}} + C_{ducts}{P_{exh}}^{n_{ducts}} \qquad (A2)$$

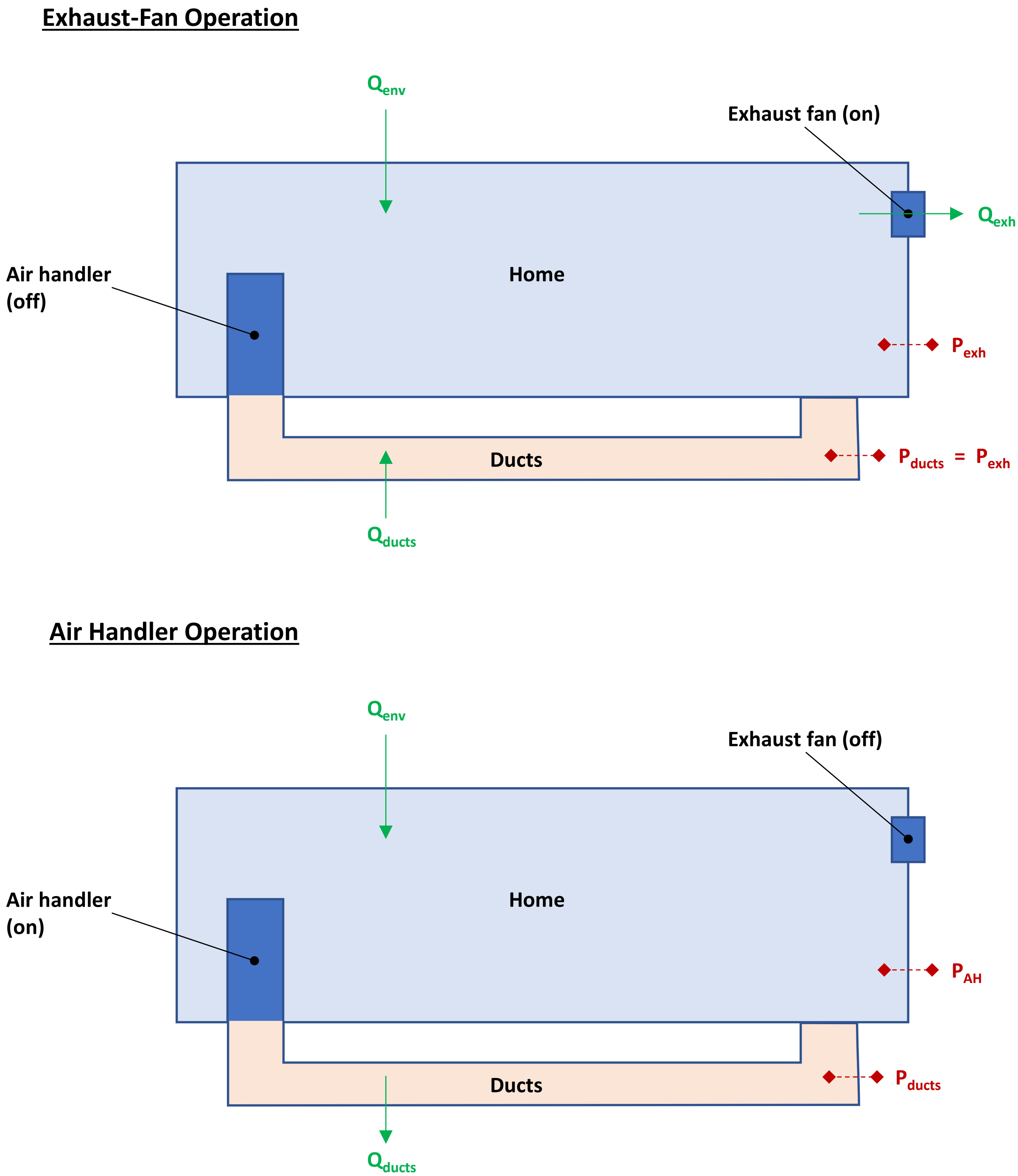
And during air-handler operation,

$$C_{env}{P_{AH}}^{n_{env}} = C_{ducts}{P_{ducts}}^{n_{ducts}} \qquad (A3)$$

Solving Equation A3 for C_{env},

$$C_{env} = \frac{C_{ducts}{P_{ducts}}^{n_{ducts}}}{{P_{AH}}^{n_{env}}} \qquad (A4)$$

Figure 24. Two-zone model of air leakage under exhaust-fan and air-handler operation.



And then substituting Equation A4 into Equation A2 and solving for C_{ducts}:

$$C_{ducts} = \frac{Q_{exh}}{\frac{P_{ducts}{}^{n_{ducts}} P_{exh}{}^{n_{env}}}{P_{AH}{}^{n_{env}}} + P_{exh}{}^{n_{ducts}}} \qquad (A5)$$

Since

$$Q_{ducts} = C_{ducts} P_{ducts}{}^{n_{ducts}} \qquad (A6)$$

duct leakage is then given by:

$$Q_{ducts} = \frac{Q_{exh} P_{ducts}{}^{n_{ducts}}}{\frac{P_{ducts}{}^{n_{ducts}} P_{exh}{}^{n_{env}}}{P_{AH}{}^{n_{env}}} + P_{exh}{}^{n_{ducts}}} \qquad (A7)$$

Equation A7 can be rearranged as:

$$Q_{ducts} = \frac{Q_{exh}}{\left(\frac{P_{exh}}{P_{AH}}\right)^{n_{env}} + \left(\frac{P_{exh}}{P_{ducts}}\right)^{n_{ducts}}} \qquad (A8)$$

Substituting the assumptions that $n_{env} = 0.65$, $n_{ducts} = 0.60$ and $P_{ducts} = 25$ Pa, yields the final duct leakage equation expressed in terms of quantities measured in the protocol:

$$Q_{ducts} = \frac{Q_{exh}}{\left(\frac{P_{exh}}{P_{AH}}\right)^{0.65} + \left(\frac{P_{exh}}{25}\right)^{0.60}} \qquad (A9)$$

APPENDIX B — BLOWER-DOOR AND DELTAQ TEST RESULTS FOR THE FSEC MH LAB

Envelope Leakage Tests

Date	Duct System in Use	Duct Leakage Condition	Test Type *	Obs	Fitted Parameters**		r^2	CFM50
					n	C		
7-Feb-22	Ceiling	Normal	BD -	5	0.631	129.2	0.999	1,524
11-Feb-22	Ceiling	Normal	DQ -	962	0.619	147.1	0.990	1,656
			DQ +	902	0.715	114.4	0.985	1,874
		Added Leak	DQ -	984	0.703	115.6	0.996	1,810
			DQ +	923	0.645	149.9	0.982	1,870
15-Jun-22	Ceiling	Normal	BD -	7	0.628	137.9	0.999	1,611
3-Feb-23	Floor	Normal	DQ -	1,055	0.621	140.5	0.979	1,597
			DQ +	776	0.626	146.2	0.978	1,695
		Added Leak	DQ -	1,171	0.645	145.9	0.967	1,822
			DQ +	824	0.556	213.7	0.964	1,878
14-Feb-23	Ceiling	Normal	DQ -	1,069	0.661	125.8	0.997	1,673
			DQ +	844	0.661	136.2	0.995	1,809
		Added Leak	DQ -	1,125	0.628	149.2	0.997	1,742
			DQ +	883	0.596	180.9	0.984	1,864
21-Mar-23	Floor	Normal	DQ -	1,059	0.619	150.4	0.995	1,695
			DQ +	826	0.636	150.9	0.991	1,816
		Added Leak	DQ -	1,110	0.612	170.4	0.987	1,870
			DQ +	892	0.584	201.9	0.980	1,983

**Test Type Key:

DQ = DeltaQ test (envelope leakage derived from flow and pressure data recorded during air-handler OFF portion of testing)
BD = Multi-point blower-door test
- = depressurization test
+ = pressurization test

**Fitted flow (Q) vs. pressure (P) relationship: $Q = CP^n$

Duct Leakage Tests

Duct Pressurization

Date	Duct System	Duct Condition	Duct Pressure (Pa)	Total Leakage (cfm)	Leakage to Outside (cfm)
07-Feb-22	Ceiling	Normal	+25	146	79
			-25	135	81
		Added Leak	+25	188	130
			-25	186	129
06-Feb-23	Floor	Normal	+25	--	46
		Added Leak	+25	--	167

DeltaQ (operating leakage)

Date	Duct System	Duct Condition	Supply Leakage to Outside		Return Leakage to Outside	
			cfm	(95% conf. int.)	cfm	(95% conf. int.)
11-Feb-22	Ceiling	Normal	40	(13 to 67)	9	(-18 to 36)
		Added Leak	112	(94 to 130)	46	(19 to 74)
03-Feb-23	Floor	Normal	13	(-6 to 31)	32	(9 to 55)
		Added Leak	131	(86 to 176)	76	(17 to 135)
14-Feb-23	Ceiling	Normal	45	(38 to 51)	18	(11 to 24)
		Added Leak	128	(110 to 147)	49	(30 to 67)
21-Mar-23	Floor	Normal	-5	(-28 to 18)	-30	(-54 to -6)
		Added Leak	105	(55 to 156)	24	(-29 to 78)

APPENDIX C — REGRESSION MODELS FOR THE MH LAB HOME

Model 1

Quantile regression model of the median ratio between Simplified-Protocol and blower-door based estimates of envelope leakage (CFM50):

Parameter		Coefficient	Std Error**	t-value
Exhaust flow level* (categorical)	25 cfm	-0.540	0.045	-11.89
	50-75 cfm	-0.261	0.034	-7.57
	100 cfm	-0.151	0.031	-4.89
	200 cfm	-0.068	0.020	-3.34
Windspeed during assessment (mph)		-0.010	0.003	-3.79
Windspeed / Exhaust flow Interaction	25 cfm	-0.035	0.006	-5.93
	50-75 cfm	-0.041	0.007	-5.68
	100 cfm	-0.020	0.009	-2.33
	200 cfm	-0.001	0.032	-0.04
Range-hood operating in background (binary)		-0.190	0.015	-12.83
Model Constant		1.002	0.018	56.32

n=6,730
*300-cfm base level
**bootstrap estimates clustered by date; 1,000 replications

Model 2

Quantile regression model of interquartile range for the ratio between Simplified-Protocol and blower-door based estimates of envelope leakage (CFM50):

Parameter		Coefficient	Std Error**	t-value
Exhaust flow level* (categorical)	25 cfm	0.254	0.065	3.94
	50-75 cfm	0.244	0.049	4.99
	100 cfm	0.129	0.033	3.97
	200 cfm	0.069	0.028	2.45
Windspeed during assessment (mph)		0.022	0.006	3.63
Range-hood operating in background (binary)		-0.081	0.024	-3.40
Model Constant		0.103	0.025	4.07

n=6,730
*300-cfm base level
**bootstrap estimates clustered by date; 1,000 replications

Model 3

Quantile regression model of the median ratio between Simplified-Protocol estimated duct leakage and best estimates of duct leakage (cfm per 100 ft^2 of floor area), where best estimates are the Simplified-Protocol median results (by duct configuration) for 200+ cfm of exhaust flow, range-hood off during evaluation and winds<2.5 mph:

Parameter		Coefficient	Std Error**	t-value
Exhaust flow level* (categorical)	25 cfm	-0.481	0.168	-2.85
	50-75 cfm	-0.193	0.070	-2.75
	100 cfm	-0.220	0.050	-4.40
	200 cfm	-0.064	0.054	-1.19
Windspeed during assessment (mph)		-0.00058	0.0168	-0.03
Windspeed / Exhaust flow Interaction	25 cfm	-0.078	0.026	-2.99
	50-75 cfm	-0.072	0.019	-3.71
	100 cfm	-0.024	0.020	-1.21
	200 cfm	-0.005	0.020	-0.24
Range-hood operating in background (binary)		0.087	0.032	2.75
Model Constant		1.053	0.035	30.40

n=6,729
*300-cfm base level
**bootstrap estimates clustered by date; 1,000 replications

Model 4

Quantile regression model of interquartile range for the ratio between Simplified-Protocol estimated duct leakage and best estimates of duct leakage (cfm per 100 ft^2 of floor area), where best estimates are the Simplified-Protocol median results (by duct configuration) for 200+ cfm of exhaust flow, range-hood off during evaluation and winds<2.5 mph:

Parameter		Coefficient	Std Error**	t-value
Exhaust flow level* (categorical)	25 cfm	-0.099	0.319	-0.31
	50-75 cfm	0.005	0.280	0.02
	100 cfm	0.023	0.253	0.09
	200 cfm	0.113	0.322	0.35
Windspeed during assessment (mph)		0.161	0.031	5.18
Range-hood operating in background (binary)		-0.257	0.054	-4.79
Model Constant		0.325	0.247	1.31

n=6,729
*300-cfm base level
**bootstrap estimates clustered by date; 1,000 replications

APPENDIX D — FIELD EVALUATION HOME DETAILS

Region	ID #	State	Number of sections	Floor Area (ft^2)	Volume (ft^3)	Vent. Type[a]	Date	Envelope Leakage[b] (CFM50)	Duct Leakage (to outdoors)[c] (CFM25)
Southeast	SE00	FL	2	1,620	14,400	P	2/11/22	1,527	79
	SE01	LA	2	1,457	11,656	P	11/1/22	2,137	33
	SE02	LA	1	1,140	9,120	P	11/1/22	1,394	61
	SE03	LA	2	1,620	12,960	P	11/2/22	1,698	13
	SE04	LA	2	1,920	16,320	P	11/2/22	1,912	393
	SE05	LA	1	1,153	9,224	P	10/16/22	1,376	51
	SE06	LA	1	1,153	9,224	P	10/16/22	871	50
Northwest	NW00	WA	3	2,636	21,474	E, P	10/3/21	1,300	126
	NW01	OR	1	891	7,128	E	2/17/22	525	33
	NW02	OR	2	1,512	13,608	E	3/7/22	1,290	45
	NW03	OR	2	1,280	10,880	E, P	3/8/22	910	99
	NW04	OR	2	1,280	11,520	E	3/30/22	525	33
	NW05	OR	2	2,024	17,204	E	4/22/22	900	55
	NW06	OR	2	1,983	17,847	E	6/6/22	980	52
	NW07	OR	2	1,333	11,997	E	3/30/22	560	25
	NW09	OR	2	1,782	15,593	P	8/15/22	1,075	48
	NW10	OR	2	1,680	15,960	E	8/17/22	1,200	100
	NW11	OR	2	1,200	10,800	E	8/17/22	870	85
	NW12	OR	2	2,006	18,054	E	8/17/22	3,006	21
	NW13	OR	2	1,275	10,838	E	8/18/22	1,010	56
	NW14	OR	2	1,512	12,096	E	8/22/22	760	38
	NW15	OR	2	1,296	10,368	E	8/22/22	576	52
	NW16	WA	3	1,920	17,280	E	10/18/22	970	83
	NW17	WA	2	1,600	13,600	E	10/18/22	530	38
	NW18	OR	2	1,793	15,241	E	10/19/22	650	45
	NW19	OR	2	1,430	12,870	E	12/14/22	1,155	122
	NW20	WA	2	1,439	12,016	E	11/14/22	897	64
	NW21	WA	2	1,439	12,016	E	11/15/22	955	81
Midwest	MW01	WI	2	960	8,640	P	11/2/22	1,056	77
	MW02	WI	2	1,173	10,557	P	11/2/22	1,003	107
	MW03	WI	2	1,493	13,437	P	11/2/22	1,082	90
	MW04	WI	2	1,227	11,043	P	11/2/22	1,425	106
	MW05	WI	2	1,280	11,520	P	11/2/22	1,066	59
	MW06	WI	1	1,173	10,557	P	11/3/22	922	126
	MW07	WI	1	1,173	10,557	P	11/3/22	835	85

a. whole-home ventilation type: E = whole-house exhaust fan; P = POS (ducted positive pressure system)
b. Blower-door test, CFM at 50 Pascals of depressurization
c. Duct pressurization test, CFM at 25 Pascals of pressurization, with zero pressure difference between house and ducts

APPENDIX E — STOCHASTIC SIMULATION MODEL

This appendix describes a stochastic simulation model of the Simplified Protocol in the presence variation in house-to-outside pressure-measurement measurements to due wind noise and uncertainty in flow exponents associated with envelope and duct leakage.

Consider the Simplified Protocol calculation for envelope leakage:

$$Q_{env,50} = Q_{exh}(50/P_{exh,adj})^{0.65} \qquad (E1)$$

where,

> Q50 is the protocol-estimated envelope leakage (cfm at 50 Pascals);
>
> Qexh is the measured total exhaust flow; and,
>
> Pexh is the baseline-adjusted house-to-outside depressurization during exhaust-fan operation.

The measured net house-to-outside depressurization above can be conceptually decomposed into:

$$P_{exh,adj} = (P_{exh} + P_{s1} + P_{w1}) - (P_{s0} + P_{w0}) \qquad (E2)$$

where,

> P_{exh} is the underlying true depressurization effect of exhaust operation;
>
> $P_{s0,1}$ is stack-effect pressure during the baseline measurement (Time 0) and during exhaust operation (Time 1); and,
>
> $P_{w0,1}$ is wind-induced pressure at Times 0 and 1.

Rearranging—and assuming that the stack-effect pressure does not change appreciably between the measurements—it can be seen that the exhaust depressurization measurement used in the protocol is a combination of the true exhaust depressurization effect plus any change in wind pressure between measurements:

$$P_{exh,adj} = P_{exh} + \Delta P_{w1-0} \qquad (E3)$$

where

$$\Delta P_{w1-0} = P_{w1} - P_{w0} \qquad (E4)$$

is the change in wind-induced pressure between the two protocol measurements. These moment-to-moment changes in wind-induced pressures introduce error into the calculated envelope leakage because the calculation incorrectly assumes that all pressure effects unrelated to the actual exhaust-induced effect are netted out when the baseline reading is subtracted from the exhaust-operation reading.

The stochastic simulation models the effect of these errors on the resulting calculated leakage values using recorded changes in baseline pressure measured during the FSEC MH Lab home evaluation. The data collected at the MH Lab home allow for characterizing wind-induced pressure changes over intervals between readings from 5 to 30 minutes, and for measurement averaging periods from 5 to 30 seconds. All values are the simple signed difference between two measurements, both using the same averaging period.

The results of this analysis show that averaging the (natively 1-second) pressure readings over longer periods reduces the variability in moment-to-moment changes in baseline pressure, especially in windy conditions (Figure 25), but the interval between measurements does not have a strong impact on baseline variability (Figure 26). Within 2.5-mph windspeed bins, the distribution of baseline pressure changes appears to be approximately normally (Gaussian) distributed (Figure 27), with a standard deviation that increases linearly with windspeed (Figure 28).[15]

[15] As Figure 27 shows, the distribution is actually somewhat leptokurtic (i.e. "peakier" than a true normal distribution). This makes the simplifying assumption of normality somewhat conservative in terms of the impact of wind noise on calculated leakage.

Figure 25. Distribution of baseline house-to-outside pressure difference at the FSEC MH Lab home, by averaging period and windspeed.

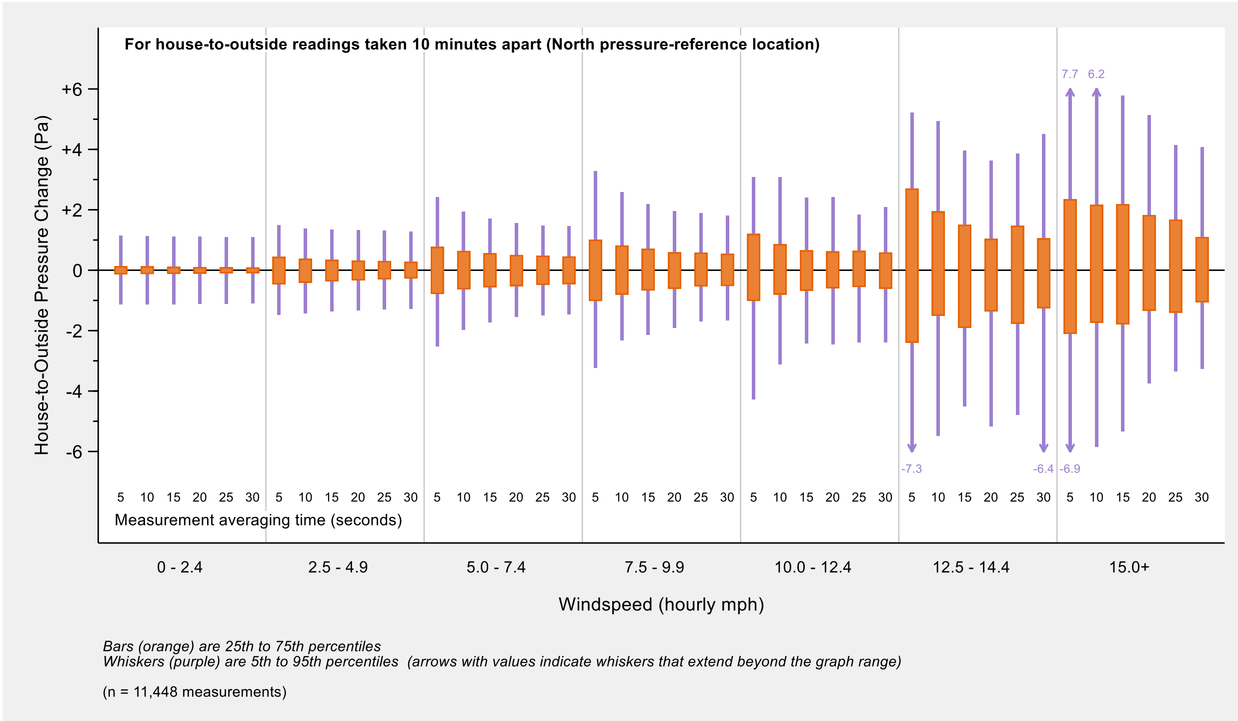


Figure 26. Distribution of baseline house-to-outside pressure variability at the FSEC MH Lab home, by measurement interval and windspeed.

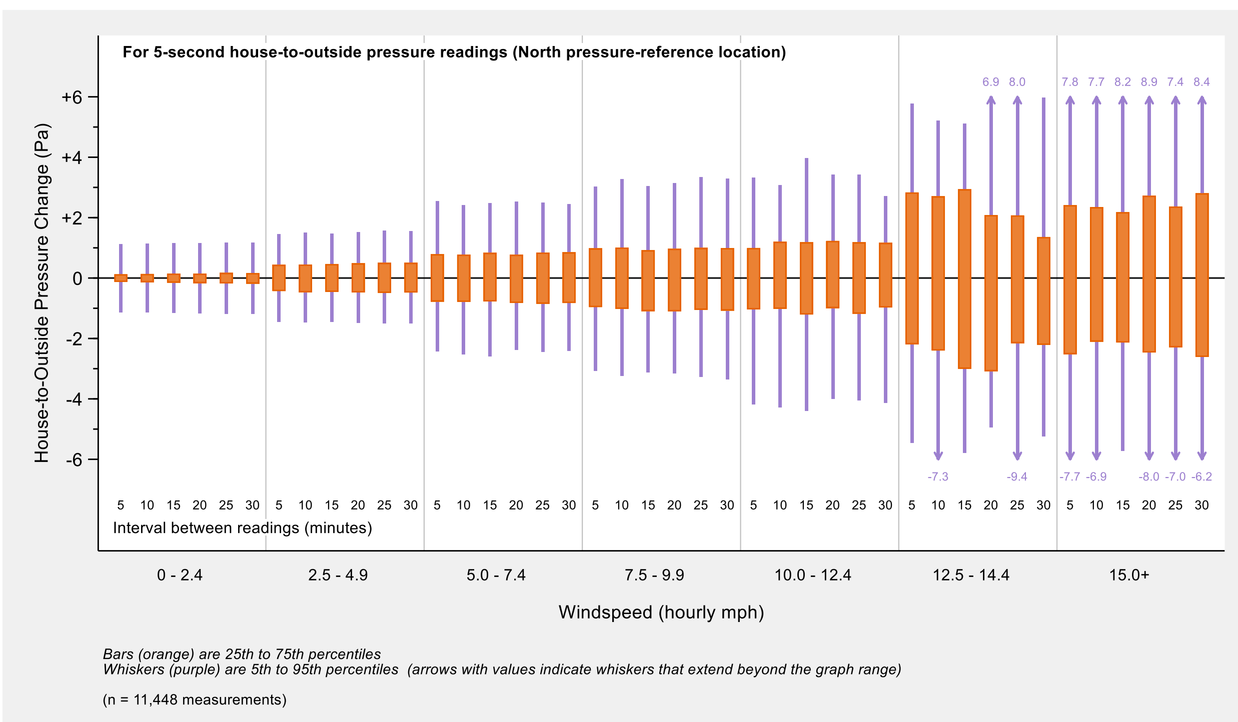


Figure 27. Distribution of change in house-to-outside pressure for winds between 2.5 and 5.0 mph, by pressure tap.

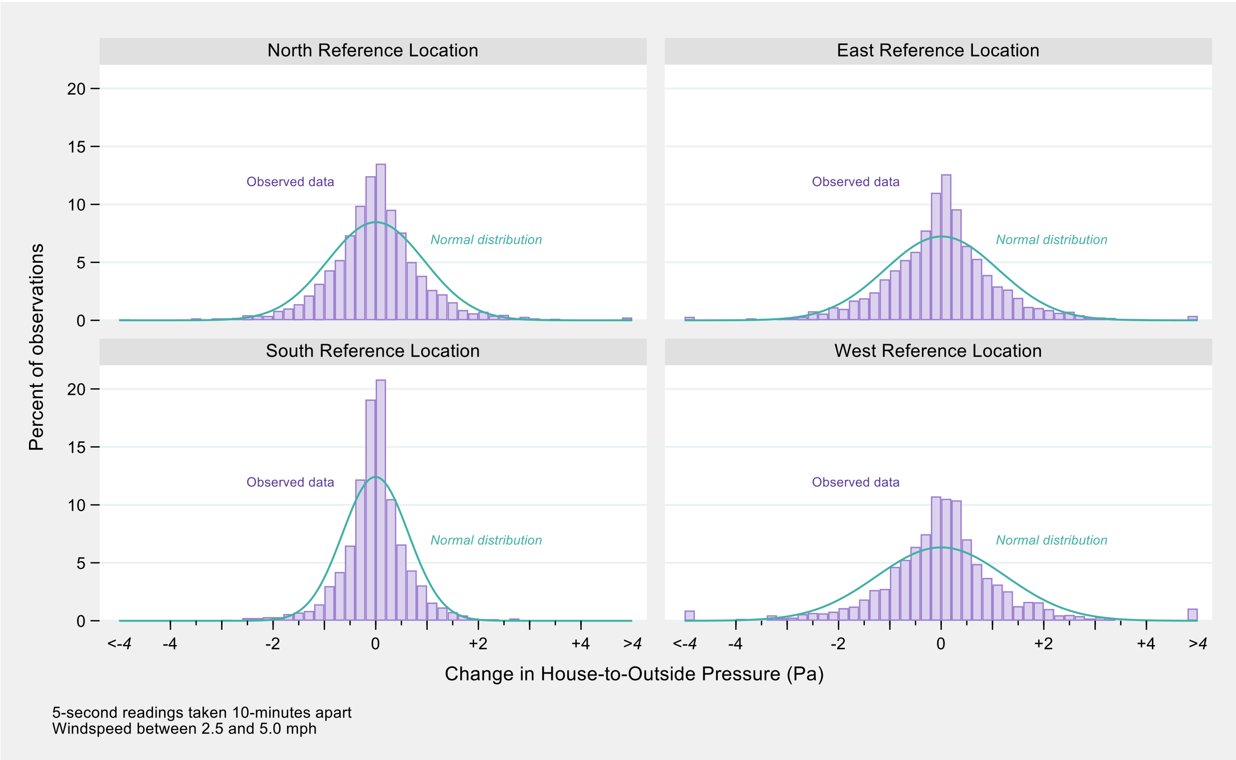
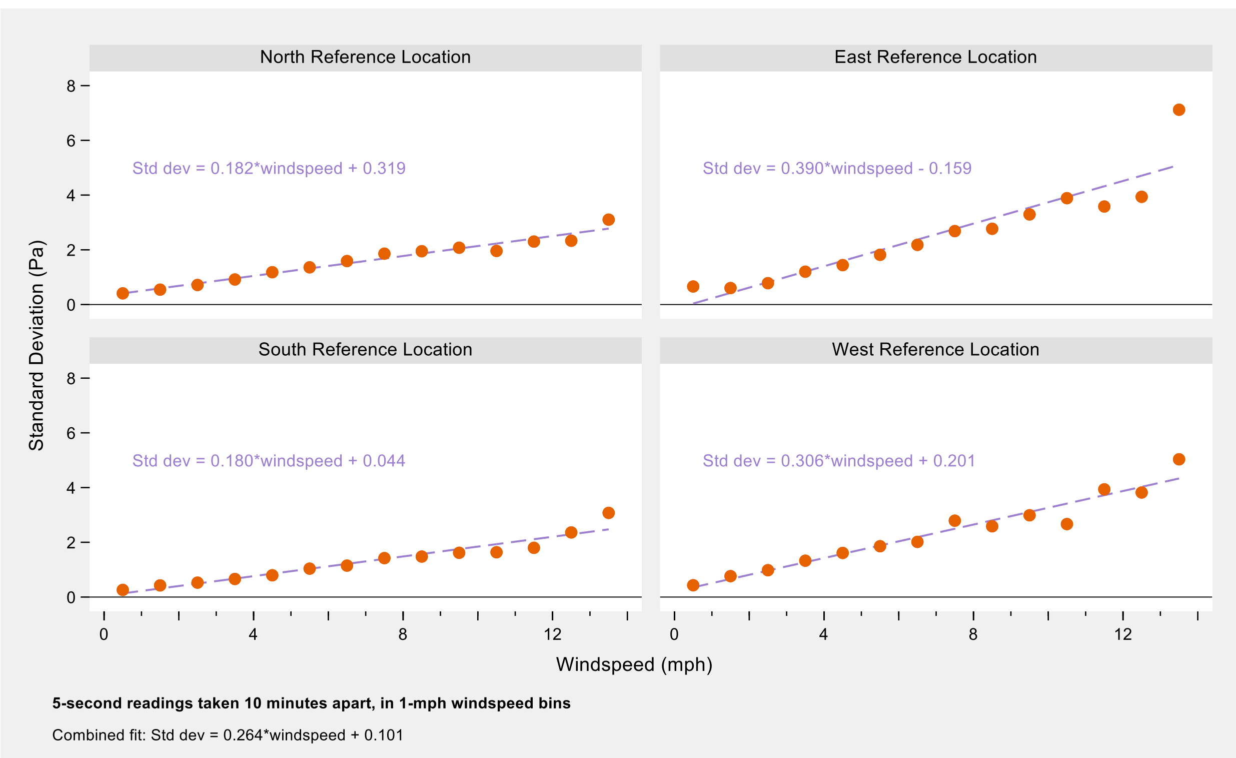


Figure 28. Standard deviation of change in house-to-outside pressure versus windspeed, by pressure tap.



The stochastic model starts with a series of home- and assessment-related input parameters:

Q_{50} — Blower-door based air leakage (CFM50)

Q_{ducts}— Operating duct leakage (cfm)

n_{env} — the envelope-leakage flow exponent

n_{ducts} — the duct-leakage flow exponent

P_{ducts} — effective average duct operating pressure at duct leaks (Pa)

Q_{exh} —Level of exhaust flow during assessment (cfm)

W — Windspeed at the time of assessment (mph)

Note that while the envelope flow exponent n can be determined directly from blower-door testing, for the purposes here, it is more appropriately modeled as an unknown value that is allowed to vary uniformly between 0.6 and 0.7, or $\boldsymbol{U}(0.6, 0.7)$. Similarly, the duct-leakage exponent is modeled as a $\boldsymbol{U}(0.55,0.65)$ distribution, reflecting the fact that duct leaks tend to be centered around a somewhat lower exponent value of 0.60.

The duct operating pressure (P_{ducts}) is the average pressure across duct leaks. This can vary substantially, depending on the extent to which the duct leaks occur close to the air handler where the system pressure is high, towards the end of the duct system where the pressure is low, or somewhere between these extremes. For the purposes here, P_{ducts} is modeled as a $\boldsymbol{U}(10,40)$ pascal distribution.

The model further specifies that the change in wind pressure between two house-to-outside measurements as a function of windspeed corresponds to:

$$\Delta P_{W1-0} = \boldsymbol{N}(0, mW + b) \qquad (E5)$$

where $\boldsymbol{N}$(mean, std. dev.) denotes a normal distribution with a mean of zero and a standard deviation related to windspeed (W) with slope factor m and constant b. Based loosely on the empirical data above, m is set to 0.25 and b is set to 0.10 for the simulation.

For specified fixed values of Q_{50}, Q_{ducts}, Q_{exh} and W, the model execution proceeds by generating 10,000 cases and for each:

1. Generate random flow exponents, $n_{env} = \boldsymbol{U}(0.6, 0.7)$ and $n_{duct} = \boldsymbol{U}(0.55, 0.65)$
2. Generate a random value for $P_{ducts} = \boldsymbol{U}(10, 40)$
3. Derive the envelope leakage area, C_{env}, as:

$$\boldsymbol{C_{env}} = \frac{\boldsymbol{Q_{50} - Q_{ducts}(\frac{50}{P_{ducts}})^{n_{ducts}}}}{\boldsymbol{50^{n_{env}}}} \qquad (\boldsymbol{E6})$$

4. Derive the leakage area, C_{ducts}, for the duct leaks as:

$$\boldsymbol{C_{ducts}} = \frac{\boldsymbol{Q_{ducts}}}{\boldsymbol{P_{ducts}}^{\boldsymbol{n_{ducts}}}} \qquad (\boldsymbol{E7})$$

5. Solve for the true induced house-to-outside depressurization from exhaust operation $P_{act(exh)}$ by using 10 bisection iterations to solve for $P_{act(exh)}$ such that:

$$Q_{exh} - C_{env}(P_{act(exh)})^{n_{env}} - C_{ducts}(P_{act(exh)})^{n_{ducts}} = 0 \qquad (E8)$$

6. Solve for the true induced house-to-outside depressurization from air-handler operation $P_{act(AH)}$ as:

$$\boldsymbol{P_{act(AH)}} = \boldsymbol{e}^{[(\ln(\boldsymbol{Q_{ducts}}) - \ln(\boldsymbol{C_{env}}))/\boldsymbol{n_{env}}]} \qquad (\boldsymbol{E9})$$

7. Generate three random wind pressures corresponding to wind pressure during the baseline house-to-outside measurement (at time t=0), the exhaust-flow measurement (t=1) and the air-handler measurement (t=2):

$$\boldsymbol{P_{Wt}} = \boldsymbol{N(0, (0.1 + 0.25W)/\sqrt{2})} \qquad (\boldsymbol{E10})$$

(Note: the √2 adjustment is needed so that the *change* in wind pressure between measurements in the subsequent calculations corresponds to the empirical **N**(0,0.1+0.25*W*) relationship observed in the FSEC MH Lab home data.)

8. Calculate the observed net house-to-outside pressure during exhaust operation as:

$$P_{obs(exh)} = P_{act(exh)} + (P_{W1} - P_{W0}) \qquad (E11)$$

9. Similarly, calculate the observed net house-to-outside pressure during air-handler operation as:

$$P_{obs(AH)} = P_{act(AH)} + (P_{W2} - P_{W0}) \tag{E12}$$

10. Calculate the protocol-estimated envelope leakage as:

$$\boldsymbol{Q_{50,calculated} = Q_{exh} * \left(\frac{50}{|P_{obs(exh)}|}\right)^{0.65}} \tag{E13}$$

where $Q_{50,\ calculated}$ is expressed as a negative value if $P_{obs(exh)}$ indicates pressurization.

11. Get the protocol-calculated duct leakage as:

$$\boldsymbol{Q_{ducts,calculated} = \frac{Q_{exh}}{\left(\frac{|P_{obs(exh)}|}{|P_{obs(AH)}|}\right)^{0.65} + \left(\frac{|P_{obs(exh)}|}{25}\right)^{0.60}}} \tag{E14}$$

where $Q_{ducts,\ calculated}$ is expressed as a negative value if $P_{obs(exh)}$ or $P_{obs(AH)}$ indicate pressurization.

The resulting distribution of calculated envelope and duct leakage values can then be examined in relation to the starting values of actual leakage for any level of exhaust flow and wind speed. Figure 29 shows example distributions for two levels of envelope leakage at various exhaust-flow levels in moderate winds (with envelope leakage here expressed in ACH50 terms assuming a typical double-wide conditioned volume of 12,500 ft^3. At one extreme, the results for a tight home (4 ACH50) with high exhaust flow (400 cfm) has a very narrow range of protocol-calculated leakage centered around the true leakage rate. At the other extreme, a loose home (8 ACH50) with low exhaust flow (50 cfm) shows a much wider distribution of calculated leakage and a considerable low bias for the median protocol-calculated ACH50.

The bi-modal nature of some of the plots may seem surprising. It is, however, a natural consequence of the fact that the modeled wind noise appears in the *denominator* of the envelope-leakage calculation. As the exhaust-operation depressurization signal declines toward zero due to the combined effects of a leaky envelope and/or low exhaust flow, the calculated envelope leakage increasingly resembles a reciprocal normal distribution, which is characterized by very long tails and a gap around the zero value (Figure 30).

When run with known parameters for the FSEC MH Lab home, the model does a reasonable job of replicating the observed envelope-leakage calculated values from the automated evaluation (Figure 31). It produces wider estimates of the interquartile range than the observed data would suggest for intermediate exhaust flows, but otherwise does a good job of replicating the median result as well as the 5th and 95th percentiles. The tails of the distribution are especially important for establishing confidence intervals for protocol-calculated values under specified conditions.

Figure 29. Modeled distribution of protocol-calculated envelope leakage for actual leakage of 4 and 8 ACH50 at selected exhaust flow levels.

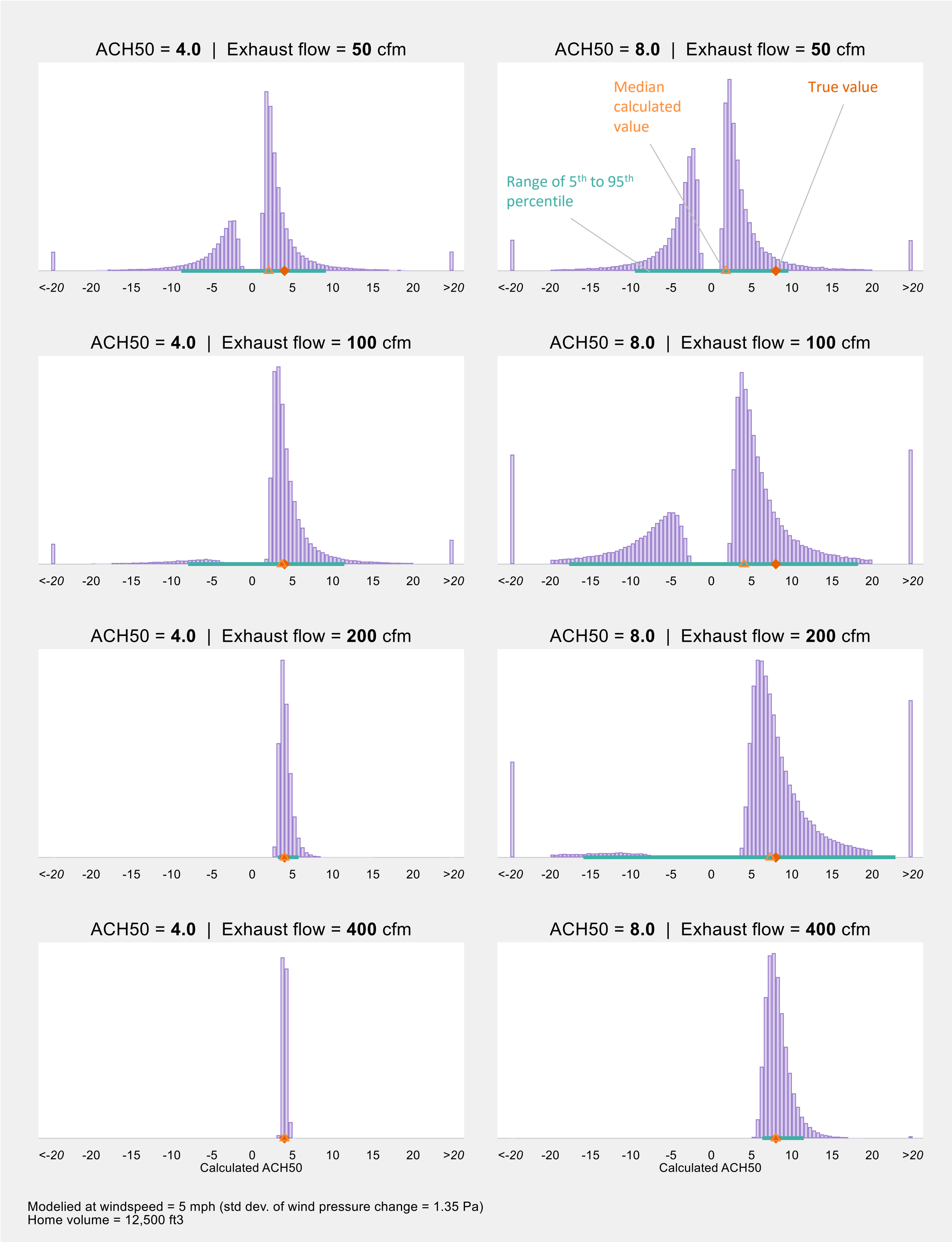


Figure 30. Normal and inverted-normal distributions with mean = 0 and standard deviation = 1.

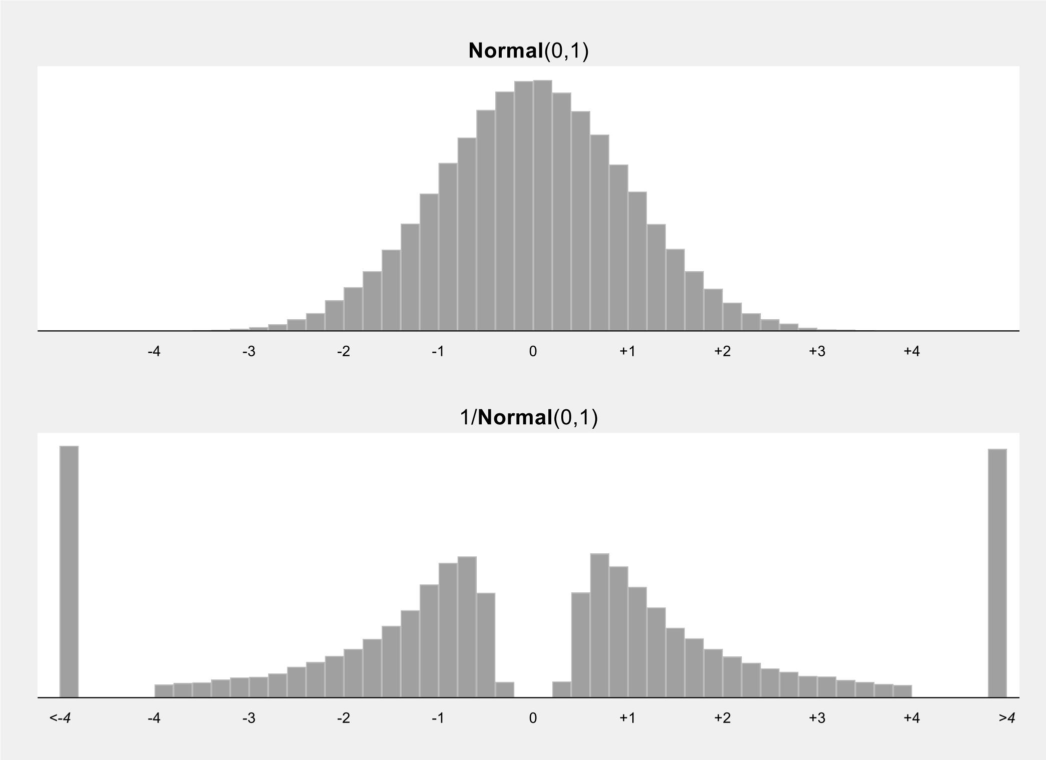
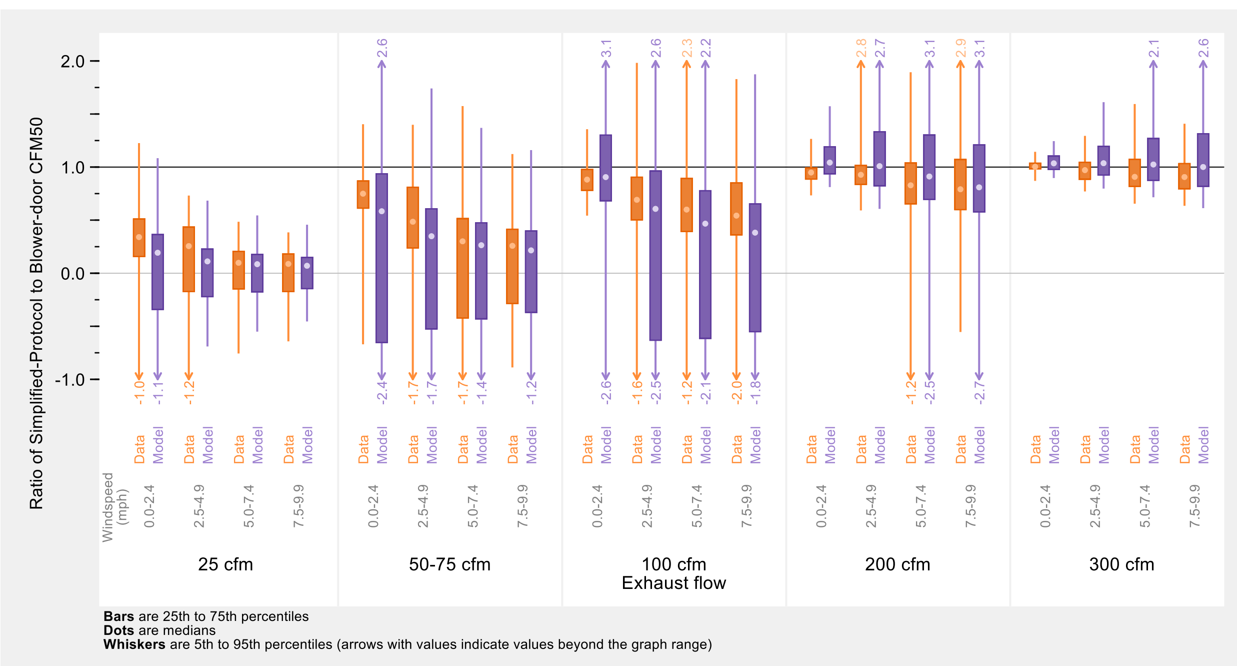


Figure 31. Comparison of empirical data and stochastic model for the FSEC MH Lab home.



In practice, negative calculated values of envelope leakage would be rejected and the assessment re-run. This eliminates the lefthand side of the bi-model distributions seen in Figure 29 and reduces overall evaluation variability, though at the expense of a high assessment rejection rate under higher envelope leakage and lower exhaust flow (Figure 32). At the extremes, half of all assessments may be rejected.

The stochastic model can be used to calculate confidence intervals for protocol-calculated leakage estimates at any confidence level *p*. This is done by generating the probability distribution of protocol-calculated leakage across a range of actual leakage rates, then finding the highest and lowest values of actual leakage that leave *p*/2 proportion of the distribution above or below the protocol-calculated value in the corresponding tails of the actual-leakage distribution.

Duct leakage confidence intervals are conditional on the calculated envelope leakage rate; that is, probability distributions for calculated envelope and duct leakage are generated across many combinations of specified actual envelope and duct leakage levels, and the confidence intervals are calculated based on the distribution of actual duct leakage for given levels of calculated envelope and duct leakage (under specified wind and exhaust-flow conditions).

Confidence intervals for the more qualitative version of the protocol that does not include measuring exhaust flow are based on the probability distribution of actual leakage for given simulated observed depressurization levels.

In all cases, confidence intervals are based on simulated valid results: i.e., calculated negative leakage rates are not included.

The results here are derived from the simulated probability distributions of protocol-calculated leakage for slightly more than 1 million combinations of wind, exhaust flow, actual envelope leakage and actual duct leakage, as follows:

- 4 windspeed levels: 0, 1, 5 and 10 mph[16];
- 15 exhaust-flow levels: 50 to 400 cfm, in 25 cfm increments
- 231 envelope-leakage levels: 200 to 2,500 CFM50, in 10 CFM50 increments
- 76 duct-leakage levels: 0 to 750 cfm, in 10 cfm increments

Figure 33 through Figure 43 on the follow pages show selected confidence intervals for protocol-calculated envelope and duct leak from the stochastic model, both for the case where exhaust flow is measured and where exhaust flow is unmeasured but the rated flow is known.

Note again that results at stated windspeeds are based on data from the FSEC MH Lab home, and the relationship windspeed and variability in house-to-outside pressure will likely vary among homes. Also, these confidence intervals do not include additional sources of uncertainty such as changes in the magnitude of the flow exponent or leakage area as a function of the level of flow or complex interactions among stack effects, wind-induced leakage, and exhaust-induced flow.

[16] The 0-mph wind scenario eliminates all wind effects to allow examination of the uncertainty due solely to exponent and duct pressure uncertainty.

Figure 32. Modeled distribution of protocol-calculated envelope leakage for actual leakage of 4 and 8 ACH50, at selected exhaust flows, with rejection of calculated ACH50<0.

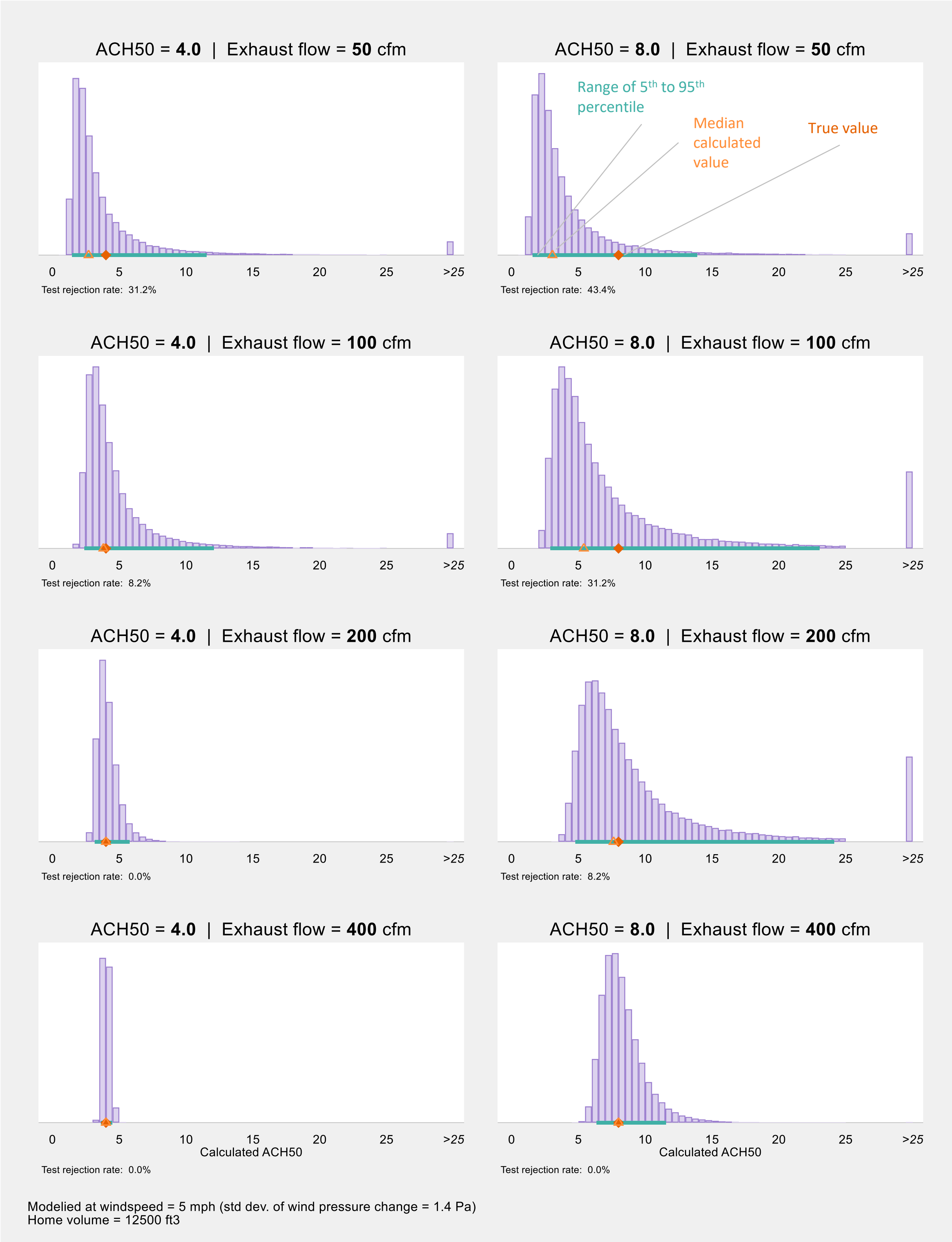


Figure 33. Confidence intervals for protocol-calculated envelope leakage with measured exhaust flow, no wind effects.

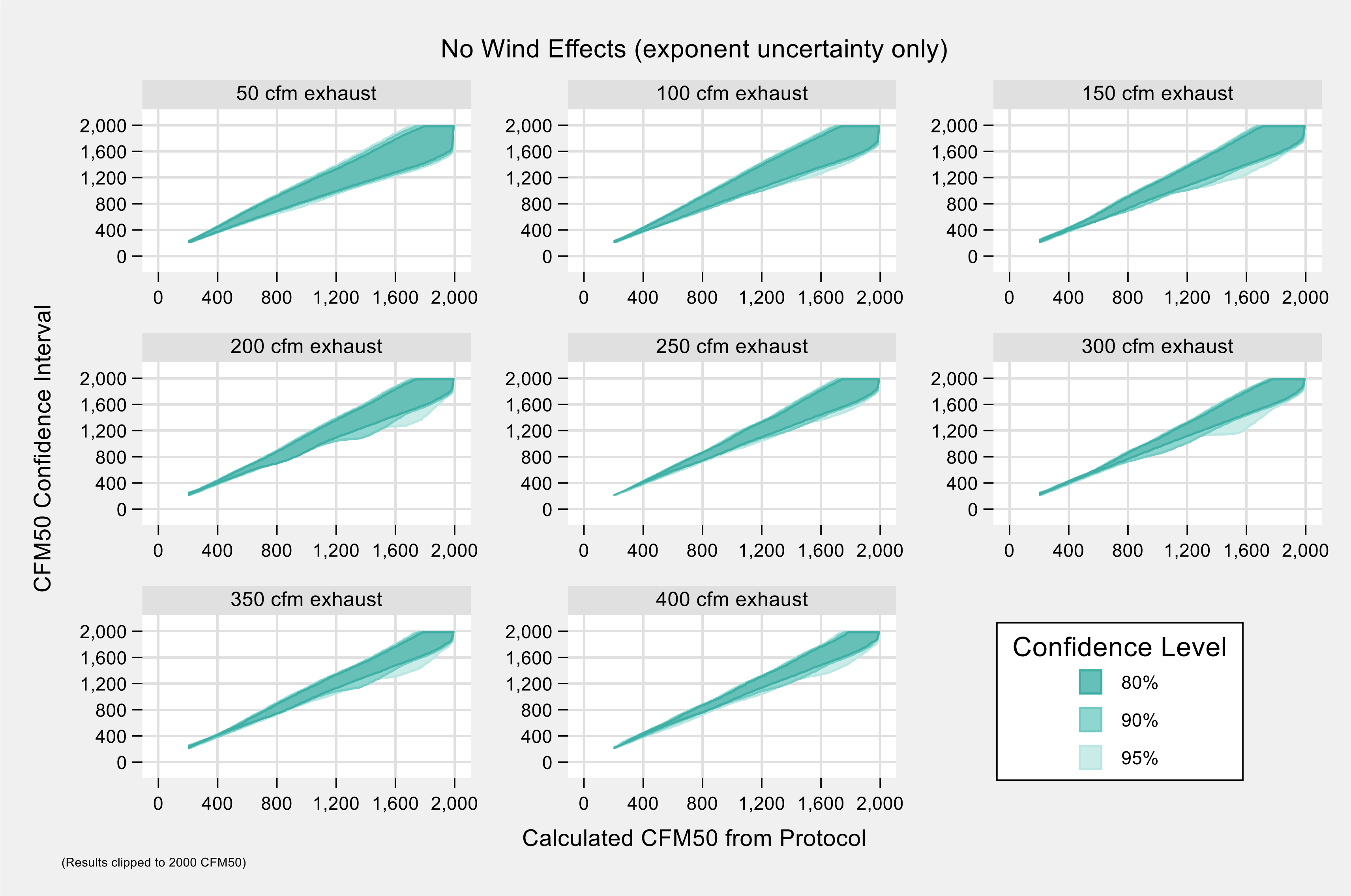


Figure 34. Confidence intervals for protocol-calculated envelope leakage with measured exhaust flow, 1-mph wind.

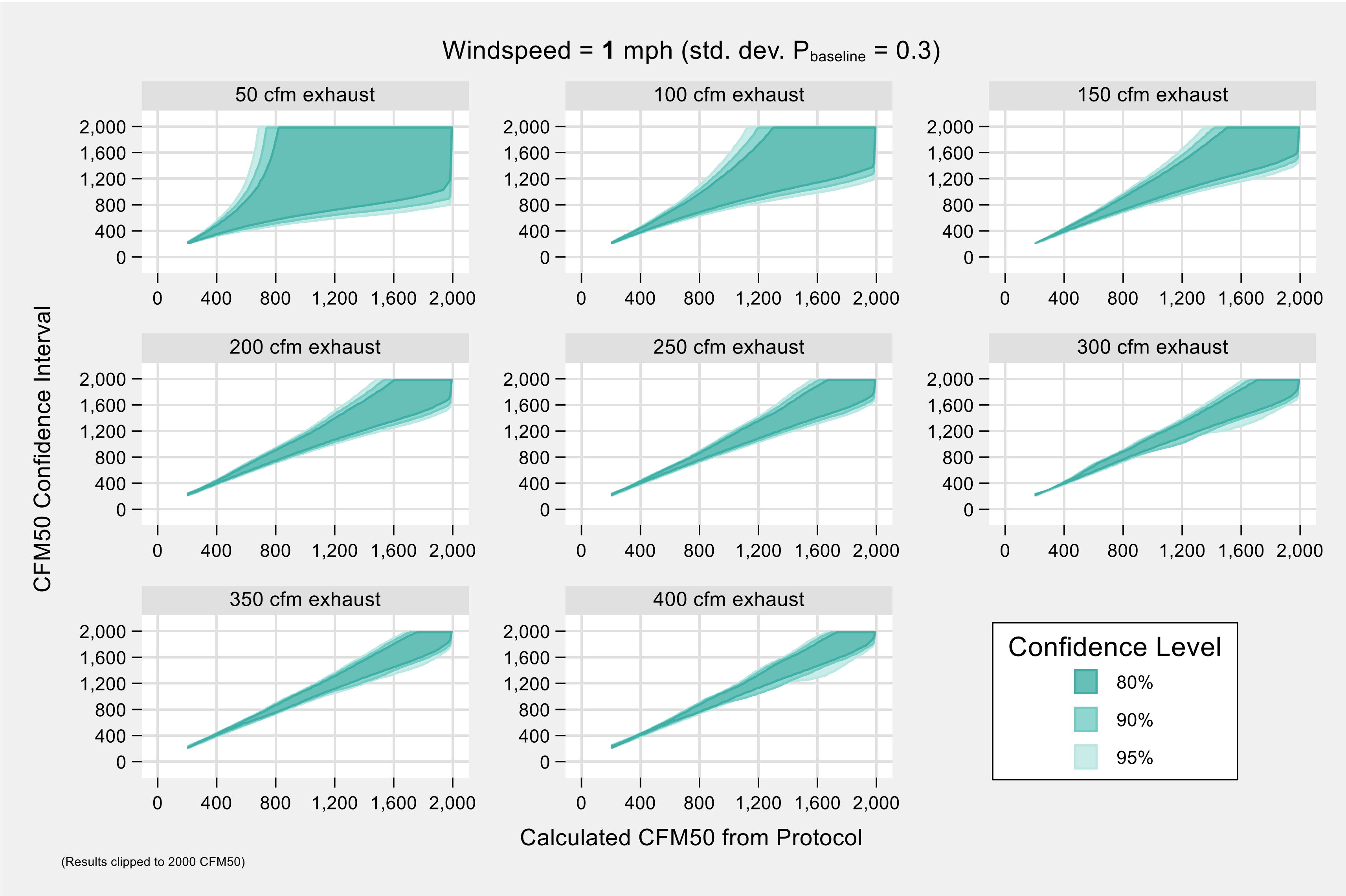


Figure 35. Confidence intervals for protocol-calculated envelope leakage with measured exhaust flow, 5-mph wind.

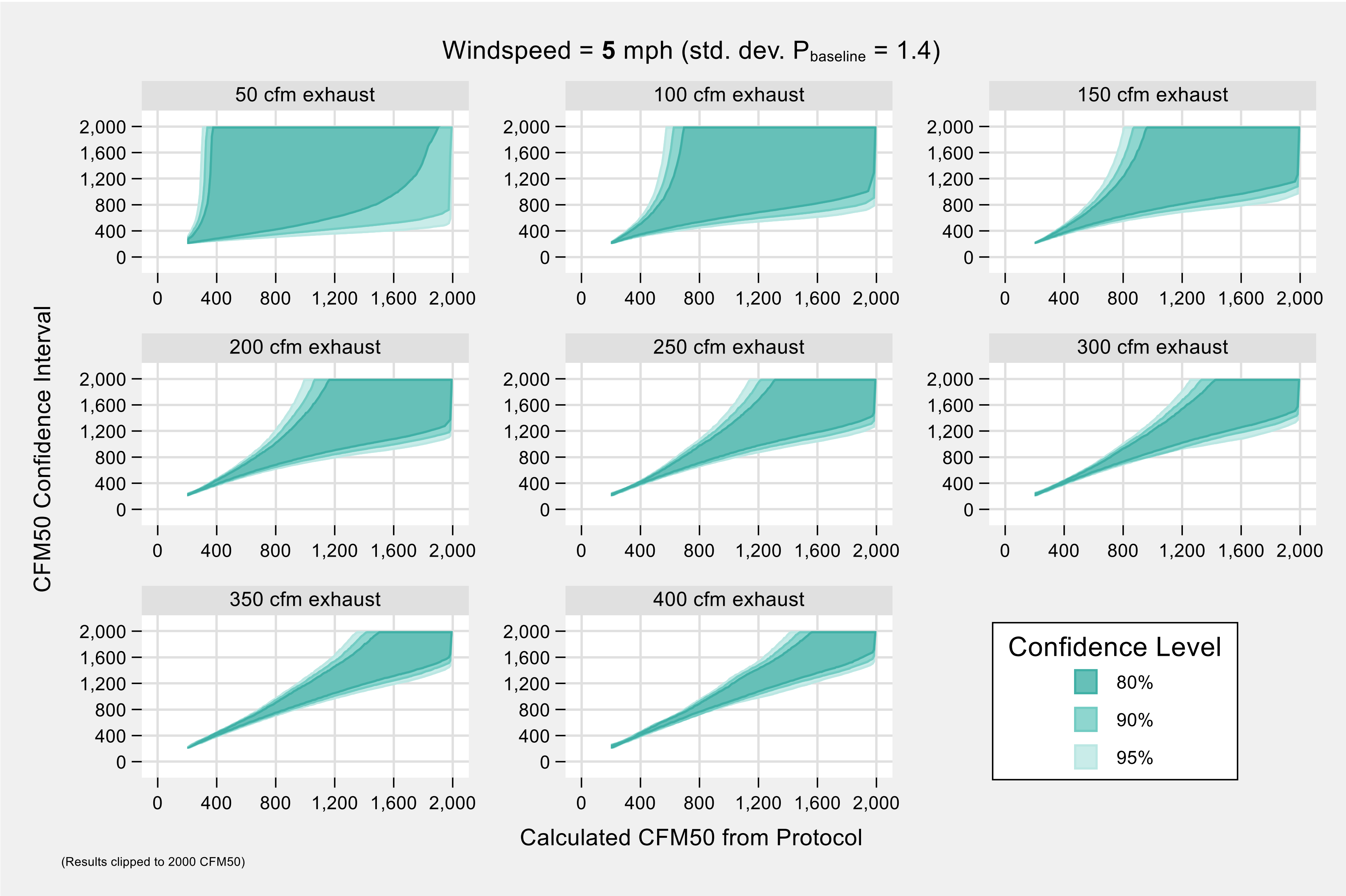


Figure 36. Confidence intervals for protocol-calculated envelope leakage with measured exhaust flow, 10-mph wind.

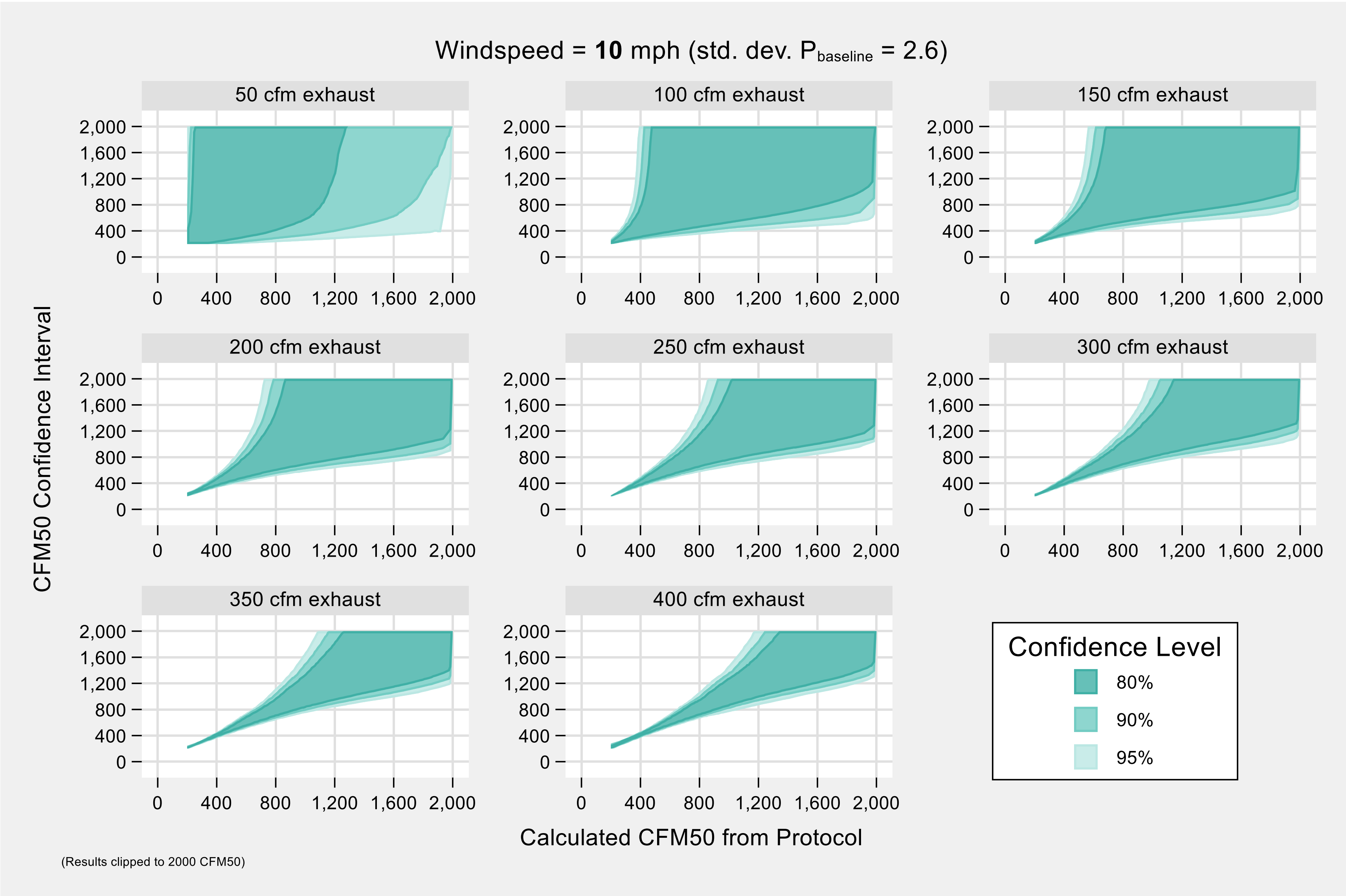


Figure 37. Confidence intervals for protocol-calculated envelope leakage based on observed house depressurization and rated (but unmeasured) exhaust flow, 1-mph wind.

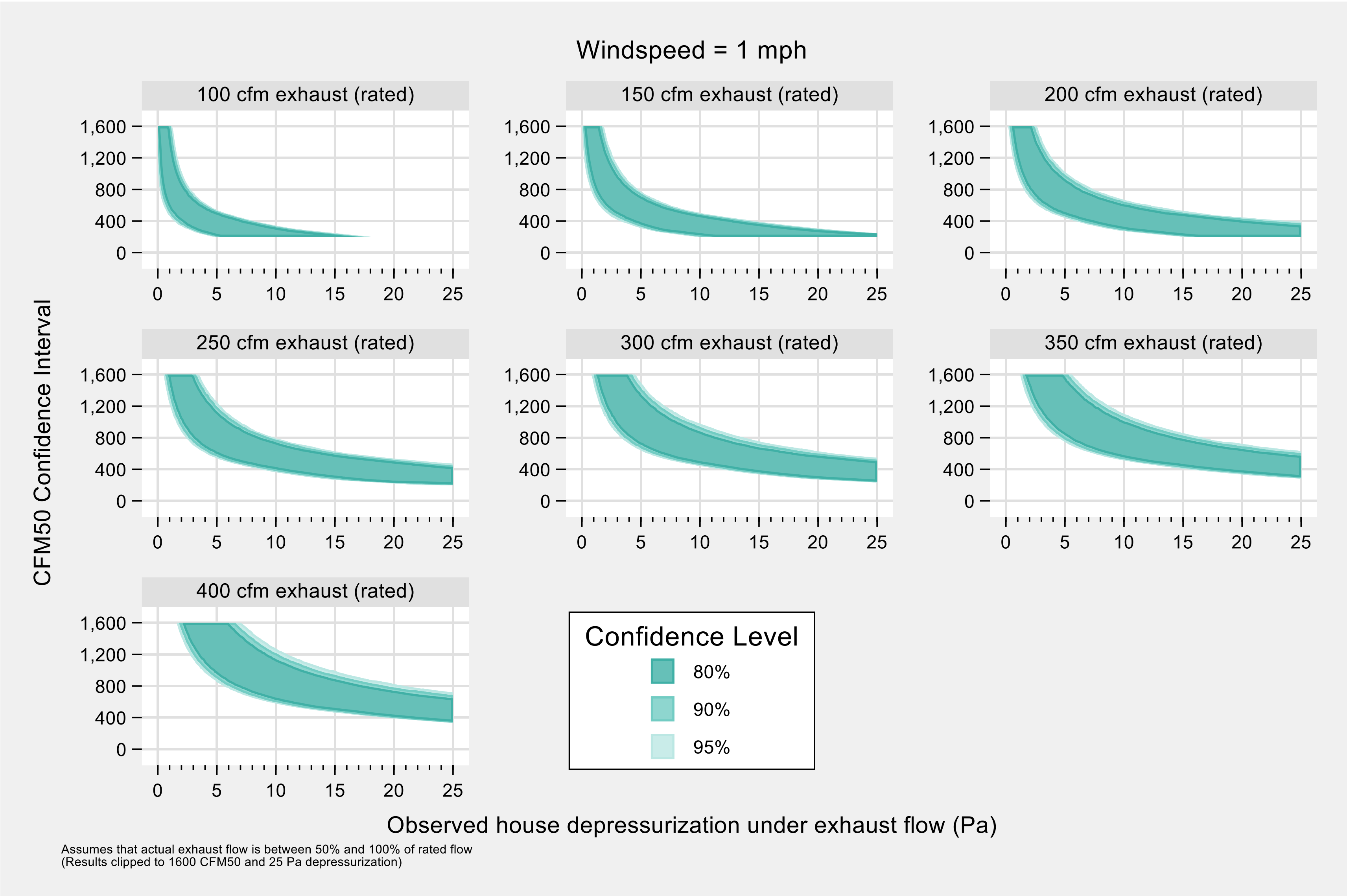


Figure 38. Confidence intervals for protocol-calculated envelope leakage based on observed house depressurization and rated (but unmeasured) exhaust flow, 5-mph wind.

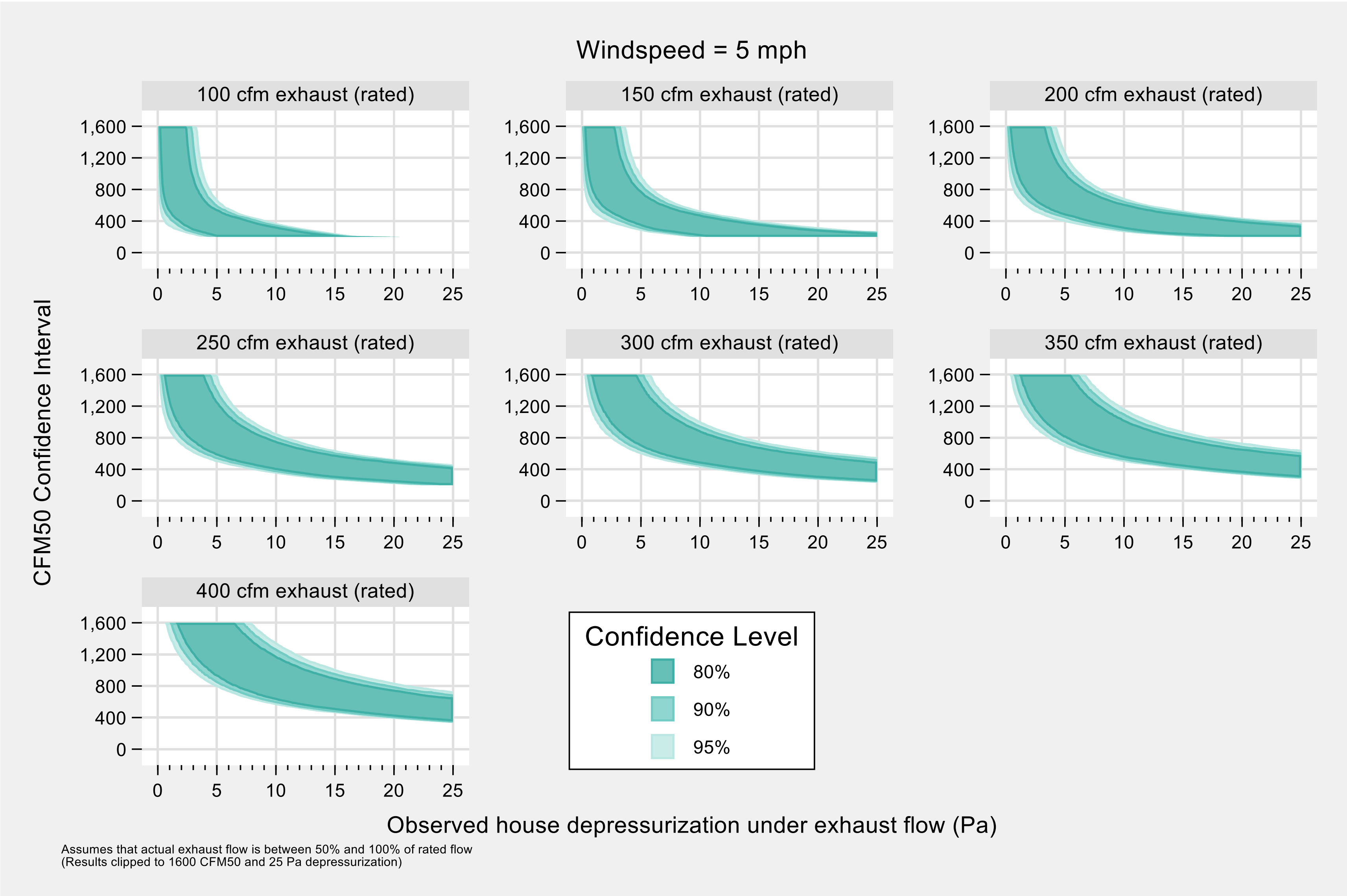


Figure 39. Confidence intervals for protocol-calculated envelope leakage based on observed house depressurization and rated (but unmeasured) exhaust flow, 10-mph wind.

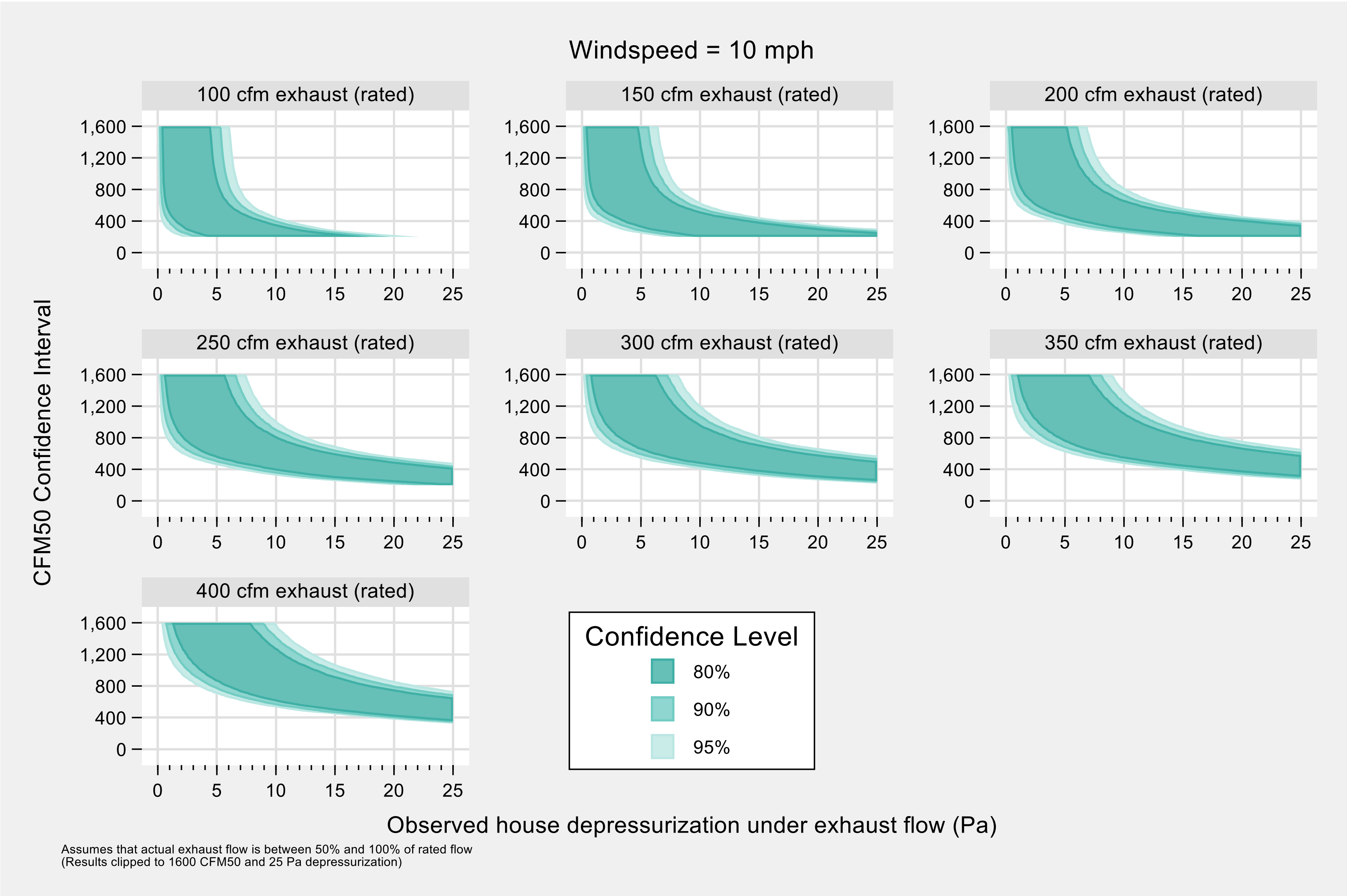


Figure 40. Confidence intervals for protocol-calculated duct leakage with measured exhaust flow, for selected exhaust-flow and protocol-calculated envelope leakage levels, 1-mph wind.

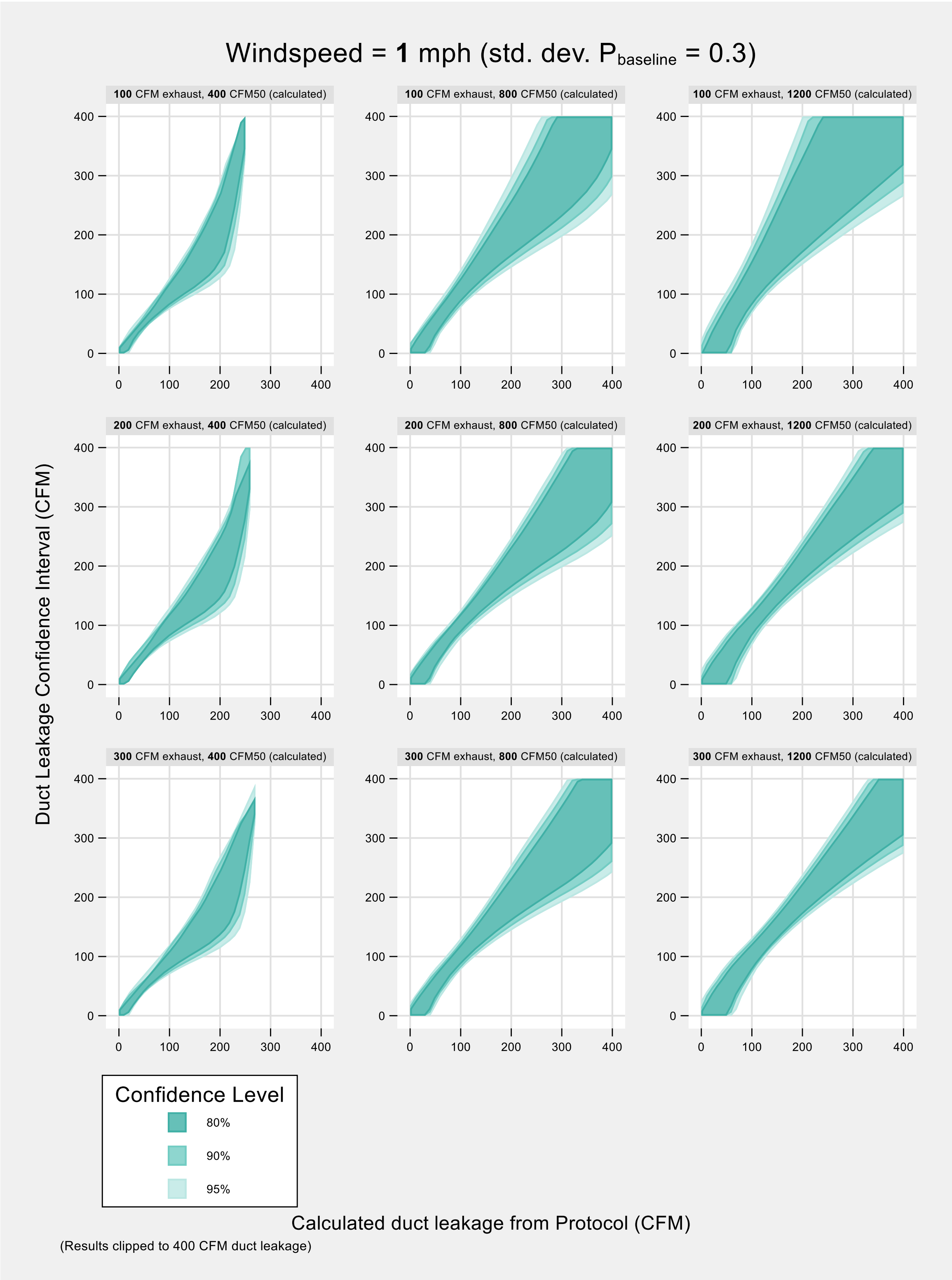


Figure 41. Confidence intervals for protocol-calculated duct leakage with measured exhaust flow, for selected exhaust-flow and protocol-calculated envelope leakage levels, 5-mph wind.

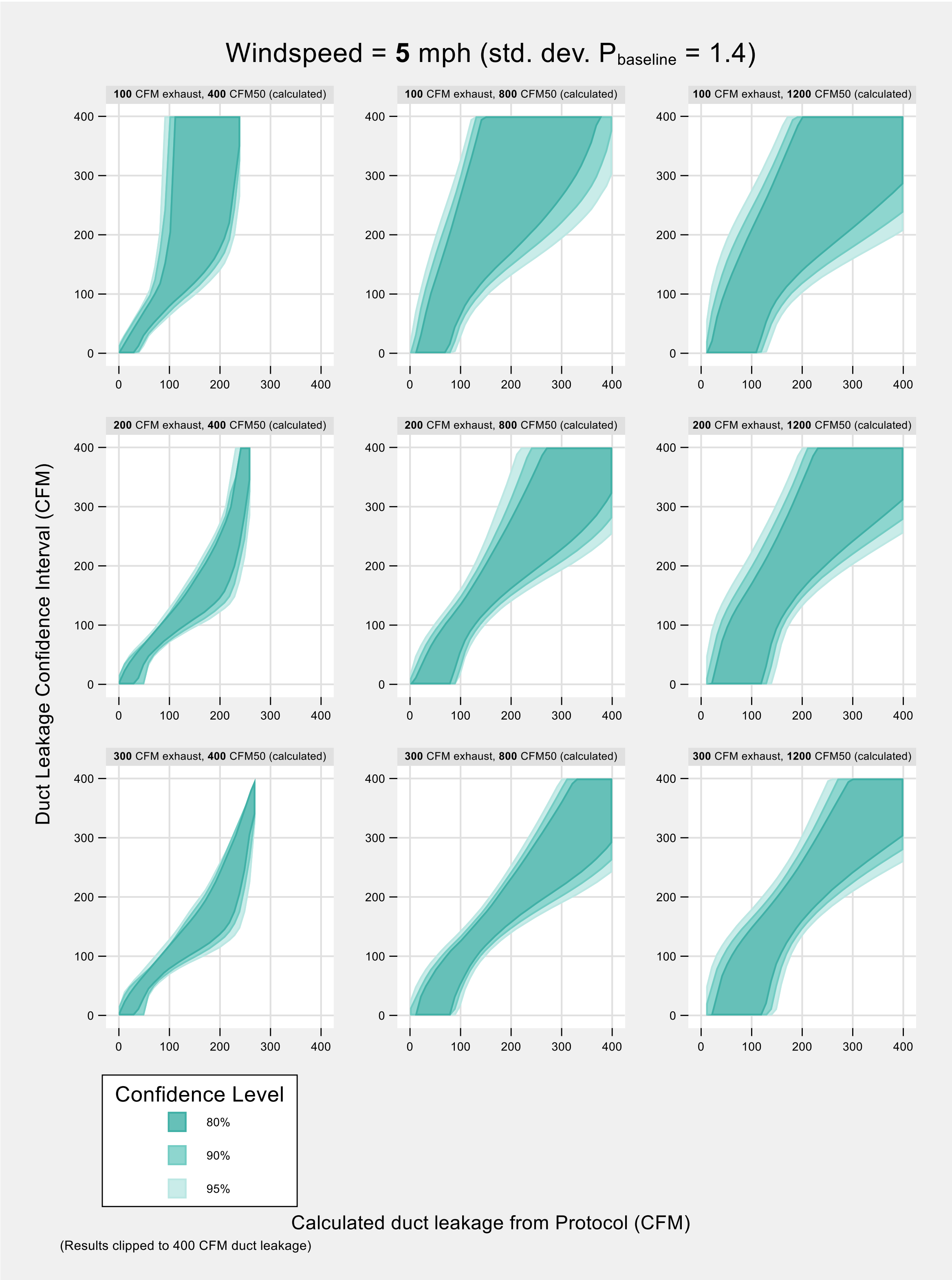


Figure 42. Confidence intervals for protocol-calculated duct leakage with measured exhaust flow, for selected exhaust-flow and protocol-calculated envelope leakage levels, 10-mph wind.

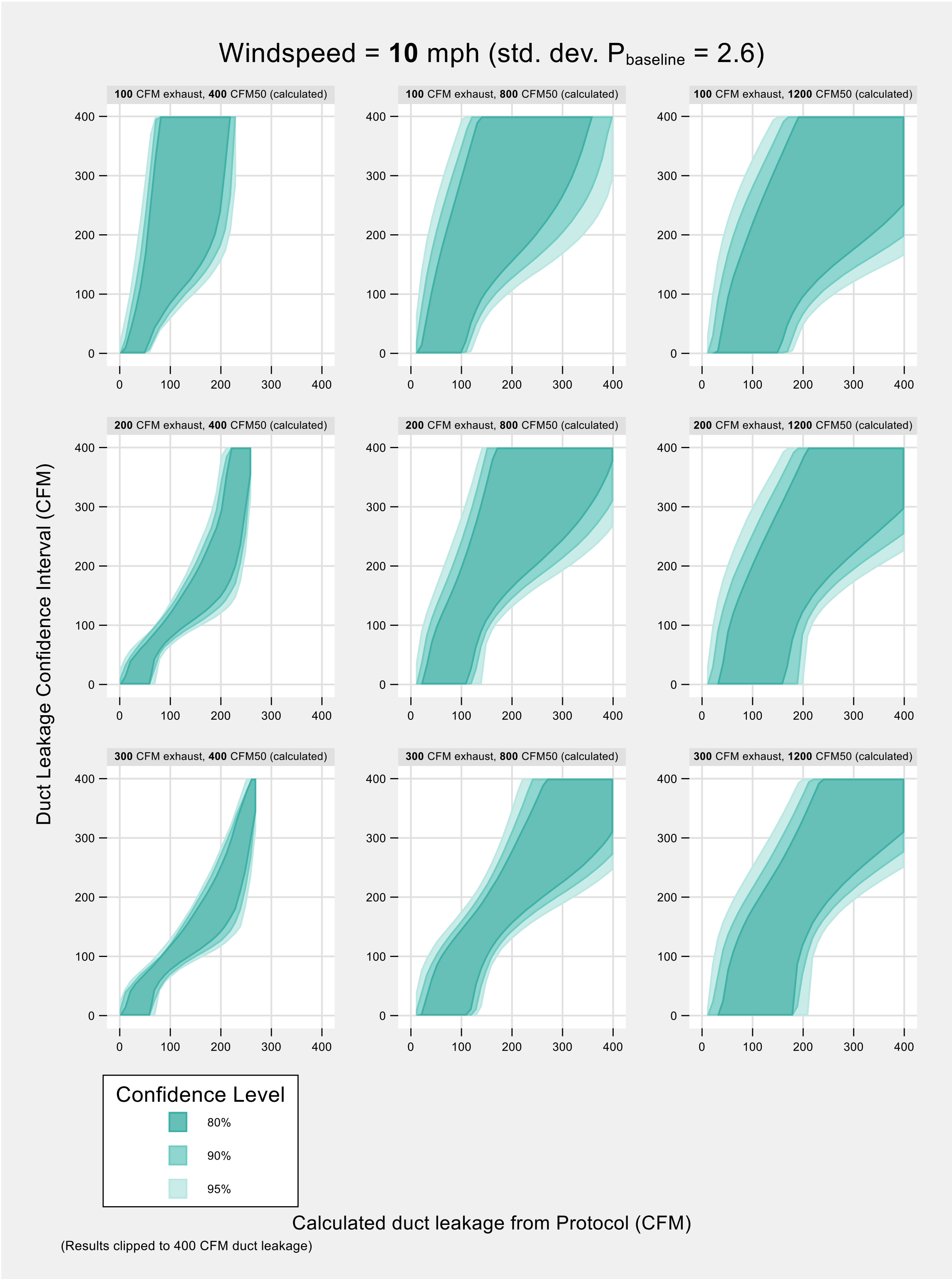


Figure 43. Confidence intervals for protocol-calculated duct leakage vs. observed house depressurization during air-handler operation, for selected levels of observed house depressurization during exhaust operation and windspeed, for 150 cfm of rated (but unmeasured) exhaust flow.