Residential Commissioning to Assess Envelope and HVAC System Performance

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ABSTRACT

Residential commissioning is a new procedure to ensure that a house can perform optimally, or at least meet basic safety, health, comfort, and energy intents. Many procedural elements, such as visual inspection and functional performance diagnostics, already exist in a fragmented environment. Most can be integrated into new industry guidelines for testing and tuning system performance in new and existing houses.

This paper describes a consolidated set of practical diagnostics that can be used now to commission envelope and HVAC system performance. Where possible, we discuss the accuracy and usability of available diagnostics based on recent laboratory work and field studies. We also describe areas in need of research and development, such as practical field diagnostics for envelope thermal conductance and combustion safety.

INTRODUCTION

Houses do not perform optimally or even as many codes and forecasts predict. For example, Walker et al. (1998a) found large variations in thermal distribution system efficiency—as much as a factor of two even between side-by-side houses with the same system design and installation crew. This and other studies (e.g., Jump et al. 1996) indicate that duct leakage testing and sealing can readily achieve a 25% to 30% reduction in installed cooling capacity and energy consumption. As another example, consider that the building industry has recognized for at least 20 years the substantial impact that envelope airtightness has on thermal loads, energy use, comfort, and indoor air quality. However, Walker et al. (1998a) found 50% variances in airtightness for houses with the same design and construction crews within the same subdivision.

A substantial reason for these problems is that few houses are now built or retrofitted using formal design procedures. Most are field assembled from a large number of components, and there is no consistent process to identify problems or to correct them. Solving the problems requires field performance evaluations of houses using appropriate and agreed upon procedures. Many procedural elements already exist in a fragmented environment; some are ready now to be integrated into a new process called residential commissioning (Wray et al. 2000). For example, California's Title 24 energy code already provides some commissioning elements for evaluating the energy performance of new houses.

A house consists of components and systems that need to be commissioned, such as building envelopes, air distribution systems, cooling equipment, heat pumps, combustion appliances, controls, and other electrical appliances. For simplicity and practicality, these components and systems are usually evaluated individually, but we need to bear in mind that many of them interact. Therefore, commissioning must not only identify the energy and non-energy benefits associated with improving the performance of a component, it must also indicate how individual components interact in the complete building system. For this paper, we limit our discussion to diagnostics in areas of particular concern with significant interactions—envelope and HVAC systems. These areas include insulation quality, windows, airtightness, envelope

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moisture, fan and duct system airflows, duct leakage, cooling equipment charge, and combustion appliance backdrafting with spillage.

The remainder of this paper first describes what residential commissioning is, its characteristic elements, and how one might structure its process. Subsequent sections describe a consolidated set of practical diagnostics that the building industry can now use. Where possible, we also discuss the accuracy and usability of these diagnostics based on recent laboratory work and field studies. We conclude by describing areas in need of research and development, such as practical field diagnostics for envelope thermal conductance and combustion safety.

There are several potential benefits for builders, consumers, code officials, utilities, and energy planners of commissioning houses using a consistent set of validated methods. Builders and/or commissioning agents will be able to optimize system performance and reduce consumer costs associated with building energy use. Consumers will be more likely to get what they paid for and builders can show they delivered what was expected. Code officials will be better able to enforce existing and future energy codes. As energy reduction measures are more effectively incorporated into the housing stock, utilities and energy planners will benefit through greater confidence in predicting demand and greater assurance that demand reductions will actually occur. Performance improvements will also reduce emissions from electricity generating plants and residential combustion equipment. Research to characterize these benefits is underway.

WHAT IS RESIDENTIAL COMMISSIONING?

Commissioning has its roots in shipbuilding, where the term describes the process that ensures a new vessel is seaworthy and ready for service. This process has many specific definitions. The variation relates to the scope of commissioning and the activities related to it. Some commissioning projects begin early in the design stage and continue through ongoing operations and maintenance. Others include activities to optimize performance beyond design intents (super-commissioning) or to adjust performance of existing facilities (retro-commissioning).

In a narrow sense, one can simply think of residential commissioning as a process only for new houses. This process would assure the owner that all required equipment is installed correctly, the final product is assembled correctly, and the house can perform as intended. Such a process might be carried out after installation and construction are complete and before the buyer occupies the new house. For the purposes of this paper, we broaden our definition of residential commissioning to include many other activities, such as rating, auditing, super-commissioning, or retro-commissioning. As such, it represents an expansion of processes currently carried out by people, such as home energy raters, home inspectors, auditors, and weatherization contractors. This expansion includes the energy performance of the large number of existing houses, as well as the indoor environmental performance of all houses.

Characteristic Elements

Residential commissioning, like every other commissioning process, includes the following three characteristic elements.

Metrics. For whole buildings, there are two broad performance objectives of interest—energy performance (e.g., consumption, peak load) and indoor environmental performance (e.g., IAQ, comfort). Various qualitative or quantitative metrics can represent each objective. Each metric is simply a scale to rank the performance element of interest for the relevant components or systems. Three examples of a metric are specific leakage area, which is a metric for the airtightness of the building envelope; duct leakage, which is a metric for the air leakage from a duct system; and house depressurization, which is a metric for the backdrafting potential of combustion appliances.

It is necessary to consider relationships between such metrics due to the energy and indoor environmental performance interactions between components and systems (Koles et al. 1996). For example, it is necessary to quantify specific leakage area, duct leakage, and house depressurization to understand the impact that reducing duct leakage flows to save energy can have on combustion safety in tight houses.

Diagnostics. Diagnostics are usually defined as relatively quick short-term field procedures. These procedures involve measurements and perhaps analyses to evaluate performance metrics for a system or component under functional test or actual building site conditions. An example of a diagnostic is a duct leakage test.

While it is also possible and sometimes preferable to evaluate metrics using data taken over an entire season, time limitations make it impractical to collect and analyze such long-term information during residential commissioning. These limitations will be largely dependent on the value of the commissioning process to the involved parties. However, for an existing house, commissioning can often use readily available historical data either as part of diagnostics or to set norms.

Norms. Norms are benchmarks against which component or system performance is compared. Examples of norms are the various building standards that specify requirements for minimum or maximum specific leakage area, for maximum duct leakage, and for maximum house depressurization levels. A specific example is the California Title 24 norm that duct leakage be 6% or less of the nominal total airflow through the air handler.

New and existing houses can use the same metrics and diagnostics, although some diagnostics may not be appropriate at all stages of the construction process. However, the norms for existing houses will have to be adjusted to account for the stage of the house in its life-cycle and the economic viability of meeting stricter standards than those in place at the time of construction. For example, a house built in 1930 does not come close to meeting current energy consumption limits. The retrofitting required to meet new insulation level requirements in this example would be prohibitively expensive.

The Commissioning Process

When commissioning is discussed, many in the building industry think of commercial buildings, although it is still uncommon to commission these buildings at any stage of their life cycle. Most descriptions of commercial building commissioning include the following three general steps: develop a commissioning plan, carry out inspections and functional performance tests, and review operations, maintenance, and training procedures (Wray et al. 2000).

Commissioning processes for houses are different. One reason is that commercial buildings tend to be more unique compared to one another, are large, have complex control systems, and have staff who manage operations and maintenance (O&M). As a result, a common step in the commissioning process for these buildings is developing unique documentation: a distinct commissioning plan and a building-specific O&M manual. This step is not warranted for most houses because they tend to be more similar compared to one another, are small, have few control systems, and have no O&M staff. Another reason is that we anticipate residential commissioning can sometimes provide better performance than is called for in the design; most commercial commissioning ignores this goal.

The residential commissioning process that we envision has three main phases, which are generic guidelines geared to specific commissioning issues or system and component types can probably encompass:

Audit and Diagnostic. In the first phase of commissioning, metrics for the house are surveyed. The results of this survey are then compared with the norms for the house. For new construction, the norms will be those such as California Title 24 standards or the equivalent local building codes. For an existing house, the norms may be based on design intents (if any were ever documented) or on what a particular component should be able to do compared to other similar houses.

Tuning and Tweaking. The performance of many components and systems may not meet the norms, but it may be possible to improve their performance by making minor adjustments, repairs, or retrofits on the spot. An example is sealing leaky ducts. Such tuning and tweaking can often provide significant improvements in performance for very little marginal cost. The purpose of this step is to improve the performance of the house to at least the design intent. Sometimes, that intent will be unknown. In those cases, the optimization will be to other norms, such as the best performance achievable within cost limits.

Opportunity Identification. After the tuning and tweaking, there still may be components that are not performing up to their potential. This commissioning step provides the client with information about what potential repair or retrofit opportunities need further consideration. Even when components are performing to their norms, the improved performance of new components or systems may make replacement worthwhile.

BUILDING ENVELOPE DIAGNOSTICS

The building envelope is important to house performance because envelope loads dominate its heat transfer mechanisms. HVAC system thermal loads, equipment sizing, structural durability, and occupant comfort are based on having the envelope perform as intended. In new houses, installation failures cause immediate problems. For example, Christian et al. (1998) indicate that insulation deficiencies can increase whole-wall heat transfer by about 14%, which will increase energy consumption and reduce comfort. Having an appropriate window type installed correctly can be even more important. Carmody et al. (2000) indicate that for double-glazed windows in a typical southern-climate house, a low-e film and vinyl frame can reduce peak cooling loads by about 25% compared to using clear glazing and an aluminum frame. Window emittance is the most important contributor to this difference. Consequently, mislabeled windows that are installed with an inappropriate emissivity or orientation can cause substantial energy and comfort problems. As the building ages, loss of durability caused by poor material selection and installation (e.g., insulation settling, air barrier damage from pre-installation UV exposure, water intrusion) can result in further performance reductions over time.

Insulation Quality

Visual Inspection. Several quantitative techniques for evaluating the thermal performance of insulation systems are described in the literature (Wray et al. 2000). These include the use of field diagnostic tools, such as heat flux transducer arrays, hot boxes, and the Envelope Thermal Test Unit (Modera et al. 1984), which is based on the guarded hot box concept. Some field techniques involve whole-building thermal conductance tests (Janssen and Rasmussen 1985; Sandberg and Jahnsson 1995). However, due to measurement biases in some cases, lack of portability or commercial availability in other cases, the need for expert users, excessive time requirements, and high equipment costs, these diagnostics are impractical in a residential commissioning environment. As a result, qualitative visual inspections (Consol 1999) will often play a key role instead.

Visual inspection determines the presence or absence of deficiencies, such as incorrect framing, incorrect insulation type, incorrectly installed insulation, incorrect air and vapor barrier placement, barrier damage, and blocked ventilation pathways (e.g., between attic and soffitt vents). Such inspections are simpler and most useful when carried out, during construction. The inspection of building assemblies should happen before the framing and insulation is sealed from view, when it is easier to correct problems. Inspection of these assemblies in existing houses often cannot be carried out and techniques that are more complex are generally required to avoid destroying the exterior or interior surfaces of the assembly.

These inspections do not quantify assembly thermal resistance or conductance (*R*-value or *U*-factor). However, data from these inspections, in conjunction with building plans or an assembly material audit, can subsequently be used to calculate assembly thermal performance. These calculations can be carried out using well-developed commercially available software. Some of this software can also predict thermal parameters, such as local and average surface temperatures as well as heat loss or gain rates. Unfortunately, most of this software is intended for research use rather than design or commissioning. Current efforts sponsored by the ASHRAE Technical Committee on Energy Calculations to create simplified methods of analysis may help alleviate this shortcoming.

Infrared Inspection. Infrared thermography systems and thermometers (radiometers) detect long-wave radiation during a scan of a building assembly and convert the long-wave radiation signal to a surface temperature using a fixed surface emissivity. Most thermographic systems and scanning radiometers produce false color images of the scan on a video display for easier viewing of intensity differences. Thermographic scanning equipment is expensive—the cost of a new system is in the range of $12,000 to $60,000. "Point source" radiometers are substantially less expensive (a few hundred dollars). They simply display a spot-area-average temperature as a meter reading. The spot area increases as the distance from the surface of interest increases. This device can be used as a crude screening mechanism to rapidly locate envelope element deficiencies.

The field use of any infrared inspection technique (ASTM 1990) is limited and may not be repeatable for several reasons. These include equipment thermal instability at very high or very low outdoor temperatures, poor resolution at low indoor-outdoor temperature differences, and distortion of surface temperature patterns by solar radiation and wind effects, differential heating or cooling rates of dry and wet areas, and nonuniform or specular emissivities. Infrared inspection generally cannot quantify assembly thermal conductance or even framing fractions (DEG 2000).

Within the limitations described above, infrared inspection can qualitatively identify areas of anomalous heat transfer caused by design and/or construction deficiencies of the building envelope. Examples include lack of insulation, displaced or improperly installed insulation, wet insulation, thermal bridging, air leakage, and air intrusion. Pressurizing or depressurizing the building using a blower door during a thermographic scan can highlight air leakage paths that might otherwise be confused as insulation anomalies. Thermographic scanning can also be useful in identifying envelope sections with internal convective loops.

Windows

Until recently, there were no practical field diagnostics to evaluate window radiative properties and behavior (e.g., glazing gap thickness, emittance, solar heat gain coefficient, daylight transmittance, and UV transmittance). A few inexpensive quantitative tools are now commercially available and more tools are under development. An example is a prototype handheld spectrometer to determine window emittance class (Griffith 1999). This surface-contact tool uses an infrared emitter and detector to evaluate the aggregate normal reflectance of a multipane glazing assembly. Simple LEDs are used to indicate whether the glazing is clear, has high-solar-gain low-e coating, or has low-solar-gain low-e coating. The spectrometer cannot distinguish which pane has the coating. However, another tool that uses laser reflection to measure glazing gap thickness is available for this purpose (EDTM 2000). Visible differences in laser reflection intensity indicate which pane has the coating.

Using noncontact infrared thermographic techniques in the field to assess window performance is generally impractical due to radiation transmission and reflection effects. The magnitude of these effects can be highly variable depending on the physical properties of the glass, the presence of surface coatings, and the surface finish.

Airtightness

Three diagnostic techniques can be used to quantitatively evaluate the airtightness of building envelope elements. They include using a blower door, AC pressurization (Sherman and Modera 1986), or pulse pressurization (Modera et al. 1987). Only the first technique is well developed and commercially available. A blower door consists of a calibrated flow meter combined with a fan mounted in a fabric or rigid panel, which is located in an open door or window. It is used to determine airflow through the envelope as a function of pressure difference imposed by the blower (ASTM 1999; CGSB 1986).

A two-point blower door test with multiple pressure difference and flow readings at each point provides a statistically better envelope leakage estimate than multiple points with a single reading at each point (Sherman and Palmiter 1994). However, a two-point test cannot distinguish leakage differences due to envelope changes at different pressures (e.g., a vent damper opening as the pressure differential increases). Multiple points can more clearly show such compliance, as well as instrumentation failures. Single-point tests, although quick, are unreliable for quantifying leakage because there is no method to check the accuracy of the result. However, single-point tests are useful qualitatively during air-sealing work to assess progress toward a planned airtightness goal.

Blower door tests are susceptible to wind effects (Modera and Wilson 1990) and stack effects. A practical wind speed limit with a single outdoor pressure tap located in a sheltered region is approximately 8 mph (13 km/h) or less. This constraint limits the times when accurate testing can be carried out. Manifolds connecting pressure taps on four faces of a building can be used in some cases for linear pressure-difference averaging and fluctuation damping in an attempt to reduce wind-effect-related precision errors and to extend conditions under which the test may be carried out (CGSB 1986). General guidelines suggest testing only when the outdoor temperatures are in the range of 41ºF to 95ºF (5ºC to 35ºC). In cold climates, this constraint severely limits times when accurate testing can be carried out.

Envelope Moisture

Diagnostics to assess moisture-damage susceptibility are not well developed. In particular, most diagnostics can only evaluate the presence of moisture rather than the susceptibility to moisture damage. These diagnostics typically involve visual and electrical inspection techniques. In some cases, infrared thermography has been used (Knehans and Styer 1983; Wild et al. 1998). However, that method requires substantial further development before it is ready for use in residential commissioning. There are no formal standards for assessing water damage or measuring the moisture content in building assemblies. Two diagnostic protocols have been developed recently by inspection agencies in an attempt to fill this void (NHCID 1998, GAHI 2000). These protocols are meant to address water damage that has occurred in southeastern U.S. houses clad with exterior insulation and finish systems (EIFS).

Visual Inspection. A visual surface inspection for excess moisture within the building envelope can be carried out by determining the presence or absence of deficiencies, such as wetness, microbiological growth (e.g., mold and mildew), discoloration, texture changes, and material dimensional changes, decay, or structural dislocation. Surface inspections are a useful screening technique, but the absence of visible deficiencies does not exclude the presence of excess moisture within the envelope. As a result, invasive tests may be necessary when occupants have associated allergic symptoms and/or there is high relative humidity indoors with no significant internal moisture sources and proper ventilation. Invasive tests can include tactile probing of envelope sections with a sharp probe and dismantling of envelope sections for internal inspection. Internal inspection involves looking for similar problems as those listed for surface inspections, as well as for problems, such as leaks, from plumbing systems.

Visual inspection focuses on observing existing problems. It is not appropriate in general for use during construction except for evaluating envelope detailing and plumbing system integrity. To evaluate moisture-damage susceptibility of new construction, checklists can be used in visible inspections of likely defects that may lead to future damage. As a supplement to visual inspection, impermeable or absorbent materials temporarily applied to surfaces can be used in qualitative comparative tests (Lichtman et al. 1999). However, these supplemental tests tend to be impractical because they are time consuming.

Electrical Inspection. Two types of electrical devices are well developed and commercially available for field assessments of the moisture content in building materials—surface scanning dielectric meters and penetrating conductance meters.

Surface scanning devices emit low-frequency electromagnetic waves and detect their disturbance to determine average moisture content. These devices are believed to be good indicators of high relative moisture content near the surface of nonconductive porous building materials (wood, drywall, plaster, roofing, insulation, carpet, and concrete). As a result, they are best used for comparative sampling over different regions of a surface to indicate the range of moisture content (e.g., a suspected wet region compared to a known dry region of similar material). Apparent high moisture content regions can then be checked with a subsurface resistance probe. An advantage of this device is that it does not damage envelope surfaces. A further advantage is that it can rapidly test large regions and provide continuous readings.

Penetrating conductance devices determine the moisture content of nonconductive porous building materials near their exposed surfaces. This method is based on measuring the resistance between the probes, which varies with moisture content. A disadvantage of this method is that it damages the envelope surface during probe insertion. It is also time consuming to insert and remove probes at each test site. However, probe insertion has the advantage that it can also provide a tactile indicator of subsurface structural decay.

All these electrical devices are sensitive to conductive materials, such as metal fasteners, flashing, and joints, which can cause false positive readings. Scanning device readings also require correction to account for material type. Although several studies report accuracy when these devices are used with wood products (James 1988; Warren 1994; ASTM 1998a), there appear to be no published data describing their accuracy for other materials, especially when combined as building assemblies.

AIR DISTRIBUTION SYSTEM DIAGNOSTICS

Residential air distribution systems include fans and ducts for space conditioning and ventilation. Poor construction and operation of the air distribution systems can cause comfort problems, poor indoor air quality, and structural moisture problems, as well as wasted energy. In particular, ducts that are part of the thermal distribution system may be the single worst performer in the energy performance of a house (Jump et al. 1996). Much of the problem can be attributed to installing ducts outside conditioned space, duct leakage, duct insulation compression, and other poor installation practices. Compared to the space conditioning system, the ventilation system in most houses is simple. It consists of operable windows, infiltration, and a few (if any) intermittently operated local exhaust fans. However, such systems are not always reliable for their intended purposes. To address this issue, more houses are beginning to also use whole-house ventila-

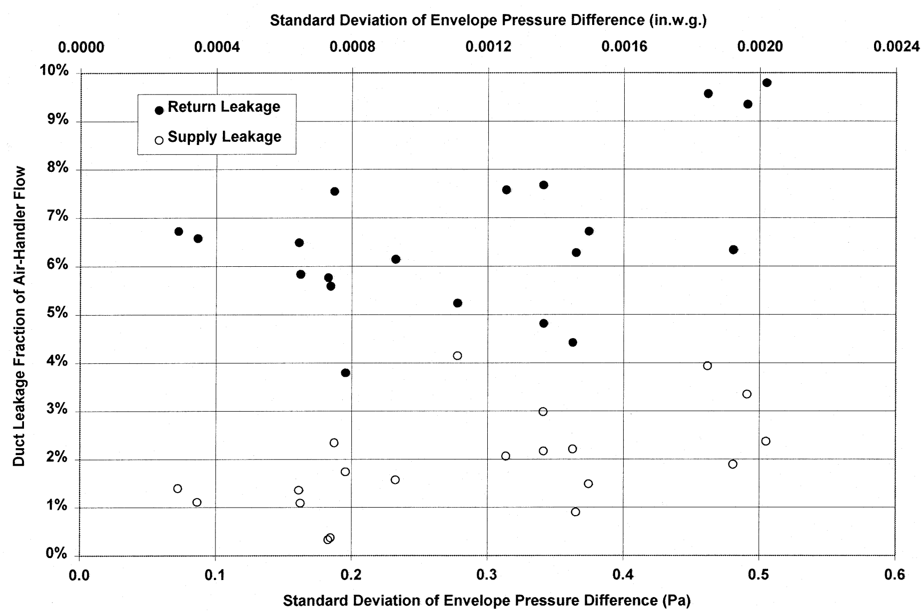

Figure 1 *Repeatability of DeltaQ duct leakage test.*

tion, which is sometimes directly linked to the space conditioning system. Furthermore, the proposed ASHRAE Standard 62.2 is expected to require mechanical ventilation in all new houses. Such ventilation practices and requirements mean that minimizing the impact of air-handler and ventilation airflows on fan power is of increasing importance to utilities and energy planners (in terms of peak power) and residents (higher energy bills). At the same time, ensuring good delivery effectiveness and room-by-room distribution efficiency of thermal and ventilation distribution systems depends on maintaining proper airflow through these systems.

Duct Leakage

Several quantitative diagnostics are available to uniquely determine duct leakage (Walker et al. 1998a; Walker et al. 1999; Francisco and Palmiter 2000)—the DeltaQ test, the duct pressurization test, the house pressure test, and the nulling pressure test. The pressure pan test (Siegel and Manclark 1998) is not included in this list because its pressure indication does not uniquely determine leakage. As a result, it is not recommended for commissioning except as a rapid screening supplement to more elaborate tests. The cost and accuracy of duct leakage testing is in the process of being improved by several researchers and the ASTM standard test method for measuring duct leakage is being rewritten to include newer methods (E1554 – which will be completed in 2001). The standard (and our discussion) focuses on the DeltaQ and duct pressurization tests because they are the simplest in terms of equipment and procedure, are more robust, and, in some cases, are more flexible in terms of the types of houses or systems that can be tested.

DeltaQ Test. This test is based on changing the airflows through distribution system leaks by turning the air handler on and off while pressurizing and then depressurizing the building envelope to various pressure differentials using a blower door. The advantages of this test (compared to duct pressurization) are that it determines envelope leakage at the same time as duct leakage, and there are no requirements for grille sealing or for separation of the supply and return systems at the air handler by a seal. This makes the test less time consuming and less susceptible to leakage caused by poor sealing or seal failure during the test. Air leakage to outside through supply and return leaks is determined directly with the ducts at operating pressures. Testing the system at operating pressure significantly reduces the uncertainty that occurs when converting measured duct leakage at other than operating pressures to measured operating pressures. The DeltaQ test can only be used in finished houses because it requires an envelope that can be pressurized.

Test precision and bias are susceptible to wind speed and direction variation that result in envelope pressure fluctuations. Resulting fractional errors in duct leakage can be large, although absolute flow errors will remain small. The practical limit for wind speeds when accurate testing can be carried out is not currently known. Research is in progress to determine the wind limitations for this test. As Figure 1 shows, preliminary data for a single building indicate good repeatability—0.5% to 1.0% of air-handler flow for a 95% confidence interval (Wempen 2000). These data are from 20 tests in mild weather for wind speeds of 5 mph (8 km/h) or less with a tight duct system and envelope (about 7% return leakage, 2% supply leakage, and a normalized envelope leakage of about 0.5).

This test is also susceptible to stack effects, which may affect the apparent leakage area of the envelope and duct system. This bias is not expected to be large. Outdoor temperature limits to reduce stack-effect-induced pressure variation are unknown, but we expect that the suggested outdoor temperature limitations for envelope airtightness tests are probably also applicable.

Duct Pressurization Test. This test can be used in unfinished or finished houses. It uses a small fan-assisted flow meter (and in some cases a blower door as well) to determine duct leakage by pressurizing the duct system to 25 Pa with the supply-and-return grilles sealed. Sealing grilles can be difficult (e.g., hard to reach on high vaulted ceilings) and time consuming (e.g., taping each grille, often while standing on a ladder). Sometimes it is also difficult or impossible to install the air-handler seal due to the equipment configuration. All of these seals are susceptible to failure during the test. If separate supply-and-return leakage data are required, then the supply-and-return sections at the air handler must be separated by a seal. Duct leakage to outside is determined by pressurizing the house with a blower door to the same pressure as the duct system (25 Pa), so there is no pressure difference to drive flows across duct leaks to inside.

The duct pressurization test requires that the operating static pressure in the supply and return duct systems be measured. Measured operating pressures at plenums are then used to convert leakage measured at the imposed pressure (25 Pa) to operating conditions. An advantage of measuring these pressures is that they are also a useful indicator of ducts that are undersized or that are restrictive due to their topology and fittings. However, these operating pressures may be a poor indicator of the pressure at duct leaks, whose location is unknown. As a result, the duct pressurization test is less appropriate in houses with leaky ducts. The precision is primarily affected by conversion from imposed to operating pressure—conversion increases uncertainty. The absolute precision error in flow increases with increasing duct leakage flow, but the fractional uncertainty remains approximately constant.

The duct pressurization test is also susceptible to wind and stack effects, but less so than for the DeltaQ test because it does not use envelope pressure in its calculations to determine duct leakage.

Air-Handler Airflow

Several diagnostic tools and techniques can be used to determine airflow through the air-moving equipment of cooling and heating systems. However, there is currently no reference method for field use. Two of the most promising practical and commercially available tools include a fan-assisted flow meter (Walker et al. 1999) or a flow plate and grid (Palmiter and Francisco 2000).

Other techniques include using the air temperature difference across the air-handler (Downey and Proctor 1999), a tracer gas (Walker et al. 1998b), the sum of duct branch flows, or fan curve interpolation. Of these other techniques, the first is prone to errors of more than 20% in many cases and near a factor of two in worst cases due to flow nonuniformities and radiant effects (Palmiter and Francisco 2000). While using a tracer gas can be very accurate, it requires expensive, delicate equipment and a well-trained technician. It is also subject to errors induced by flow nonuniformity, which are difficult to assess in the field. Measuring individual duct branch flows and summing them can lead to substantial errors because of the addition and subtraction of many uncertain numbers. As described later in this paper, much of the uncertainty is due to inaccuracy when commercially available flow hoods are used or when duct leakage is not properly taken into account. Fan curve interpolation cannot be relied upon because manufacturer's fan curve data are not easily or generally available for residential systems. When it is available, it may not accurately represent the installed performance of the fan due to system effects. These effects can vary significantly and are difficult to estimate. In addition, it is not possible to measure the static pressure drop in the duct system at the same locations as those used to produce the manufacturer's fan curve.

Fan-Assisted Flow Meter. This device uses a calibrated flow meter combined with a fan to determine air-handler airflow. It can be attached to the air-handler cabinet at its access door or at a return grille if the return ducting is well sealed. With the air handler running, air is blown into the air handler or return (with the return sealed if connecting to the air handler). The goal of this test is to reproduce the pressure difference between the supply plenum and conditioned space under normal system operating conditions. If this operating pressure cannot be achieved due to capacity limits of the fan on the flow meter, then multiple measurements of flow and supply plenum static pressure are used to extrapolate to the operating pressure.

It is time consuming to attach the flow measurement device to the air handler or return. Additional time is required to seal off the return upstream of the air handler if the device is connected to the air-handler cabinet. Based on field tracer gas tests (Walker et al. 1998b), we expect the accuracy of this test method is approximately ±10%. However, the actual accuracy is unknown at this time and cannot be easily estimated due to the possibility of flow pattern changes within the air handler or static pressure measurement errors. Further research is needed to establish the accuracy of this method.

Flow Plate and Grid. This new device uses a calibrated multiple-orifice plate with attached upstream and downstream pressure manifolds to determine air-handler airflow. The device is inserted into an air filter body in place of the filter. The pressure drop of the device is intended to be similar to that of an air filter. In general, the "measured" airflow needs to be corrected to account for the difference in supply plenum static pressure with the device installed instead of the filter. Also, when the flow plate is mounted at a filter grille, the return duct leakage needs to be added to the measured flow.

Using fan-assisted flow meter measurements as a reference, preliminary comparisons of airflows obtained using the flow plate and grid in 74 houses indicate its measurements are within 17% of the "reference" method (Palmiter and Francisco 2000). In 54% of the house, differences are less than 5%. Reasons for differences are not reported, but they might be related to plenum static pressure measurement errors. Francisco (2000) has indicated that upstream flow disturbances, such as 90º bends in the return duct as close as 3 in. (75 mm) to the plate, do not adversely affect measurement accuracy.

Distribution System Airflows

Several diagnostics are available to determine airflow rates through air distribution systems. They include a fan-assisted flow hood (Walker et al. 1999), a conventional flow hood (no fan assist), anemometry, a pitot tube traverse, or a flow grid. Of these, only the first is accurate and reliable. The other methods are error prone due to the effects of flow nonuniformities, difficulties in estimating effective flow areas (anemometry), uncertainty in determining insertion depth (pitot tube), low velocities, misaligned sampling of the airstream, fouling (flow grid), and duct leakage.

Of particular note, conventional nonpowered flow hoods are sometimes an order of magnitude less accurate than what many in the HVAC industry believe. Laboratory test data shown in Figure 2 demonstrate the large unacceptable imprecision of several commercially available flow hoods. We obtained these data using a single-branch duct with and without various grilles, with an inline flow nozzle as a reference.

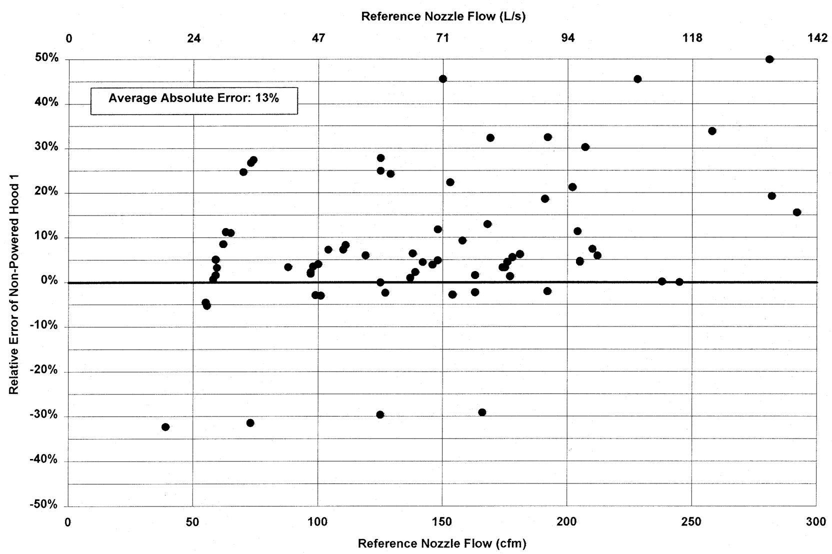

Figure 2a Accuracy of conventional nonpowered flow hood 1.

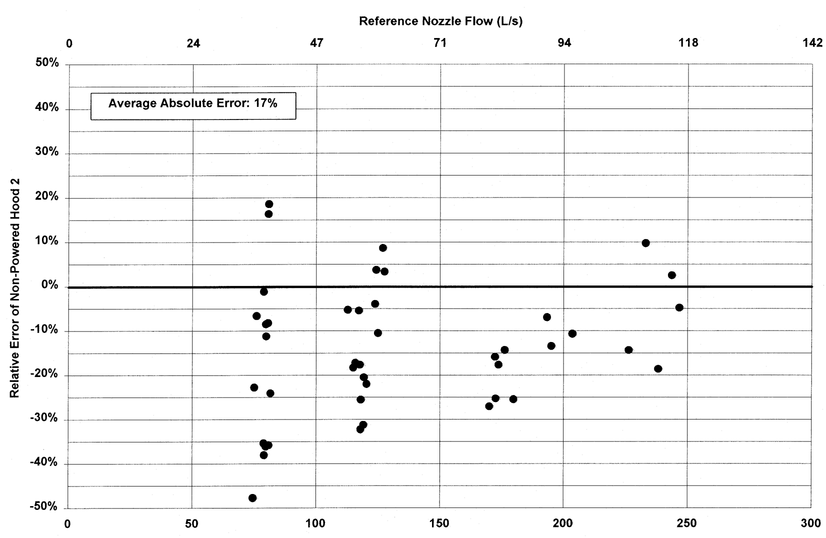

Figure 2b Accuracy of conventional nonpowered flow hood 2.

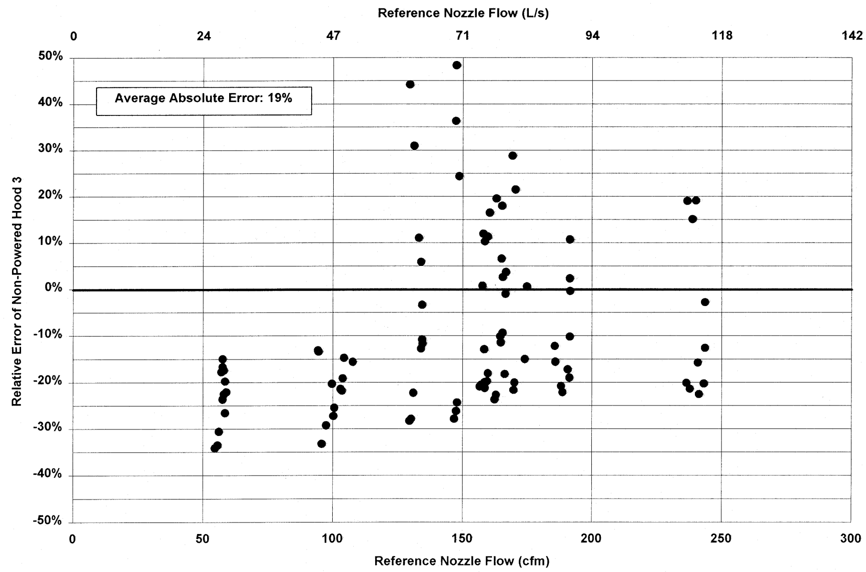

Figure 2c *Accuracy of conventional nonpowered flow hood 3.*

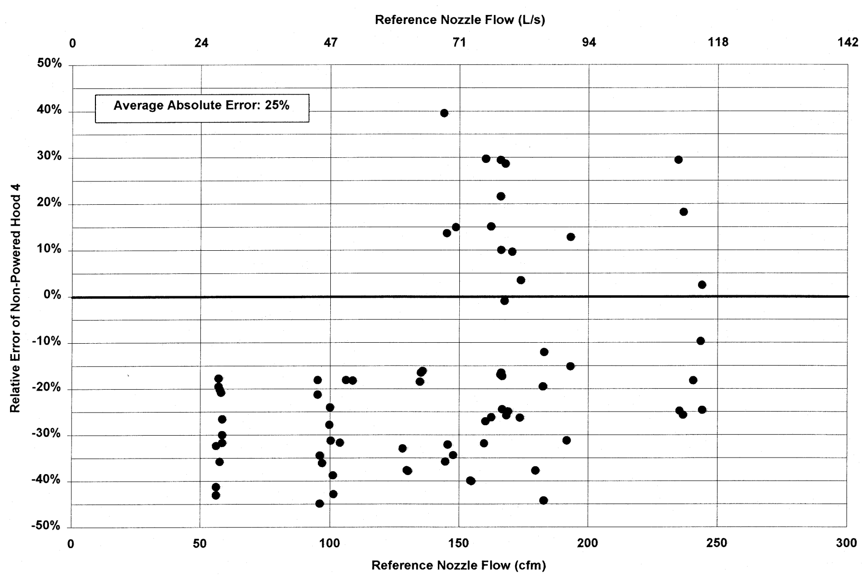

Figure 2d *Accuracy of conventional nonpowered flow hood 4.*

In some cases, measurement errors are as large as 50%, but they are typically about 15% to 25%. Field data that we have gathered using a fan-assisted flow hood for comparison support these findings. The measurement errors are likely due to recirculation regions that occur within the hood and nonuniformity of flow at the flow hood sampling points. Manufacturers recommend using a hood size close to the grille size to reduce this problem. However, this is often not possible because most of these hoods are intended for use in commercial buildings and are much larger than most residential grilles. The extent of this problem also depends on flow rate, duct topology upstream of the grille (e.g., nearby elbows), and grille type. Grilles with more side discharge than direct discharge are more likely to cause recirculation regions. ASHRAE (1988) recommends using a pitot tube traverse of the duct section upstream of a grille, with and without the hood in place, to determine a flow correction factor that will account for measurement errors. Such a practice is impractical for most residential systems. First, traverses can be difficult or impossible in many cases. Second, the correction can be very specific to a given grille. Obtaining this correction factor for each grille makes the use of the flow hood redundant.

Fan-Assisted Flow Hood. A fan-assisted flow hood is similar to a conventional hood but also has a fan-assisted flow meter attached by a flex duct. Unlike a conventional hood, this device does not require an elaborate seal at the gap between the hood and the adjacent building surface because the integrated fan maintains a relatively neutral pressure difference between the interior and exterior of the hood. At the same time, the fan assist also eliminates the backpressure problems that are created by conventional flow hoods. The location of the measurement device at the end of 6 ft (2 m) or more of flex duct attached to the flow hood virtually eliminates errors due to flow nonuniformities.

Figure 3 shows data from laboratory tests of a fan-assisted flow hood that were obtained in a manner similar to those described above for the conventional flow hoods. It appears this device can achieve significantly better accuracy—its average relative error is approximately 2%, and no error is worse than 5%. Unfortunately, such devices are not yet commercially available but can be easily constructed of readily available components. Such a device is under development now to address this need, but it will require field testing to assess its accuracy and usability.

COOLING EQUIPMENT DIAGNOSTICS

Even in new houses, cooling systems rarely perform as intended (Sherman et al. 1987). Aside from inadequate airflow across evaporator coils, low refrigerant charge levels are a significant cause of this problem. Refrigerant charge has a particularly important impact on the capacity and efficiency of cooling equipment without a thermostatic expansion valve (TXV). For example, laboratory test data from Farzad and O'Neal (1988) for capillary-tube-controlled equipment indicate that a common charge deficiency of 15% can reduce equipment cooling capacity by 8% to 22% and the energy efficiency ratio (EER) by 4% to 16%, depending on outdoor conditions.

Refrigerant Charge Level

Several diagnostic techniques are available to assess the refrigerant charge level in residential cooling equipment. These techniques include superheat or subcooling tests, a gravimetric test, a sight glass, thermostatic expansion valve (TXV) frosting, "feeling the lines," or motor signature analysis. Of these, only the superheat and subcooling tests are quantitative, practical, well developed, and reliable. Those tests are not standardized but are commonly specified by equipment manufacturers.

The other techniques are qualitative in some cases, unreliable, time consuming, or not well developed. Although the gravimetric test can accurately determine the amount of refrigerant and noncondensable fluids in a cooling system, it is problematic because the amount of refrigerant required for optimal system performance is often unknown. This problem occurs due to the use of refrigerant line lengths and coils that do not conform to manufacturer's specifications. In particular, it is difficult to quickly estimate the internal volume of coils, especially when tubing wall thickness is unknown. Furthermore, volumetric calculations are insufficient to account for evaporator heat transfer characteristics that differ from those of the manufacturer-specified coil. Only a functional performance test, such as the superheat and subcooling tests, can account for this difference.

Superheat/Subcooling Tests. These tests (Downey and Proctor 1999) assess charge level by determining the refriger-

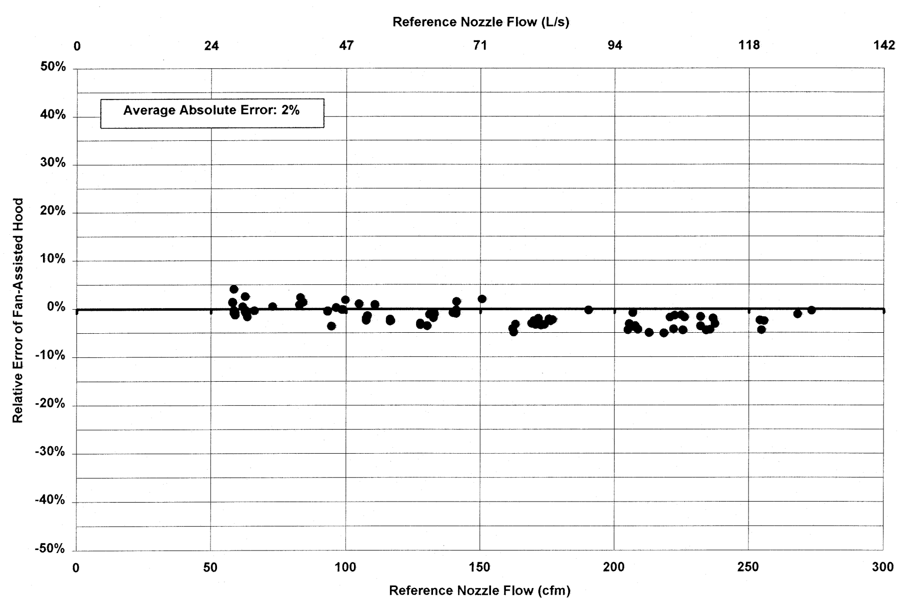

Figure 3 *Accuracy of fan-assisted flow hood.*

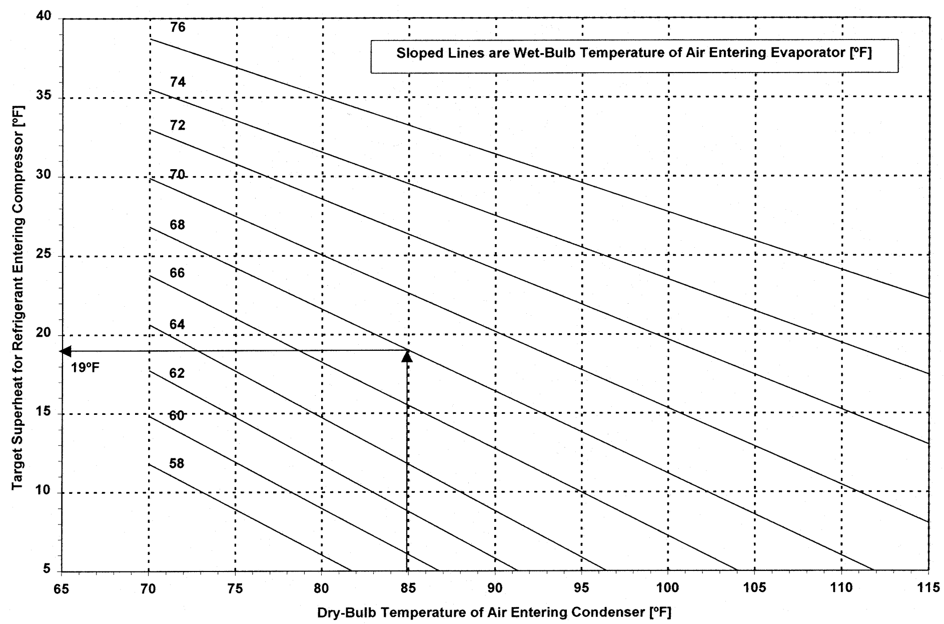

Figure 4 *Refrigerant superheat charging chart.*

ant thermodynamic state at a specific point in the system. For the superheat test, which is used for cooling equipment with a fixed metering device (capillary-tube or short-tube orifice), the location is the compressor inlet at the condensing unit. The concept here is to make sure that the refrigerant is fully evaporated upon leaving the evaporator. For the subcooling test, which is used for TXV-equipped cooling equipment, the location is the condenser exit at the condensing unit. In this case, the concept is to make sure that the refrigerant is fully condensed upon leaving the condenser.

Consider the superheat method. Refrigerant suction line temperature and pressure, condenser inlet air dry-bulb temperature, and evaporator inlet air wet-bulb temperature are measured after the cooling equipment runs for about 15 minutes to achieve equilibrium (steady-state operation). "Measured" superheat is based on the difference between the measured suction line temperature and the refrigerant saturation temperature corresponding to the measured refrigerant pressure. Proper charge is typically indicated by a "measured" superheat not lower than 5ºF (3ºC) and within 5ºF (3ºC) of a target superheat at test conditions. Refrigerant charge is low if the "measured" superheat is more than 5ºF (3ºC) above the target superheat at test conditions. Charge is high if the "measured" superheat is more than 5ºF (3ºC) below the target superheat at test conditions.

The target superheat is determined using the equipment "superheat chart." Figure 4 (Downey and Proctor 1999) shows such a chart, which typically relates superheat (5ºF to 40ºF, 3ºC to 22ºC) as a function of outdoor air dry-bulb and return air wet-bulb temperatures. The intent of these targets is to facilitate equipment charge evaluation when it is operating at other than design conditions.

At this time, there are no standards specifying temperature and pressure measurement accuracy or specific measurement locations for a superheat test. As a result, there can be significant variability in "measured" superheats. Example problems include measuring the indoor wet-bulb within the house rather than within the return plenum downstream of return duct leaks, measuring outdoor air temperature remotely from the condensing unit in direct sunlight with an unshielded sensor, and measuring refrigerant line temperature downstream of a line restriction or with an uninsulated sensor that has poor surface contact. Uncertainties in these measurements can easily lead to "measured" superheat errors of 10ºF (6ºC) or more. Laboratory test data from Farzad and O'Neal (1988) for capillary-tube-controlled equipment indicate a 10ºF (6ºC) superheat error can result in a charge assessment difference of about 5% to 9%, depending on outdoor temperature.

The superheat method cannot be used in cool weather (outdoor air temperature less than 50ºF or 10ºC). This limitation is primarily to protect the compressor from failure due to insufficient lubricant circulation under these conditions. The method also cannot be used in hot, dry climates (e.g., summer in Fresno, California) when there is a low return air wet-bulb temperature coincident with a high outdoor air dry-bulb temperature. Testing in the spring when outdoor air dry-bulb temperatures are not too hot can circumvent this problem. Alternatively, the indoor wet-bulb can be elevated artificially by overheating and humidifying the house. This latter technique requires further development to determine appropriate strategies.

COMBUSTION APPLIANCE DIAGNOSTICS

While poor design or installation of the building envelope, combustion equipment, or air-moving equipment can reduce efficiency, it can also lead to downdrafting and possibly backdrafting with combustion gas spillage. Downdrafting is inward airflow from outdoors through a flue or chimney when no connected combustion appliance is operating. Appliance backdrafting is the failure of an operating combustion appliance to reverse a downdraft and to establish a proper flow of combustion gas products toward outdoors through the attached flue or chimney. Spillage is the entry of combustion gas products into the indoor air. Any of these phenomena can be caused by excessive depressurization of a house when exhaust equipment are operating. Such events, along with insufficient ventilation for unvented combustion appliances, can directly affect the indoor environment by causing health, comfort, or indoor air quality problems.

Substantial work has been carried out in Canada and the United States over the past 20 years in an attempt to understand backdrafting and spillage events related to combustion equipment venting and the operation of exhaust devices in houses, how long such events last, and how frequently they occur. Several "snapshot" style test protocols have been developed (CGSB 1995; ASTM 1998b) to indicate the potential for problems. Specifically, four tests available to assess the backdrafting and spillage potential are the house depressurization test, the downdrafting test, the appliance backdrafting test, and the cold-vent establishment pressure (CVEP) test.

Due to the short time span of these tests, it may be desirable to sample multiple times over the life cycle of the building, particularly when the envelope airtightness, air-moving equipment, or combustion appliances change. However, long-term monitoring is probably impractical as a commissioning tool to achieve this end. All these tests are problematic, because they are susceptible to wind effects, which can easily result in false positive or negative test results (Nagda and Koontz 2000). Further research is needed to assess their accuracy and repeatability. However, given that life safety and chronic health problems have been associated with combustion gas spillage, it is still better to use these imperfect methods than not.

RESEARCH AND DEVELOPMENT NEEDS

For every building element discussed above, practical diagnostics are available now to commission envelope and HVAC system performance. However, some of these diagnostics require further research and development to assess or improve their usefulness and accuracy, so that they can be used more extensively and reliably. In particular, the following eight areas need further work:

1. A practical diagnostic is needed to evaluate the in situ thermal conductance of envelope assemblies.
2. Formal standards are needed for assessing water damage and measuring the moisture content in building assemblies.
3. The impact of wind effects, as well as envelope and duct leakage, on the accuracy and repeatability of the new DeltaQ duct leakage test needs further research.
4. Formal standards are needed for the calibration and use of airflow diagnostic tools, such as flow hoods with and without fan assist, and the flow plate and grid that temporarily replaces an air filter.
5. Formal standards are needed for superheat and subcooling tests of cooling equipment.
6. Research is needed to develop a method of assessing refrigerant charge in cool weather.
7. The utility of temporarily elevating indoor enthalpy needs to be examined to extend the periods when the superheat method can be used to test cooling equipment in hot, dry climates.
8. The accuracy and repeatability of methods that determine the potential for backdrafting and combustion gas spillage needs further research.

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